

Principles of optimization of combustion by radiant energy signal and its application in a 660 MWe down- and coal-fired boiler

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Abstract—For the optimization of combustion in utility coal-fired boilers, a simple analytic model was set up to relate the radiant energy signal (RES) with the combustion rate (heat release rate) based on the heat transfer equation inside a boiler furnace. It was pointed out that as the air flow rate into the furnace changes, the highest RES corresponds to the highest efficiency, making RES a sensitive quantity for optimization of combustion in boilers. Experiments carried out in a 660 MW down- and coal-fired utility boiler confirmed the characteristics of RES as an indicator of combustion rate inside the furnace and its ability to reflect the boiler thermal efficiency varied with the air flow rate. The utilization of RES in the optimization of combustion can generally improve the boiler thermal efficiency at different unit loads, and the efficiency was raised about 1.0% especially at the rated and lower unit loads. It should be stated that except the lower unit load, the NO_x emission from the boiler after optimization of combustion by RES would increase due to the limitation in supply of adequate air flow rate into the boiler, and some new combustion technologies are now available to solve the contradiction.

Key words: Optimal Combustion Control, Down-fired Furnace, Radiant Energy Signal, Flame Image Processing

INTRODUCTION

The pulverized-coal combustion process in utility boilers is among the very complex physical and chemical processes occurring in large scale, 3-dimensional spaces. Down-fired boilers are one of the most important fossil fuel combustion equipments developed to burn low volatile and anthracite coals in recent years in China [1,2]. Down-fired boilers have good performance of burning low quality coals, but there are some serious shortcomings to restrict their application, such as serious slagging, high NO_x emission, high carbon contents in fly ash and poor stabilization of combustion [3]. Experimental and numerical studies have been carried out on the combustion characteristics in down-fired boilers [4-8], and recently measurement of 3-D temperature distribution in a 660 MWe down- and coal-fired boiler was reported [9].

It is a very complex process for the burnout of the fuel after it is fed into a furnace, since it is hard to grasp the combustion behavior inside furnaces in real time [10]. As reported previously in the past decades, flame image processing techniques have been studied mostly on laboratory-scale combustion systems and premixed flames. The main approaches are to compute some geometrical and luminous properties of the flames extracted from gray-scale flame images, classifying the flame into arbitrarily defined states [11], predicting various quantities such as the flicker rate [12], the un-burnt carbon [13], or CO₂ and NO_x emissions [14]. Cheung [15] used digital imaging and image processing technique to study the information in a

gas turbine combustor by stereo cameras. On-line visualization of 3-D temperature distribution in utility coal-fired boilers by flame image monitoring system could obtain the real-time combustion information in the boiler furnaces [9,16]. The reliable 3-D temperature monitoring technology is strongly demanded by power plants for clean coal combustion in face of soaring price of coal and the challenge of stricter environmental law for air pollution.

The process from feeding of fuel and air into a furnace to producing qualified steam by the boiler is a long-delay, multiple-factor-controlled process, and it is very hard to build a strategy for fast optimization of combustion directly from the information obtained from the combustion process itself to overcome the disturbances to the supply of energy by the fuel and air fed into the furnace. Radiant energy signal (RES) is an important parameter which can reflect not only the quantity but also the quality of the fuel fed into the furnace [17]. The radiative image processing system for temperature distribution monitoring together monitoring of RES was introduced into combustion control systems to improve the boiler thermal efficiency and reduce pollutant emissions in several tangentially coal-fired boilers in recent years [17-19]. But it has not yet been employed in down- and coal-fired boilers. Furthermore, the principle for application of RES in optimization of combustion in utility boilers has not been described quantitatively yet.

Alternatively, attempts have been made to optimize the combustion processes in utility/industrial furnaces/boilers by artificial intelligence (AI), for example, artificial neural networks (ANN) and genetic algorithms (GA) were suggested for modeling the carbon burnout behavior in a tangentially fired boiler and optimizing the operating conditions to achieve the highest boiler efficiency [20]. An empirical model to predict the boiler efficiency and pollutant emissions was developed with artificial neural networks based on the

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experimental data on a 360 MW W-flame coal fired boiler [21]. A review to illustrate how AI techniques might play an important role in modeling and prediction of the performance and control of combustion process is available [22]. Essentially, the main task of optimization of combustion is to achieve at excess air optimization for utility/industrial steam boilers fired with fossil fuels [23]. In [24], a compact optimization strategy for combustion was proposed, in which a parameter representing the secondary air assignment mode was determined directly according to the volatile matter and the heating value of coal. A simple-to-use predictive tool for predicting the natural gas combustion efficiency as a function of excess air fraction and stack temperature rise (the difference between the flue gas temperature and the combustion air inlet temperature) was used in follow-up calculations to determine relative operating efficiency and to establish energy conservation benefits for an excess air control program [25]. It is still meaningful to seek for a simple method to optimize the supply of combustion air in utility boilers.

In this paper, for the optimization of combustion in utility coal-fired boilers, a simple, analytic model would be established to relate RES with the combustion rate (heat release rate) based on the heat transfer equation inside the boiler furnace. Then experiments were carried out in a 660 MW down- and coal-fired utility boiler to reveal the characteristics of RES as an indicator of combustion rate inside the furnace and to show the effects of RES on improving the boiler thermal efficiency through optimization of secondary air flow rate. Finally, some concluding remarks are given.

PRINCIPLES OF OPTIMIZATION OF COMBUSTION

1. Definition and Acquisition of Radiant Energy Signal (RES)

Radiant energy signal (RES), E_r , is defined as follows [17],

$$E_r = \varepsilon_f \sigma_0 T_f^4 \quad (1)$$

where T_f is the flame temperature (K), ε_f the flame emissivity, σ_0 the Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$. The radiant energy signal, E_r , reflects the radiative heat flux transferred from the flame to the water-wall surfaces inside a furnace. As studied in [9,15-17], the flame temperatures, T_f , inside a furnace can be reconstructed from multiple flame images captured from the furnace, and ε_f , the flame emissivity, can be also got from the flame images, and generally, the radiant energy signal is normalized for convenience of application [17].

As also suggested in [17], under a certain condition, the gray value of a color flame image varies with the radiant energy received by the image sensor, and it can be taken as a representative of the radiant energy signal. Generally, G the gray value of an image pixel can be obtained from its red, green and blue data, r , g and b in the image pixel as

$$G = 0.3r + 0.59g + 0.11b \quad (2)$$

2. RES as an Indicator for the Combustion Rate Inside a Furnace

The heat exchange equation in steady state inside a furnace can be written as

$$A_i(\varepsilon_s \varepsilon_0 T_s^4 - \varepsilon_s \sigma_0 T_s^4) = \varphi B_j(Q_c + Q_f - I_i) \quad (3)$$

where, A_i is the surface area of the water-wall (m^2), ε_s the absorp-

tivity/emissivity of the water-wall surface, T_s temperature of the water-wall surface (K), φ the heat-insulated coefficient of the furnace, B_j the fuel mass flow rate (kg/s), Q_c the heat rate released from fuel (combustion rate) inside the furnace (kJ/kg), Q_f the initial entropy of fuel and air supplied into the furnace (kJ/kg), I_i the entropy of the flue gas leaving the furnace (kJ/kg).

The combustion rate (heat release rate) F_r inside the furnace is given as

$$F_r = B_j Q_c \quad (4)$$

Then, the radiant energy signal E_r and the combustion rate F_r can be related by

$$E_r = \frac{\varphi}{A_i \varepsilon_s} F_r + \frac{\varphi B_j}{A_i \varepsilon_s} (Q_f - I_i) + \sigma_0 T_s^4 \quad (5)$$

From the above equation, it is clear that E_r changes approximately linearly with F_r , whether F_r changes with B_j and/or Q_c . This is the basis to use E_r as an indicator (feedback signal) of F_r .

Traditionally, due to the difficulty in measuring the combustion rate inside a furnace, the so-called thermal heat signal, D_Q , was widely used in the control of the thermal power generation unit, which is expressed as

$$D_Q = D_B + c_B \frac{dP_d}{dt} \quad (6)$$

where D_B is the steam mass flow rate of the boiler (kg/s), c_B the heat storage factor of the boiler (kg/kPa), P_d the steam pressure (kPa). It can be seen easily that as the combustion rate F_r changes, the radiant energy signal E_r will change soon, and after a sensible time delay, the thermal heat signal D_Q will respond.

So, the radiant energy signal E_r has two main features. One, it is the first quantity to characterize the energy level inside a furnace, and there is no such quantity existing as before. Two, it can respond quickly to the change of the combustion state inside a furnace as it is disturbed via the feeding of the mass flow rates and/or quality of fuel and/or air into the furnace. With such distinguishing features, the radiant energy signal has potential for combustion monitoring, control and optimization in fossil-fuel-fired power plants.

3. Optimization of Combustion by RES

The combustion rate (heat release rate) F_r inside the furnace can be further expressed as

$$F_r = \eta B_j H_c \quad (7)$$

where η is the combustion efficiency, H_c the heat value of the fuel (kJ/kg). The equation above shows that the combustion rate varies with the combustion efficiency even if the fuel mass flow rate and its quality does not change. Obviously, the highest efficiency η is the goal of optimization of combustion. The radiant energy signal in Eq. (5) can be revised as a function of the efficiency as

$$E_r = \frac{\varphi B_j H_c}{A_i \varepsilon_s} \eta + \frac{\varphi B_j}{A_i \varepsilon_s} (Q_f - I_i) + \sigma_0 T_s^4 \quad (8)$$

As the mass flow rate and quality of fuel unchanged, the combustion efficiency η varies with the mass flow rate of air fed into the boiler, A_m , that is

$$\eta = \eta(A_m) \quad (9)$$

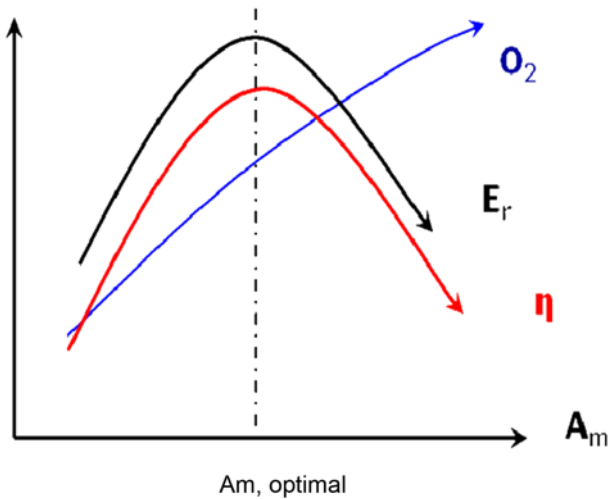


Fig. 1. The combustion efficiency η , the radiant energy signal E_r , and the oxygen content in flue gas O_2 change with the mass flow rate of air A_m .

It indicates that the radiant energy signal E_r changes proportionally to the efficiency η , which is the basis for the potential of application of the radiant energy signal E_r in optimization of combustion in utility power plants. As shown in Fig. 1, as the flow rate of air A_m increases gradually, the oxygen content in the flue gas O_2 also increases simultaneously and gradually. As the efficiency η passes

Table 1. Characteristics of coal for in-situ experiment (air dried basis)

Proximate analysis/wt%			Ultimate analysis/wt%					$Q_{LHV,ar}$ MJ/kg
M_{ad}	A_{ad}	V_{ad}	S	N	C	H	O	
1.46	28.83	17.25	2.55	0.83	54.31	2.27	3.21	20.68

through its highest value η_{max} with $A_{m,optimal}$, O_2 does not display any special change in its changing trend. According to Eq. (8), as the efficiency η passes through its highest value η_{max} with $A_{m,optimal}$, the radiant energy signal E_r will reach its highest value $E_{r,max}$ and then decreases, showing a special change in its changing trend, which can be grasped easily. Since the combustion efficiency is dominated by many factors and cannot be estimated on-line exactly, the radiant energy signal can serve as a good substitution for the combustion efficiency to achieve an optimal state.

EXPERIMENTAL RESULTS AND DISCUSSION

1. On-line Combustion Monitoring System by Flame Image Processing

The studied boiler is a 660 MW down- and coal-fired boiler manufactured by Foster-Wheeler (FW) Company, which is the biggest capacity of down-fired flame boilers in the world now. The coal analysis in the experiments is shown in Table 1.

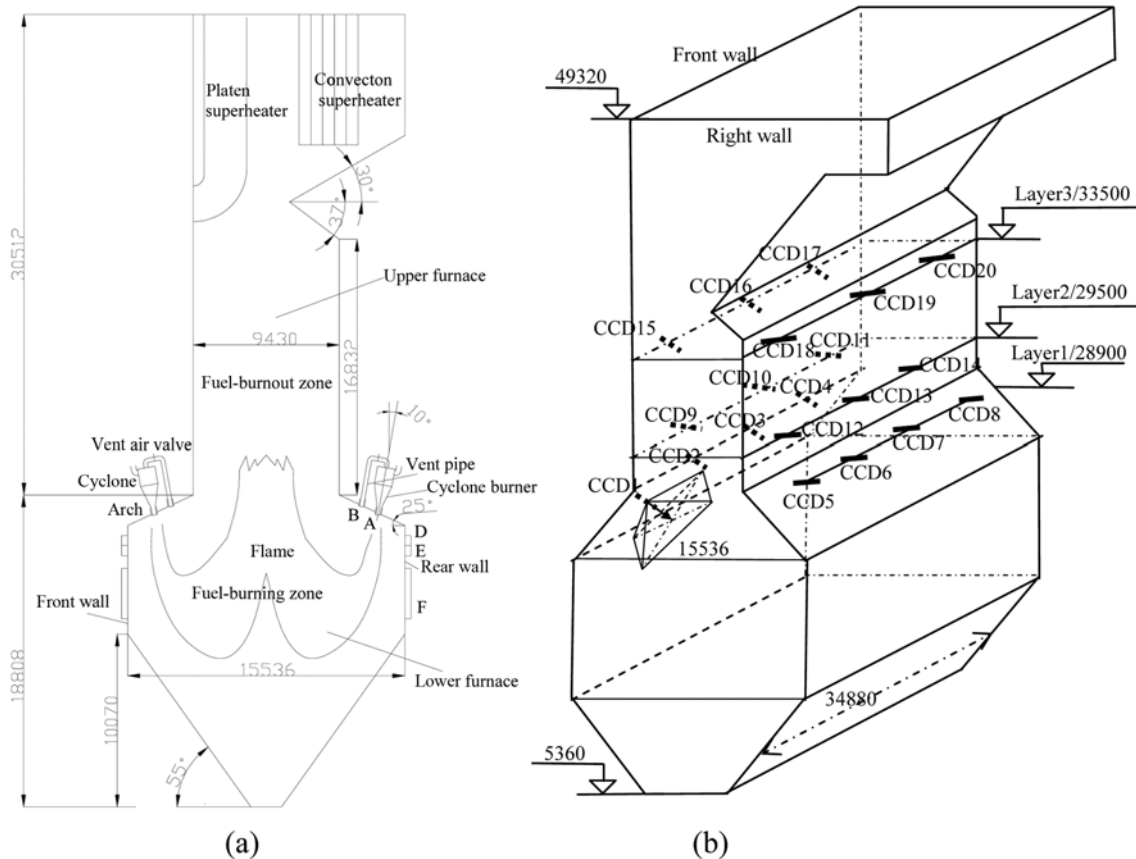


Fig. 2. (a) Cross-section of the down-fired boiler and (b) positions of image detectors for combustion monitoring.

The schematic of the boiler and an on-line combustion monitoring system is shown in Fig. 2. Twenty flame image detectors were installed at different positions of the furnace. Each of the detectors consists of a lens, an image guide, and a Samsung SCC-2313 color CCD camera. The image guide is fixed in the center of a stainless steel pipe that is inserted into the water-wall of the furnace, and cooled by compressed air to avoid overheating and keep the lens clean. All lenses of the detectors are with the same viewing angle field of 54° in the horizontal and 78° in the vertical directions. The detectors are installed at the front and rear water-walls along the evaporating tubes in three layers. Eight detectors of the first layer are installed at the elevation of 28.9 m, with a slope angle 45° to the down furnace. The detectors installed at the secondary and the third layers were mounted horizontally at elevation of 29.5 m and 33.5 m, respectively, each layer with six detectors. The twenty flame images are made into one image of the combustion flame by a frame maker, and as shown in Fig. 3, from the output signal the 3-D temperature distribution is reconstructed and the radiant energy signal is deduced. The description about the monitoring system in detail is available in [9].

2. Characteristics of RES as Indicator of Combustion Rate

Experiments were conducted to obtain the relationship between RES and the operating parameters of the power generation unit in

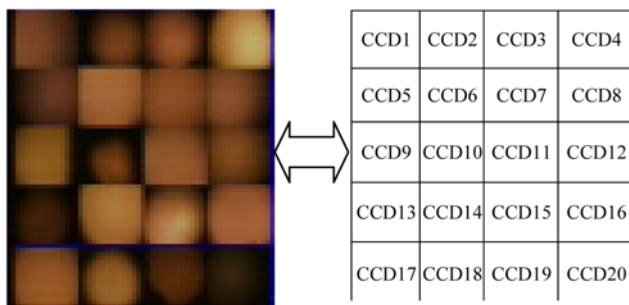


Fig. 3. Arrangement of flame images in this study.

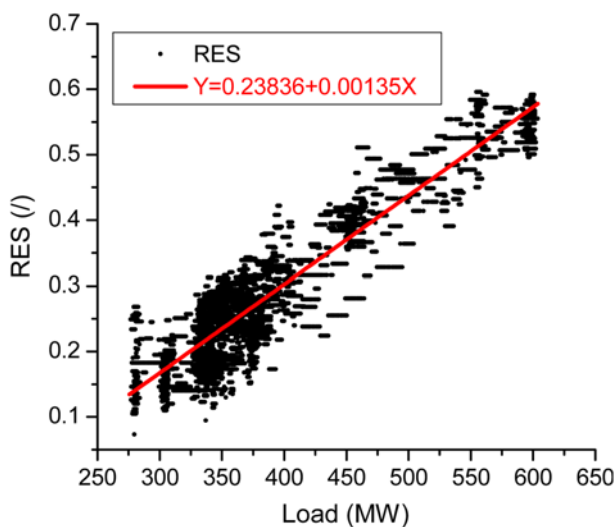


Fig. 4. Relationship between RES and the unit load. The fitted linear equation gives the ideal values for RES at different unit loads.

the wide range of unit load from 280 MW to 620 MW. The experimental data in Fig. 4 were captured in two days in Oct. 2008 with a sampling time of 5 seconds. From the figure it can be seen that, as the unit load increases, the RES increases accordingly, confirming the characteristics of RES varies with the combustion rate inside the furnace, as indicated in Eq. (5). Furthermore, a fitting linear formula can be obtained from Fig. 3 as follows:

$$\text{RES} = -0.23836 + 0.00135 \text{Load}, \quad \text{Load} \in (280 \text{ MW}, 620 \text{ MW}) \quad (10)$$

Obviously, Eq. (10) gives the normal relationship between the unit load and the ideal radiant energy signal in the steady states.

Theoretically, RES required at different unit loads should meet with Eq. (10). In fact, as shown in Fig. 4, the radiation energy signal is sometimes greater than the ideal value in the red line, and sometimes less than that under the same unit load. When RES is greater than the ideal value, it means that the combustion rate is larger than that required by the current unit load, and the energy supply inside the furnace exceeds the normal value. This case occurs during the load-increasing stage, in which the fuel and air mass flow rates should be increased in advance to increase the supply of energy into the furnace. When RES is lower than the ideal value, it occurs during the load-decreasing stage.

But it is necessary to maintain the energy supply into the furnace within a limited, given margin for safe and economic operation of the combustion and boiler system. If RES exceeds the ideal value much more, the energy supply into the furnace will be wasted much more, and it may result in overheating of boiler tubes, threatening the safe operation of the boiler. Otherwise, if RES lowers that the ideal value much more, the energy supply into the furnace will be not adequate for the ignition and stable combustion in the furnace, threatening the normal combustion of the boiler. As an example, Fig. 5 shows transient curves of unit load, main steam temperature, RES and steam pressure of the unit as the unit load increases from 520 MW to 640 MW. It is obviously seen from Fig. 5 that RES was significantly higher than the ideal level required for increasing the unit load from 17:44 to 17:49, which led to an obvious rise of the main steam temperature at 17:46. This phenomenon may be caused by over-regulating of the fuel, and the coal mass flow rate was greater than that needed. At that time, RES increased abnor-

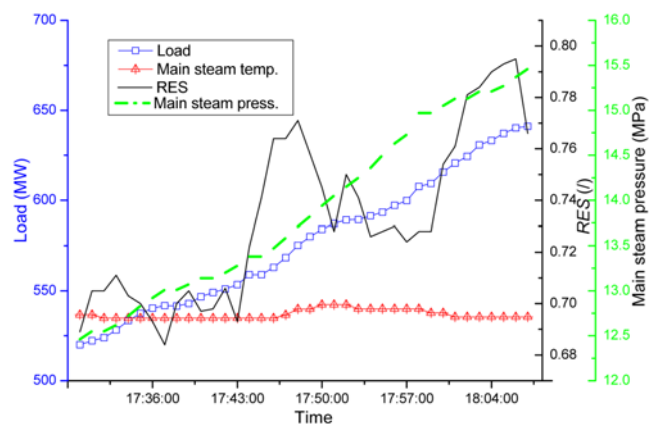


Fig. 5. Transient curves of unit load, main steam temperature, RES and steam pressure of the unit as the unit load increases from 520 MW to 640 MW.

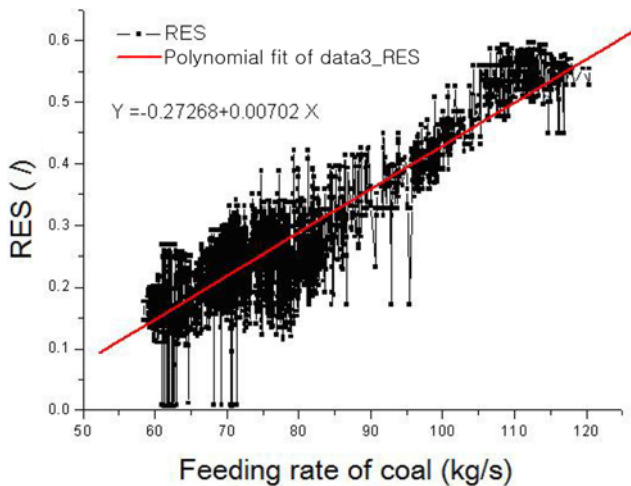


Fig. 6. Variance of RES with the feeding rate of coal into the furnace.

mally and reached a local peak value, and the steam temperature was raised by 7.56°C abnormally during the period, which is not desirable for the boiler operation. As illustrated in Fig. 5, RES can reflect the change of boiler combustion in real time, and it can be used for in-situ combustion control as a backward signal of combustion rate inside the boiler furnace.

The combustion rate inside a furnace is controlled by the feeding rates of both fuel and air into the furnace, and the relationship between the radiant energy signal and the feeding of fuel and air should be checked. An example of variance of RES with the feeding rates of coal into the furnace is shown in Fig. 6. It can be easily seen that as the feeding rate of coal increases, RES increases too. But it should be stated that even with an identical feeding rate of coal, RES varies within a larger range. For example, as the feeding rate of coal is nearly 80 kg/s, RES varies from about 0.15 to 0.40. This phenomenon is caused by the variance of the feeding rate of air into the furnace with the same feeding rate of coal at different operating conditions. Different values of radiant energy signal, and consequently different combustion rates inside the furnace, can be reached as the feeding rate of air varies, which demonstrates the necessity of optimization of combustion.

3. RES for Optimization of Combustion

Experiments were done for validation of the characteristics of RES as an efficient substitution for the combustion efficiency, and an example of experimental results is shown in Fig. 7. During the experiment, the feeding rate of coal was kept as constant. As shown in Fig. 7(a), the secondary air flow rate was increased gradually, and at the time of 15.1–15.2 h, it reached the highest value. Then it was decreased gradually. During this period, as shown in the figure, the oxygen content changed with the secondary air flow rate gradually with the same trend. An interesting phenomenon can be seen from Fig. 7(b). The power output of the unit experienced a peak between 14.6 and 14.7 h during the increase of the secondary air flow rate, which is about 5 MW higher than that in the initial time as the secondary air flow rate increased. As the secondary air flow rate reached its peak in Fig. 7(a), the increases of the power output of the unit disappeared completely. As the secondary air flow decreased from its peak value, another peak in the unit load between

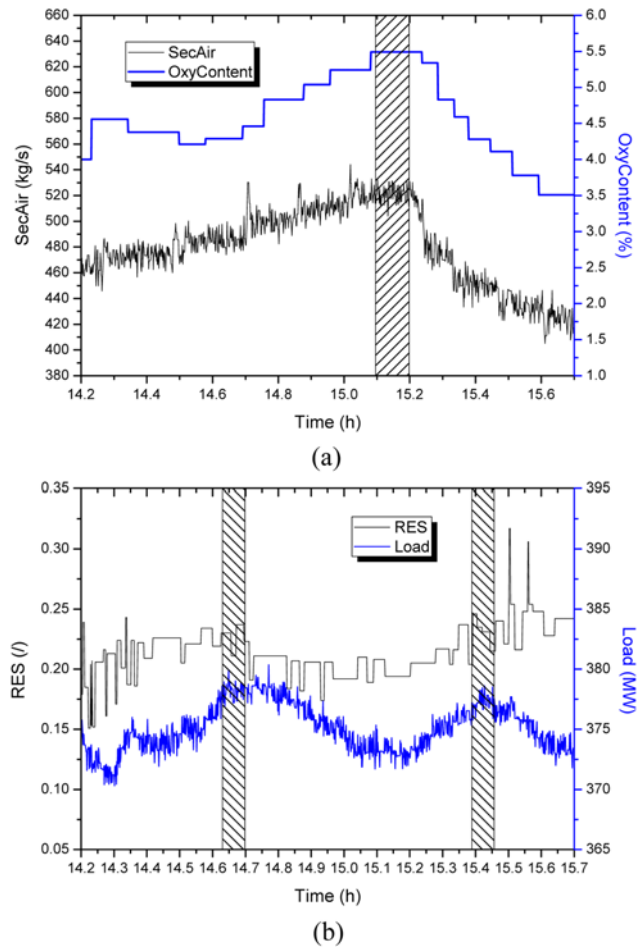
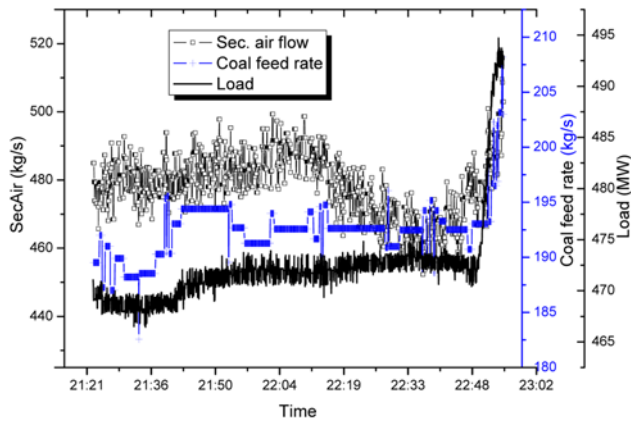


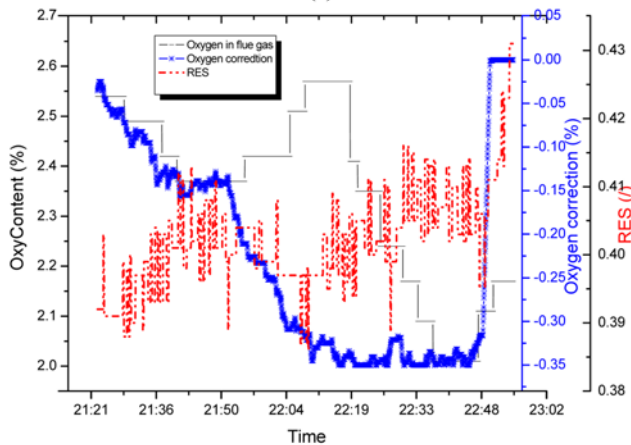
Fig. 7. (a) The variance of the secondary air flow rate and the oxygen content in flue gas, and (b) the unit load and the radiant energy signal in an experiment of increasing and then decreasing the secondary air flow rate with a constant mass flow rate of coal.

15.4 and 15.5 h appeared again, demonstrating the appearance of the higher boiler efficiency of the unit. This is just a validation of the characteristics of RES illustrated in Fig. 1.

The thermal heat signal has been used as a feedback signal for the combustion rate inside a furnace to control the fuel and air mass flow rates, and it belongs to the parameters of the steam side of the boiler essentially [4]. In the combustion optimization strategy, however, the air mass flow rate is regulated quickly through the rapid response of RES. The principle of combustion control algorithm and configuration in DCS has been put forward in [19]. In this paper, experiments on application of RES into optimization of combustion of the 660 MWe down- and coal-fired power generation units were carried out. To show the effects of combustion optimization by RES, Fig. 8 displays the transient curves of the main parameters after RES was used to the secondary air mass flow rate control loop at the unit load of 472 MWe. It should be stated that in the dynamic regulating process of the unit load, the mass flow rates of fuel and air are adjusted according to the demand of the unit load. After the regulating procedure for the unit load is over at about 22:10 in Fig. 8, the mass flow rate of fuel is kept as a constant, and then the secondary air mass flow rate and the oxygen content in flue gas



(a)

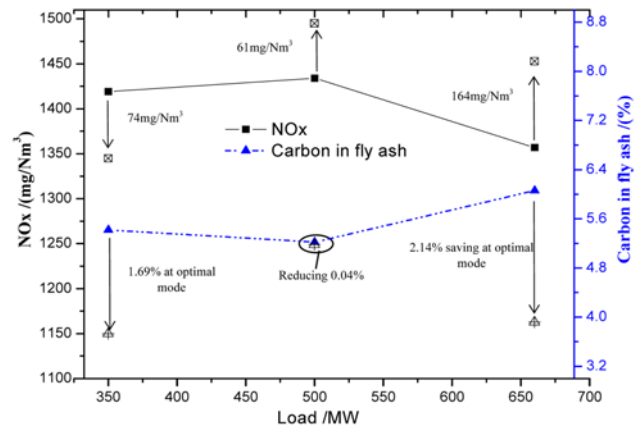


(b)

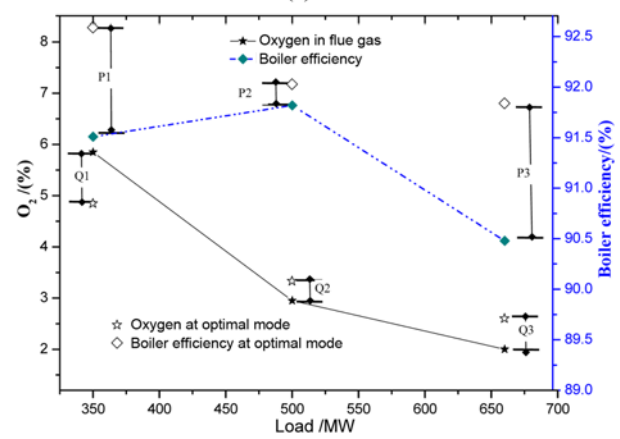
Fig. 8. Effects of real-time optimization of combustion as RES was used to the secondary air mass flow rate control loop at the unit load of 472 MW.

are optimized according to RES. It can be seen that, until 22 : 40, the oxygen content was reduced and RES increased gradually, and the power output of the unit increased nearly 2 MWe. In this period, the mass flow rate of coal was kept nearly constant, which means no more fuel was fed into the boiler to increase the power output of the unit. It can also be seen from Fig. 8 that RES and the oxygen content changed in opposite directions, and the correct change trend for the oxygen content should correspond to the positive change trend for RES in the optimization procedure of combustion.

The effects of the optimization of combustion by RES were compared with the original combustion strategy without RES at 3 unit loads, i.e., the rated unit load of 660 MW, a moderate unit load of 500 MW, and a low unit load of 350 MW. Table 2 and Fig. 9 show



(a)



(b)

Fig. 9. Emissions of NO_x, carbon in fly ash, oxygen in flue gas and boiler thermal efficiency at different unit loads. (a) Variation of NO_x and carbon in fly ash; (b) Change of oxygen and boiler efficiency.

NO_x emissions, the unburnt carbon in fly ash, the oxygen content in flue gas and the boiler efficiency varied at different unit loads. At the unit load of 350MWe, as illustrated in Table 2, the setting value of oxygen content was reduced from 5.85% to 4.85% (Q1 in Fig. 9(b)), NO_x emissions was reduced 74 mg/Nm³ (Fig. 9 (a)), the unburnt carbon in fly ash fell 1.69%, the carbon content in furnace bottom slag fell 1.04%, and the boiler efficiency increased by 1.08%, all the data demonstrating an improvement of the combustion with higher efficiency and low emission. By contrast, at unit load 500 MW, an increase of the oxygen content from 2.95% to 3.33% and a reduction of carbon in fly ash from 5.22% to 5.8% made a slight increase of the boiler efficiency of 0.21% but an increase of NO_x

Table 2. Comparison of effects of combustion control before and after introducing RES into DCS of the down-fired boiler

Load (MW)	NO _x emission (mg/Nm ³ at 6%O ₂)		Carbon in flyash (%)		Carbon in bottom slag (%)		CO in flue gas (ppm)		Setting of O ₂ (%)		Boiler efficiency (%)	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
350	1419	1345	5.42	3.73	10.21	9.17	14.5	13.5	5.85	4.85	91.51	92.59
500	1434	1495	5.22	5.18	8.68	8.32	21.5	20.5	2.95	3.33	91.82	92.03
660	1295	1440	6.06	3.92	2.8	2.56	1737	42	1.5	2.6	90.48	91.84

emission of 61 mg/Nm³. At the rated unit load of 660 MW, before optimization, the oxygen content in flue gas at the exit of air-heater was only 1.5%, CO in flue gas reached 1,737 ppm, and the unburnt carbon in flue gas was 6.09% and relatively high. After optimization, the oxygen content rose to 2.6%, CO decreased to 42 ppm as normal in flue gas, and the unburnt carbon in fly ash was reduced 2.14%, resulting in an obvious increase of boiler efficiency by 1.37%. As discussed in [4], the lower boiler thermal efficiency of this kind of boilers is one of the main disadvantages needing to be resolved at present.

Unfortunately, it is also obvious that NO_x rose nearly 164 mg/Nm³ after introducing RES into DCS in the boiler at the rated load, and the reason can be described as below. Due to the narrow upper furnace above the arch in the down-fired boiler as shown in Fig. 2, no more secondary air mass flow rate can be supplied into the furnace, which limits seriously supplying adequate air flow rate for the boiler. Generally, an optimal combustion requires larger air flow rate into the furnace at higher unit load, which benefits the boiler thermal efficiency but is unfavorable for reduction of NO_x emission. For high thermal efficiency and low emission of this kind of boiler, some new combustion technology, such as over-fire air (OFA) [6,7] and downward inclination of F-layer secondary air [8], was suggested to solve the contradiction between the thermal efficiency and the NO_x emission in the down- and coal-fired boilers.

CONCLUSIONS

A quantitative analysis model has been set up to relate the radiant energy signal (RES) with the combustion rate (heat release rate) inside a utility coal-fired power plant boiler through the heat transfer equation inside the furnace, demonstrating the principle of using the radiant energy signal to achieve high boiler thermal efficiency. Experiments carried out in a 660 MW down- and coal-fired utility boiler confirmed the characteristics of RES as an indicator of combustion rate inside the furnace and its ability to reflect the boiler thermal efficiency varied with the air flow rate.

Comparative analysis from experiments done in the boiler showed that the utilization of RES in the optimization of combustion can generally improve the boiler thermal efficiency at different unit loads, and especially the boiler efficiency was raised about 1.0% at the rated and lower unit loads. It should be stated that except the lower unit load, the NO_x emission for the boiler after optimization of combustion by RES will increase because of the limitation of the supply of air flow rate into the boiler. To achieve simultaneously a high thermal efficiency and low emission in this kind of boilers, some new combustion technologies are now available to solve the contradiction.

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NOMENCLATURE

A_r : surface area of the water-wall [m²]

A_m : mass flow rate of air fed into the boiler [kg/s]
 B_j : fuel mass flow rate [kg/s]
 c_B : heat storage factor of the boiler [kg/kPa]
 D_Q : thermal heat signal [kJ/s]
 D_B : steam mass flow rate of the boiler [kg/s]
 E_r : radiant energy signal (RES) [/]
 F_r : combustion rate (heat release rate) inside the furnace [kJ/s]
 G : gray value of an image pixel [/]
 H_c : heat value of fuel [kJ/kg]
 I_l : entropy of the flue gas leaving the furnace [kJ/kg]
 O_2 : oxygen content in the flue gas [%]
 P_d : steam pressure [kPa]
 Q_C : heat rate released from fuel (combustion rate) [kJ/kg]
 Q_F : initial entropy of fuel and air [kJ/kg]
 r, g and b : Red, Green and Blue data in the image pixel [/]
 T_f : flame temperature [K]
 T_s : temperature of the water-wall surface [K]
 ε_f : flame emissivity [/]
 ε_s : absorptivity/emissivity of the water-wall surface [/]
 σ_0 : the Stefan-Boltzmann constant, 5.67×10^{-8} W/(m²·K⁴)
 φ : heat-insulated coefficient of the furnace [/]
 η : combustion efficiency [/]

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