SOFT SENSING OF COAL QUALITY

by

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This study presents a soft sensing model of coal quality for utility boilers. This model is based on the coal quality information obtained from exhaust gas. The mechanism modeling method combined with data driving theory is used in the modeling process. The procedure for solving the non-linear equations for coal quality applies the inner loop iteration of dry ash-free basis of S (S_{daf}) and outside loop iteration of dry ash-free basis of N (N_{daf}) within a limited range, and dry ash-free basis of C (C_{daf}) is searched from the entire range during outside loop iteration. The upper and lower limits of N_{daf} are defined according to the NO_X content in the exhaust gas, thereby solving the iterative initial value selection problem. Finally, the effectiveness of the proposed method is verified via several simulations and comparisons, the results show that this method is credible and effective and it can be used in power plant for control system optimization.

Key words: *coal quality, soft sensing, data driving, mechanism modelling*

Introduction

The main factors that affect furnace heat are the quantity and quality of coal. In China, the composition of coal used in coal-fired power plants is complex and changeable; a large proportion of low-quality and low volatile coal is used in daily production. In coal-fired power plants, highly accurate belt scales are commonly used to measure coal quantity, thereby making coal quality the dominant factor in coal burning. Large changes in coal composition and calorific value destabilizes furnace combustion. If coal quality can be monitored and measured on-line, the airflow and feed water systems can be adjusted in time, which is beneficial to the stability and economic operation of coal-fired power plants.

Two methods exist for coal quality analysis: elemental analysis and industrial analysis, with the latter being more convenient. Generally, power plants use only industrial analysis to measure coal moisture, ash content, volatile matter, calorific value, as well as the amount of fixed carbon. Industrial analysis is usually performed twice a day. From sample preparation to obtaining the analysis results, the procedure takes about 8 hours to 10 hours at least. This type of off-line measurement method involves long delays and the measured results cannot be used to guide combustion control, monitoring, and diagnosis systems. Therefore, knowing the elemental composition of coal on-line is highly valuable for improving the combustion process and is a useful indicator of coal quality [1, 2].

On-line measurement of coal quality (element) can be categorized into two types: direct hardware sensing and indirect soft sensing.

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Direct hardware sensing methods generally involve coal elemental analyzers based on prompt gamma neutron activation analysis (PGNAA, *e. g*., the Gamma-Metrics CQM, which is introduced by Gamma-Metrics Company, and the LB420 ash composition analyzer and neutron moisture analyzer, which is introduced by Berthold Company of Germany) and methods such as laser-induced breakdown spectroscopy [3], microwave [4], near-infrared spectroscopy [5], and terahertz spectroscopy [6]. These methods are usually highly accurate, but they require expensive hardware that is more complex to use in production. Therefore, these methods cannot be widely used in coal-fired power plants.

In recent years, indirect soft sensing methods have attracted intense research interest. These methods generally use easily measured process variables to estimate the target variable, which usually cannot be measured directly or is difficult to measure using mathematical calculations and estimation methods. The principle of the soft sensing method is to establish a mathematical model between these easily measured variables and the target variables. Three main types of soft sensing modelling methods are used. The first method is based on the reaction mechanism of the process. The model can be built according to the internal law of the process, which usually follows basic physical or chemical laws [7]. The second method is a statistical modelling method based on data driving. In this method, the object is considered a black box, a mathematical model that can be used to reflect the process characteristics deduced using the input and output data. This modelling method does not require the study of the reaction mechanism of the process. Soft sensing models can be built as long as the process data are sufficient [8-11]. The third and last modelling method is a combination of the first two and is highly useful for complex industrial processes. Current research focuses on this third method, *i. e*., the mechanism modelling method combined with data driving theory [12, 13].

On-line soft sensing methods for coal quality can be categorized into two types: one uses artificial intelligence to predict the contents of the coal based on industrial analysis. For example, the artificial neural network-based prediction of hydrogen content in coal using proximate analysis proposed in [1] is accurate and can be used to measure other elements. However, this method is only suitable when industrial analysis results can be obtained online. A different method is based on the operation data of the unit, such that analysis results can be obtained without the increment of any other hardware. One example of this method is the on-line monitoring method of coal quality and calorific value proposed in [14]. However, the model used in this method is complex and involves a large number of parameters, thereby making the initial value of the iterative calculation process difficult to obtain.

The theory of on-line soft sensing of coal quality

Exhaust gas with a certain composition is generated after the combustion of coal with a certain composition. The components of the exhaust gas contain the element information of the coal fed into the furnace, *i. e*., correspondence exists between the composition of the exhaust gas and the coal element. At present, because of environmental protection requirements, the instruments used to analyze exhaust gas composition are equipped in large-capacity units. Therefore, the proposed on-line soft sensing model for coal elements is mainly based on the law of conservation (matter and energy) and chemical analysis of coal combustion. The relevant information on the coal elements is extracted from exhaust gas components.

Unit overview

The research work is expanded based on a power plant with a 600 MW turbine. The boiler is an HG-2023/17.6-YM4 made in the Harbin boiler plant and has the following properties: sub-critical, single reheat, controlled circulation boiler drum, single furnace and Π-type layout. The turbine is an N600/16.7/537/537/-F made in the Harbin steam turbine plant and has the following properties: sub-critical, single reheat, uniaxial with four cylinders, and four exhaust-steam reaction types. Each unit is equipped with six sets of positive-pressure, direct-fired pulverizing systems. The coal feeder is an EG-24 belt weighing-type coal feeder. The mill is a ZGM-123 medium-speed roller mill.

Relationship between coal elements and exhaust gas components

Combustion of coal in a furnace is an exothermic chemical reaction between the combustible elements in the coal and oxygen in the air at high temperature. The combustible elements in coal are carbon, sulphur, and hydrogen. In the case of complete combustion, the combustion chemical reaction equation of each combustible element is:

$$\mathrm{C} + \mathrm{O_2} = \mathrm{CO_2} \tag{1}$$

$$\mathrm{S} + \mathrm{O_2} = \mathrm{SO_2} \tag{2}$$

$$2\mathrm{H_2} + \mathrm{O_2} = 2\mathrm{H_2O} \tag{3}$$

In standard conditions, the theoretical amount of air required V_{gk}^0 [Nm^{3}kg^{-1}] for complete combustion of 1 kg of coal in a furnace is:

$$V_{\mathrm{gk}}^0 = 0.0889(C_{\mathrm{ar}} + 0.375S_{\mathrm{ar}}) + 0.265H_{\mathrm{ar}} - 0.0333O_{\mathrm{ar}} \tag{4}$$

Actual boiler combustion involves a loss of incomplete combustion of solid material, in which unburned carbon content is C_{ucr} (including carbon in slag and fly ash, %), whereas the proportion of incomplete combustion of the gas is negligible, such that the actual amount of air consumed is V_{gk}, which is expressed:

$$V_{\mathrm{gk}} = V_{\mathrm{gk}}^0 - \frac{0.0889A_{\mathrm{ar}}C_{\mathrm{ucr}}}{100 - C_{\mathrm{ucr}}} \tag{5}$$

In addition, in the actual combustion process, oxygen is sufficient. The actual volume of dry flue gas produced by the combustion of 1 kg of coal in a furnace V_{gy} is:

$$V_{\mathrm{gy}} = V_{\mathrm{CO_2}} + V_{\mathrm{SO_2}} + V_{\mathrm{N_2}} + V_{\mathrm{O_2}} + \sum V_i \tag{6}$$

where

$$V_{\mathrm{CO_2}} = 0.01866\left(C_{\mathrm{ar}} - \frac{A_{\mathrm{ar}}C_{\mathrm{ucr}}}{100 - C_{\mathrm{ucr}}}\right) \tag{7}$$

$$V_{\mathrm{SO_2}} = 0.007S_{\mathrm{ar}} \tag{8}$$

$$V_{\mathrm{N_2}} = 0.008N_{\mathrm{ar}} + (1-\phi)\alpha V_{\mathrm{gk}} \tag{9}$$

$$V_{\mathrm{O_2}} = (\alpha - 1)\phi V_{\mathrm{gk}} \tag{10}$$

The volume share of each type of dry flue gas can be expressed as:

$$\gamma_{CO_2} = \frac{V_{CO_2}}{V_{gy}} \tag{11}$$

$$\gamma_{SO_2} = \frac{V_{SO_2}}{V_{gy}} \tag{12}$$

$$\gamma_{O_2} = \frac{V_{O_2}}{V_{gy}} \tag{13}$$

From eqs. (4) to (13), C_{ar}, H_{ar}, O_{ar}, N_{ar}, S_{ar}, A_{ar}, and M_{ar} are the ingredients of coal on an as-received basis [%]; A_{ar} is the ash content and M_{ar} is the coal moisture; V_{CO_2}, V_{SO_2}, V_{O_2}, V_{N_2}, and ΣV_t are the volumes of CO_2, SO_2, O_2, N_2, and trace gases in the fuel gas, respectively [Nm^3kg^{-1}]; α is the ratio of excess air in flue gas, and ϕ is the volume of the oxygen in the air (generally, $\phi = 0.21$ at sea level). ϕ decreases as altitude increases. Thus, ϕ has to be corrected according to altitude or atmospheric pressure.

On-line soft sensing model for coal quality

By multiplying $100/(100 - M_{ar} - A_{ar})$ by both sides of eqs. (4) to (10), we can obtain the dry ash-free basis and volume of the relevant parameters. The effects of moisture and ash are concentrated in the correction quantity of unburned carbon loss Γ_{cucr}:

$$\Gamma_{cucr} = \frac{100 A_{ar} C_{ucr}}{(100 - M_{ar} - A_{ar})(100 - C_{ucr})} \tag{14}$$

$$V_{gk,daf} = 0.0889(C_{daf} + 0.375 S_{daf}) + 0.265 H_{daf} - 0.0333 O_{daf} - 0.0889 \Gamma_{cucr} \tag{15}$$

$$V_{CO_2,daf} = 0.01866(C_{daf} - \Gamma_{cucr}) \tag{16}$$

$$V_{SO_2,daf} = 0.007 S_{daf} \tag{17}$$

$$V_{RO_2,daf} = V_{CO_2,daf} + V_{SO_2,daf} \tag{18}$$

$$V_{N_2,daf} = 0.008 N_{daf} + (1-\phi)\alpha V_{gk,daf} \tag{19}$$

$$V_{O_2,daf} = (\alpha - 1)\phi V_{gk,daf} \tag{20}$$

where

$$\alpha = \frac{\phi(1-\gamma_{O_2})V_{gk,daf} + V_{RO_2,daf}\gamma_{O_2} + 0.008 N_{daf}\gamma_{O_2}}{(\phi - \gamma_{O_2})V_{gk,daf}} \tag{21}$$

Disregarding the effect of trace gases in the flue gas:

$$V_{gy,daf} = V_{RO_2,daf} + V_{N_2,daf} + V_{O_2,daf} \tag{22}$$

Based on eqs. (11), (12), (16), (17), and (22), the following equations can be deduced:

$$S_{\text{daf}} = 14286\gamma_{\text{SO}_2}(V_{R\text{O}_2,\text{daf}} + V_{\text{N}_2,\text{daf}} + V_{\text{O}_2,\text{daf}}) \tag{23}$$

$$C_{\text{daf}} = 5359\gamma_{\text{CO}_2}(V_{R\text{O}_2,\text{daf}} + V_{\text{N}_2,\text{daf}} + V_{\text{O}_2,\text{daf}}) + \Gamma_{\text{cucr}} \tag{24}$$

Currently, γ_{O_2} and γ_{SO_2} in the flue gas are measured using the desulfurization and denitrification systems of the unit. Generally, no measuring point exists for γ_{CO_2}. By means of combustion analysis, the existence of an intrinsic relationship among the components of the flue gas can be deduced. If the effect of CO is disregarded, the relationship can be expressed as a function of fuel characteristic coefficient β:

$$\gamma_{\text{CO}_2} = \frac{\phi - \gamma_{\text{O}_2}}{1+\beta} - \gamma_{\text{SO}_2} \tag{25}$$

$$\beta = 2.35\frac{H_{\text{daf}} - 0.126\text{O}_{\text{daf}} + 0.038\text{N}_{\text{daf}}}{0.375\text{S}_{\text{daf}} + \text{C}'_{\text{daf}}} \tag{26}$$

In eq. (26), C'_{daf} is different from the carbon content of the dry ash-free basis in fuel C_{daf}, based on the results after correction of C_{daf} based on correction quantity Γ_{cucr}, where the effect of unburned carbon loss is concerned. C'_{daf} is defined as:

$$C'_{\text{daf}} = C_{\text{daf}} - \Gamma_{\text{cucr}} \tag{27}$$

In addition, the coal chemical bonds of *H:C* and *O:C* are weaker than that of *C:C*. Carbon content generally increases during coalification, whereas hydrogen content decreases [15]. A strong linear relationship is observed between $H_{\text{daf}} - C_{\text{daf}}$ and $O_{\text{daf}} - C_{\text{daf}}$. Thus, the dry ash-free hydrogen and oxygen in the coal can be expressed as a linear function of dry ash-free carbon in eqs. (28) and (29), where $O_{\text{daf}} - C_{\text{daf}}$, a_2, b_1, and b_2 are constant and obtained according to the regression of simple analysis data of 131 types of Chinese coal. $a_1 = -0.1675$, $b_1 = 18.8593$, $a_2 = 0.4044$, and $b_2 = 43.0141$ are obtained by fitting the data of the long-term test. Equation (30) can be obtained according to the composition relationship of the dry ash-free basis element:

$$H_{\text{daf}} = a_1 C_{\text{daf}} + b_1 \tag{28}$$

$$O_{\text{daf}} = a_2 C_{\text{daf}} + b_2 \tag{29}$$

$$100 = C_{\text{daf}} + S_{\text{daf}} + H_{\text{daf}} + O_{\text{daf}} + N_{\text{daf}} \tag{30}$$

Combining eqs. (14) to (30), we can compose a non-linear equation where moisture, ash, γ_{O_2}, and γ_{SO_2} in the coal are the input quantities and C_{daf}, S_{daf}, H_{daf}, O_{daf}, and N_{daf} are unknown quantities.

Method for calculating the soft sensing model

Based on the soft sensing model proposed in the section *On-line soft sensing model for coal quality*, the input parameters of coal quality are coal moisture, ash content, volume share of O_2 and volume share of SO_2. In the proposed model, the γ_{O_2} and γ_{SO_2} can be easily measured or directly obtained in the power plant. Coal moisture and ash content can be obtained using two methods. If the power plant has on-line measuring equipment, the output of such equipment can be directly used as the input of the model. However, if no measuring equipment exists, the soft sensing method can be used to obtain coal moisture and ash content.

The proposed model is calculated using non-linear equations. Such calculations are complex and involve numerous formulas. Through the analysis of the solution, a more suitable iterative optimization method is obtained. The search range of S_{ar} and N_{ar} is easily defined because the measuring transducers of SO_2 and NO_x are installed at the end of an exhaust gas tunnel. The initial value of S_{daf} is set on the basis of personal experience, and then the search range of N_{daf} is defined according to the content of NO_x in the exhaust gas.

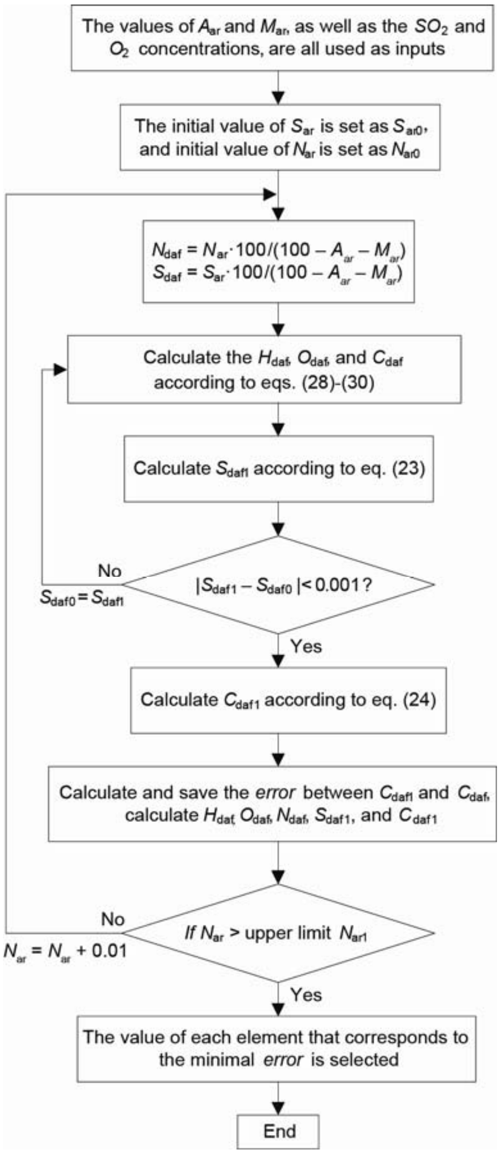

Figure 1. The calculation process of coal quality

Solution of coal quality

The procedure involves the inner loop iteration of S_{daf} and the outside loop iteration of N_{daf} in a limited range, and C_{daf} is searched from the entire range in the process of outside loop iteration. In the iteration calculation process, the *error* between C_{daf1} and C_{daf} is saved. When the value of N_{ar} reaches its upper limit, the value of each element that corresponds to the minimal *error* is obtained and used as the output. The detailed solution is presented in fig. 1.

Determine search range of N_{daf}

Raw coal contains a small amount of *N*, which accounts for only approximately 0.5% to 3.0% of the combustible medium. The main products after combustion are NO and NO_2, which are jointly referred to as NO_x. Under the normal combustion temperature, NO accounts for approximately 90% of the total NO_x in the exhaust gas, whereas NO_2 only accounts for approximately 5% to 10%.

In the combustion of coal powder, NO_x is generated by three channels, *i. e.*, thermal reaction, instantaneous reaction and fuel type reaction.

The N in the NO_x generated from thermal reaction and instantaneous reaction mainly comes from air. The temperature of pulverized coal-fired boiler is generally less than 1500 °C, and NO_x generated by these two reactions only accounts for a small amount of the total NO_x generated by the combustion process, they are not the main sources of NO_x generated during the coal powder combustion. For the total generated NO_x, the fuel type NO_x is the main source, which accounts for approximately 60% to 80%.

Under the normal combustion condition, N in the coal powder only has 20% to 25% chance to convert to the fuel type NO_x. The atomic weight of N is 14, and the molecular weights of NO and NO_2 are 30 and 46, respectively. According to the preceding analysis, the search range of N_{ar} can be obtained as follows:

$$\hat{N}_{ar} = \frac{Q_y \, \gamma_{NO_x} (60\% \sim 80\%)}{B_i 10^6 (20\% \sim 25\%)} \; \frac{14 \cdot 100}{30(0.9 \sim 0.95) + 46(0.05 \sim 0.1)} \tag{31}$$

where $\hat{N}_{ar}$ [%] is the estimated range of N, γ_{NO_x} [mgNm^{-3}] – the content of NO_x in the exhaust gas, Q_y [mgNm^{-3}] – the volume flow rate of exhaust gas, and B_i [th^{-1}] – the mass flow rate of the exhaust gas.

When the fuel-type NO_x accounts for 80% of the total NO_x generated in the combustion process, the percentage of N in the coal powder converted to the fuel-type NO_x is assumed to be 20%, the percentage of NO in the total NO_x is assumed to be 95% and the percentage of NO_2 is assumed to be 5%, the upper limit of $\hat{N}_{ar}$ is then obtained. Similarly, the lower limit of $\hat{N}_{ar}$ also can be got. Then, according to eq. (32), the search range of dry ash free basis of N (*i. e.* N_{daf}) can be obtained basing on the search range of $\hat{N}_{ar}$:

$$N_{daf} = \frac{\hat{N}_{ar} \times 100}{100 - M_{ar} - A_{ar}} \tag{32}$$

On-line measurement of coal moisture and ash content

Although the input parameters of coal moisture and ash content can be obtained using the appropriate on-line equipment, only a few power plants install such equipment. The power plant discussed in this paper did not install such equipment; thus, the soft sensing method is used to measure coal moisture and ash content.

On-line monitoring of coal moisture

In the positive-pressure, direct-fired pulverizing system, the grinding and drying of raw coal are conducted simultaneously in the mill. Accurate data on coal moisture are obtained based on the energy and mass balance of the mill system.

The total heat input in the pulverizing system consists of desiccant physical heat q_{ag1}, raw coal physical heat q_{rc}, heat generated by mill grinding q_{mac}, sealing air physical heat q_s and leaking cold air physical heat q_{1e}. The total heat output in the pulverizing system consists of heat consumed to evaporate moisture in raw coal q_{ev}, heat consumed by the spent air desiccant q_{ag2}, heat consumed for heating fuels q_f and heat loss via equipment q_5. The thermal equilibrium of the pulverizing system is considered as the equality of the total heat input of the initial section and the total heat of carryover pulsing with the consumption of the terminal section in the pulverizing system, *i. e.*:

$$q_{ag1} + q_{rc} + q_{mac} + q_s + q_{le} = q_{ev} + q_{ag2} + q_f + q_5 \tag{33}$$

In eq. (33), coal moisture M_{ar} consists of variables q_{rc}, q_{ev}, and q_f. Thus, eq. (33) can be derived as:

$$\left(\frac{100-M_{\rm ar}}{100}c_{\rm dc}+\frac{M_{\rm ar}}{100}c_{\rm H_2O}\right)t_{\rm rc}-\frac{100-M_{\rm ar}}{100}\left(c_{\rm dc}+\frac{4.187\cdot 0.048\cdot M_{\rm ar}\dfrac{R_{90}}{t_2^{0.46}}}{100-0.048\cdot M_{\rm ar}\dfrac{R_{90}}{t_2^{0.46}}}\right)(t_2-t_{\rm rc})-$$
$$-\frac{M_{\rm ar}-0.048\cdot M_{\rm ar}\dfrac{R_{90}}{t_2^{0.46}}}{100-0.048\cdot M_{\rm ar}\dfrac{R_{90}}{t_2^{0.46}}}(2500+c''_{\rm H_2O}\ t_2-4.187\ \ t_{\rm rc})=q_{\rm ag2}+q_5-q_{\rm ag1}-q_{\rm mac}-q_{\rm s}-q_{\rm le} \quad (34)$$

where $c_{\rm dc}$ [kJkg^{-1}°C^{-1})] is the specific heat capacity of coal (dry basis), $c_{\rm H_2O}$ [kJkg^{-1}°C^{-1})] – the specific heat capacity of moisture, $t_{\rm rc}$ – the temperature of raw coal fed into the system, t_2 – the desiccant temperature at the end, and the temperature of air and the powder mixture at the mill outlet can be selected as its value, R_{90} [%] – the coal fineness, and $c''_{\rm H_2O}$ [kJkg^{-1}°C^{-1})] – the average specific heat capacity of vapour at a constant pressure.

The equation is transformed into a quadratic equation and the unknown variable is the coal moisture ($M_{\rm ar}$) in the mill. The coal moisture can be determined by using the input data of the pulverizing system. Given space limitations, the detailed formula of each variable and the solution of $M_{\rm ar}$ are not presented in this paper. The calculation results are provided to prove the effectiveness of this method.

On-line motoring of ash content

Through the multiple regression analysis of 531 batches of data on coal calorific value, coal moisture and ash content of a power plant in China, the following equations are obtained:

$$Q_{\rm net,ar}=-0.3864A_{\rm ar}-0.4517M_{\rm ar}+34.1962 \quad (35)$$

i. e.

$$A_{\rm ar}=-1.169M_{\rm ar}-2.588Q_{\rm net,ar}+88.4995 \quad (36)$$

Coal moisture is obtained using the method proposed in the section *On-line monitoring of coal moisture*; the calorific value of coal and ash content also can be obtained using the soft sensing method.

The calorific value of coal is calculated based on the total heat of the boiler and the amount of coal feed. The calculation error of the calorific value is generally better than 3% except when coal blockage and powder leakage occur. Calorific value is calculated as:

$$Q_{\rm net,ar}=K\frac{Q_{\rm b}}{B_{\rm v}}10^{-3} \quad (37)$$

where $Q_{\rm b}$ [MW] is the total released heat in the boiler, K – the coefficient related to the efficiency of the boiler, $B_{\rm v}$ [kgs^{-1}] – the amount of coal feed, and $Q_{\rm net.ar}$ [MJkg^{-1}] – the calorific value of coal.

As for the total released heat in the boiler $Q_{\rm b}$, it can be got basing on the energy balance of working fluid and exhaust gas in the boiler. The amount of coal feed, the steam pressure and the steam temperature are acquired from the measure points in distributed control system (DCS). The effective heat absorbed by the working fluid is represented as the total heat absorbed by the main steam and the reheat steam minus the total heat absorbed by the feed water and the heat consumed by the desuperheating water. The enthalpy of working fluid can be calculated based on its pressure and temperature. When combined with the heat consumed by exhaust gas, the total released heat in the boiler is obtained. Then, the heat released per unit of fuel in this period is expressed as the calorific value of coal. Combined with calorific value and coal moisture, ash content can be obtained according to eq. (36).

Calculation and verification

According to the methods proposed in Sections *On-line monitoring of coal moisture* and *On-line motoring of ash content*, the results are evaluated and verified using the operating data obtained from the actual operating data of the units in August of a certain year. The coal moisture, calorific value and ash content are calculated using the soft sensing model shown in fig. 2. All calculated results are in a reasonable range.

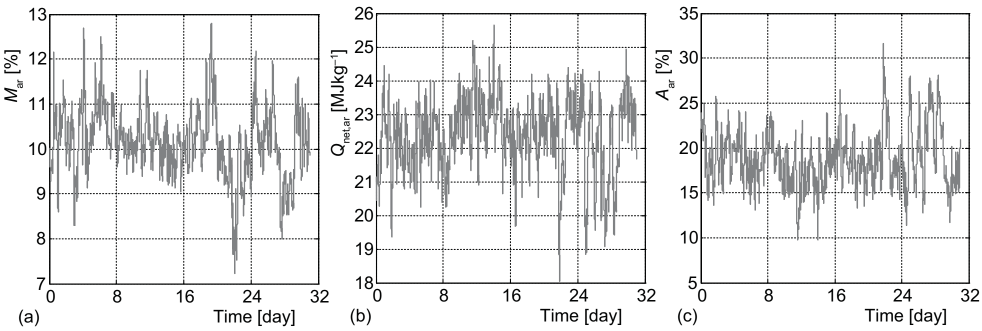

Figure 2. (a) Calculated value of coal moisture, (b) calculated value of calorific value, and (c) calculated value of ash content

Real-time measured moisture value, calorific value and ash content are not available in the plant. Therefore, the soft sensing results cannot be compared and analyzed in detail with the measured value. However, the data in the daily chemical examination report of coal quality in the furnace are used to compare the trends and fluctuation ranges of the calculated results. The contrast results are presented in fig. 3, where the black line represents the result obtained from the chemical examination report and the gray line represents the daily average soft sensing measured value. Comparison of figs. 3(a) to 3(c) indicates that the estimation

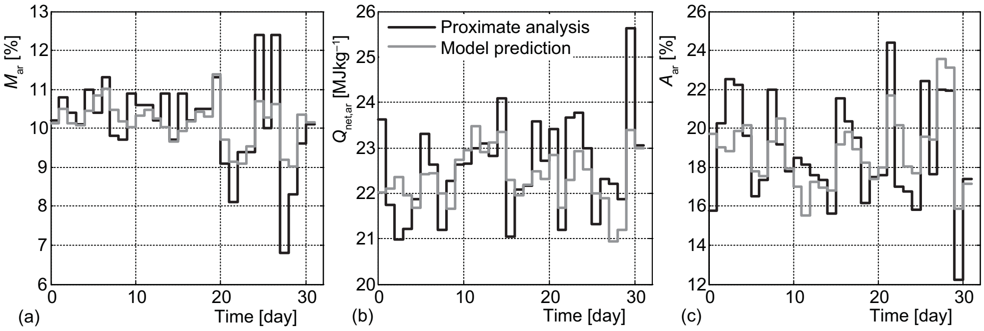

Figure 3. (a) Daily average soft sensing measured coal moisture value compared with the result of industrial analysis, (b) daily average soft sensing measured calorific value compared with the result of industrial analysis, and (c) daily average soft sensing measured ash content value compared with the result of industrial analysis

value obtained using the proposed method in this study and the value from the chemical examination is almost consistent. This result indicates that the calculated results are credible and effective, and can be used as the input of the element analysis programme.

On-line calculation and verification of coal quality

The amount of coal moisture and ash content received in the furnace based on the August data calculated in Section *On-line measurement of coal moisture and ash content*, as well as the concentrations of O_2 and SO_2 of the flue gas in the same month, are used as input signals. The upper and lower limits of N_{ar} are calculated by eq. (31) using the concentration signals of NO_x in the flue gas. The results of each element in the furnace are obtained according to the method discussed in Section *On-line monitoring of coal moisture*.

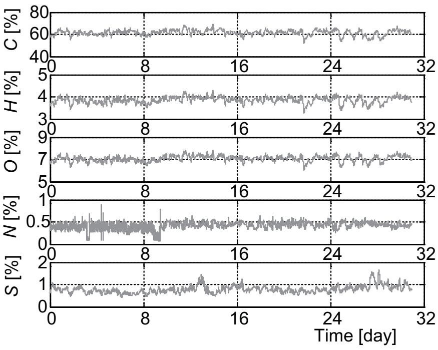

Figure 4. Calculation result of the component of each element in the furnace

Table 1. Statistical analysis of the on-line calculated results of each element component in August

Variables	C_{ar} [%]	H_{ar} [%]	O_{ar} [%]	N_{ar} [%]	S_{ar} [%]
Maximum	69.08	4.27	7.79	0.88	1.64
Minimum	51.76	3.26	5.99	0.08	0.42
Average	61.51	3.85	7.06	0.42	0.78
Standard deviation	2.43	0.14	0.26	0.07	0.17

Results of on-line calculation

The results that indicate the C_{ar}, H_{ar}, O_{ar}, N_{ar}, and S_{ar} content in August are shown in fig. 4. The statistical analysis results of the calculated values of the basic elements are reported in tab. 1. As shown in fig. 4 and tab. 1, the component of each element obtained using the on-line calculation fluctuates in a reasonable range and the calculation results are relatively stable.

Verification

Elemental analysis could not be conducted every day in the power plant, and usually it is done for the feed material if needed; thus, calculation results are difficult to verify. The results of this study are verified using two comparative analyses.

Contrast verification of total sulfur

Total sulfur value is measured in industrial analysis reports on coal fed into the furnace. In fig. 5, the daily total sulfur value obtained by industrial analysis in August of a certain year is represented by a black line and the daily average value of S_{ar} calculated using the method proposed in the section *Results of on line calculation* is represented by a gray line. Figure 5 illustrates the two lines having similar variation trends, with the data being consistent during most periods. However, from August 16 and 20, a significant difference can be observed between these trends. The main reason for this phenomenon is the mixed coal used in the power plant, *i. e.*, varying qualities of coal is mixed at a certain proportion. According to the statistical data on total sulfur shown in tab. 2, the total sulfur value of the coal bought by the power plant in August varies from 0.33 to 1.75, *i. e.*, middle-sulfur coal and low-sulfur coal are used. The average value of S_{ar} is 0.73 and the standard deviation is 0.235, which indicates that the low-sulfur coal is more plentiful. Mixing coal with a large difference in sulfur content easily causes sampling errors in the fixed sampling point if the mixing is uneven, thereby causing a large deviation between the industrial analysis results and the actual value. The method proposed in this study is mainly used to analyses the element content according to the operation data obtained after the full combustion of the mixed coal. The results of each element content are more representative and can reflect the actual sulfur content in the coal.

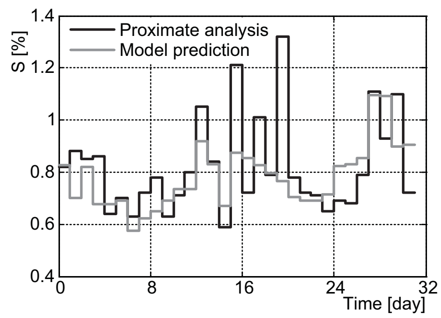

Figure 5. The total sulfur content in August

Table 2. The statistical data on total sulphur content in August

Maximum	Minimum	Average	Standard deviation
1.75	0.33	0.73	0.235

Contrast verification of calorific value obtained using two calculation methods

The element content of the available coal and the calorific value of the received basis can be calculated using the Mendeleev formula. This method is highly versatile:

$$Q_{\text{net,ar}} = 339C_{\text{ar}} + 1028H_{\text{ar}} - \\ -109(O_{\text{ar}} - S_{\text{ar}}) - 25M_{\text{ar}} \tag{38}$$

The calorific value of the received basis $Q_{\text{net.ar}}$ can be calculated according to eq. (37), with C_{ar}, H_{ar}, O_{ar}, N_{ar}, and S_{ar} calculated in the section *Results of on-line calculation* and M_{ar} calculated in the section *On-line monitoring of coal moisture*. The result is represented by a gray line in fig. 6. The calorific value of the received basis calculated using eq. (38) is represented by a black line in fig. 6. The calculation results from August 10 to 15 in fig. 6 shows that the calorific value of the received basis calculated using the two methods is highly consistent. The statistical results of the difference between the two calculated calorific values are presented in tab. 3. The maximum value of the differences is 0.98, the minimum value is –0.15, the average value is 0.35 and the standard deviation is 0.157. The results presented in tab. 3 demonstrate that the calculation results for the entire month obtained using the two methods are moderate, thereby proving indirectly that the calculation results of the established model for coal element in the furnace are correct.

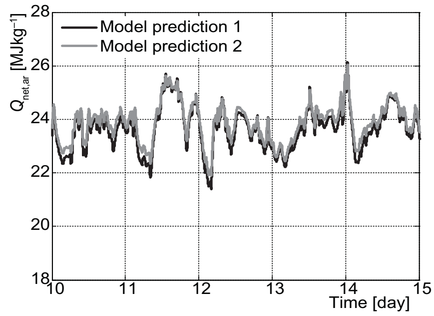

Figure 6. Comparison of results of two calorific values of received basis calculation

Table 3. The statistical results of the difference between the two calculated calorific values

Maximum	Minimum	Average	Standard deviation
0.98	–0.15	0.35	0.396

Conclusions

Based on the coal quality information obtained from exhaust gas, combined the mechanism modelling method with data driving theory, the author put forward a soft sensing method of coal quality. The procedure for solving the non-linear equations for coal is discussed; the iterative initial value selection problem is also solved according to the NO_x content in the exhaust gas and its generation mechanism. Then a case study is given, according to the operation data of power plant in August, the on-line calculation of coal quality fluctuates in a reasonable range and the calculation results are relatively stable. Also in order to verify the effectiveness of the proposed method, the data in the daily chemical examination report of coal quality in the furnace are used to compare the trends and fluctuation ranges of the calculated results, the estimation value is almost consistent with the value from the chemical examination, this result indicates that the calculated results are credible and effective and it can be used for control system optimization.

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