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Research Paper

A new method for constructing radiative energy signal in a coal-fired boiler

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HIGHLIGHTS

- A method to construct radiative energy signal in a power plant is described.
- The RES signals are derived from flame images recorded by CCD cameras.
- These signals follow the fluctuations in the combustion process.
- The RES approach has potential to improve load adjustment during power generation.

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ABSTRACT

In this paper, a systematic method to construct the radiative energy signal (RES) is proposed based on an image-processing-based combustion monitoring and control system with 16 high-temperature flame image detectors with CCD cameras mounted in a 300 MWe power generation plant. In this method, the gray value in GSU (Grey-Scale Unit) in every image is first transformed to a raw RES with the same unit and scale for the power output, and then a final RES is obtained after compensation for the load. RES signals thus calculated were found to be higher or lower than the measured power output indicating deviation of the fuel feed rate from optimal values leading to undesirable combustion conditions in the plant. As the load either increases or decreases in a large range, the RES values consistently and even synchronously varied based on increased or decreased loads. RES is successfully used to optimize the heat value signals of the power plants. The results show that RES constructed by the proposed method reveals the fluctuating level of energy in the boiler and may be used to monitor and control the operation of the system.

1. Introduction

The basic requirement of fossil-fuel-fired power plants is to meet dispatch demands, as well as to keep the main process variables such as the throttle pressure, main steam temperature and the reheat temperature at their optimal levels [1]. Thermal power generation is a continuous energy transformation process, and the essence of the control system is to make all the energy conversion levels of its sub-processes, such as fuel combustion, heat absorption by water and steam, and work done by the turbine-generator, etc., follow the electricity demands from a power grid effectively. As used in a low order boiler models [2], the typical fuel time delay value T_D (which represents the response speed of the fuel side of the furnace) ranges from 3 to 9 seconds, while the fuel and water-wall time constant T_F (which represents the response speed of water and steam side in the boiler) changes from 14 to 48 seconds. Thus, the time needed to transfer the heat released from the combustion process into water and steam enthalpy is much longer than the time required to supply the fuel to the combustion system.

Low-quality fuels and fuel blends from a variety of sources have exacerbated problems of flame stability in recent years [3], and the variation in the quantity and/or quality of fuel fed into the furnace is also the main cause for the operational state and parameters of the power plant to deviate from their optimal conditions. The combustion community has worked to develop advanced combustion monitoring and diagnosing technologies in utility boilers. Shimasaki et al. [4] proposed an onboard technology for monitoring combustion under all operational conditions using ionic current measurement. Obertacke et al. [5] developed a new sensor system based on UV emission spectroscopy in combination with tomographic evaluation procedures. Phillips et al. [6] presented an automatic system that uses color and motion information

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Table 1
Review of RES calculation methods.

Authors	Principle	Application	Results	Drawbacks
H.C. Zhou [14,15] and B.Y. Huang [16]	RES is an average gray value in the flame image	Air/coal ratio optimization	A faster main operating parameters response time	Instability for long-term operations
H. Zhou [17]	RES is a light intensity signal	Evaluating the coal identification system	High prediction accuracy	Signals were recorded over a period of 4 s
Z.X. Luo [18,19] and G.Y. Zhou [20]	RES was obtained by averaging furnace temperature	Building a new energy balance control strategy for combustion	The boiler efficiency increased by 1.0% at the rated and lower unit loads	The RES accuracy is prone to variability

computed from video sequences to locate fires. Lu et al. [7–9] studied the on-line monitoring and characterization of flames, and developed an imaging-based multifunctional instrumentation system that is capable of measuring a range of physical flame parameters. Zhou et al. engaged in a systematic digital flame image processing research and developed a monitoring technology for 2D/3D temperature distributions inside utility coal-fired furnaces for least ten years [10,11]. However, the bulk of these combustion measurement and monitoring studies have not been transformed into effective on-line technologies to improve the real-time control quality of boilers in power plants.

At the present time, fossil-fuel power plants are facing increasingly stringent emission standards, and optimal control strategy for the reduction of the emission of nitrogen oxide depends on real-time information about the furnace flue gas concentration and temperature data along the flue gas path [12]. Due to the lack of adequate, online information inside the furnace, the relatively rich information such as temperatures, pressures as well as flow of the water and steam measured from the water/steam cycle-side has been used to establish a new model to predict online information about the physical and chemical phenomena and the caloric/heat value on the furnace-side. In general, the dynamic response of the heat release derived from the steam-side of the boiler to a disturbance occurring in the fuel feed and air supply side suffers large time delay due to the thermal resistance through the boiler tubes [13].

The concept of a radiative energy signal (RES) was proposed over twenty years ago to overcome the lack of online detecting technology associated with energy production and heat release rates inside a furnace. The basic principles, applications, results and drawbacks of various RES methods are compared in Table 1.

Although the RES can quickly respond combustion process disturbance, the detectors, such as high-temperature image sensors (i.e., Charge Coupled Device, CCD), are easily covered by slag and/or deposits from the particle-laden furnace, and can even fail to work in such a high-temperature environment. Therefore, a processing method must be developed to ensure long-term RES reliability in furnace conditions. This study directly calculates RES values from the gray values of flame images, which are recorded by the control system using the data acquisition module ADAM-4117 manufactured by Advantech Co., Ltd. The dispatch can then compare the RES values to the load demand.

2. Radiation energy signal measurement system and principle

2.1. RES measurement system

The experimental investigation was carried out in a 300 MWe coal-fired power generation plant. The plant includes a 300 MW tangentially fired pulverized coal boiler with controlled flue gas recirculation. The rated load of the unit is 300 MW, steam mass flow rate was 1025 t/h, main steam pressure was 17.4 MPa, and feedwater temperature was 277 °C.

A schematic of the boiler and an on-line combustion monitoring system are shown in Fig. 1. High-temperature flame image detectors with 16 CCD cameras are mounted in four layers in different heights and different corners in the 300 MWe power generation plant. Four flame detectors were mounted in each layer of the furnace. The flame image monitoring equipment is shown in Fig. 2, including the transmission device, cleaning apparatus, cooling air and CCD camera. The image guidance was fixed in the center of a stainless steel pipe, which was inserted into the waterwall of the furnace and cooled using air to avoid overheating. The lens was cooled and kept dust free with a compressed air flow. The seesaw cleaning device prevents slag build-up on the lens.

By use of a frame-maker, the 16 video signals are combined into one video signal and transmitted to an industrial computer through an image capture card, and the flame images are processed to provide real-time RES information. Each image that has $20 \times 20 = 400$ pixels captured by the CCD sensor is processed. As shown in Fig. 1, the monitoring system connects the DCS via the data acquisition module (ADAM-4117) and data output card (PCL-726). Mean filtering is used to diminish noise effects. The RES sampling period is 1 second, which is equal to the power output period.

Typical flame images under different loads are shown in Fig. 3. The flame images gradually become brighter and brighter as the load increases, which is the basis for developing radiative energy signals from the gray values in the images.

2.2. Principle of the RES

RES is not a well-defined physical parameter, and different dimensions and scales have been used by different researchers in different years. In [18], an analytic model was established to relate the radiant energy signal, ranging from 0 to 1, with the combustion rate based on the heat transfer equation inside a boiler furnace. The flame temperature was obtained using a flame digital image processing technique. Study [11] used a modified Tikhonov regularization method to reconstruct the 3-D temperature distribution from 2-D flame temperature images. In addition, the emissivity of red (R) and green (G) was calculated from the monochromatic radiative intensity by the two-color method. So, it is necessary to define a unified, concrete, and more scientific RES for convenient application of this method.

The RES, E_a of a flame is defined by the Stephen–Boltzmann law as [18]:

$$E_a = \varepsilon \sigma_0 T^4 \tag{1}$$

where ε is the emissivity of the flame, σ_0 is the Stephen–Boltzmann constant, and T is the average temperature of the flame.

The heat release rate F_R inside the furnace is given by:

$$F_R = B_j Q_c \tag{2}$$

where B_j is the mass flow rate of coal supplied to the furnace, and Q_c is the heat rate released per unit mass of coal.

The relationship between E_a, RES and F_R, the combustion rate has been derived from [15], and takes the following form:

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