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A Brief Review of the Combustion Diagnosing Techniques for Coal-Fired Boilers of Power Plants in China

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ABSTRACT China has a large number of coal-fired power plants which are commonly suffered with many problems like uncertain coal source, frequent variation of coal quality, blended coal combustion and great fluctuation of the load. It is dire need of a system that can conduct combustion diagnosis, which can enables new horizon in optimization and to ensure the safety and efficiency of a unit. The contents of the combustion diagnosis include flame stability evaluation and temperature measurement. The latter provides quantitative information of the furnace, which can be used for unburnt carbon and pollutant emissions prediction. Diagnosing techniques are generally based on flame radiation intensity detect, flame image analysis, acoustic pyrometry and artificial intelligence analysis. The performance and engineering application of these techniques are reviewed and compared in this study. Artificial intelligence analysis based on the flame radiation intensity signal is recommended for flame stability evaluation as it is easily implemented in practical boilers with good accuracy and low cost. The challenge of the method based on flame image is thought to be that the reliability of the hardware system for flame image collection remains to be improved as they are easily affected by the high temperatures and fouling in engineering applications. The particles produced in the furnace is the hinder for application of the acoustic pyrometry in coal-fired boilers.

INDEX TERMS Combustion diagnosis, coal-fired power plants, stability evaluation, features extraction, artificial intelligence.

I. INTRODUCTION

The installed capacity of coal-fired power plants in China is more than 1 billion kilowatts. The limitation of the sources, coal-fired power plants in China commonly suffered from problems like uncertain coal source, frequent variation of coal quality and blended coal combustion. Meanwhile, in order to meet the requirement of peek load regulation of the electric grid, coal-fired power plants should frequently adjust the load substantially. It usually operates at low load (half of the full load even below) which greatly increased the difficulty to organize high-quality combustion [1]. Multi pressures of the high efficiency, low pollutant emissions, frequent variation of coal quality and poor operational conditions increases the labor intensity. It is inevitable to establish a system that is able to conduct combustion diagnosis and provide guidelines for smooth and optimum operation.

The combustion diagnosis for coal-fired boilers is different from a single flame at least in following three [2]–[4]. First, the subject of the two is different. Combustion diagnosis for coal-fired boilers was consisted on the study of general combustion state in the whole chamber, and a single flame diagnosing extended to detailed study of flame. Second, the method of the two is different. Combustion diagnosis for coal-fired boilers collected and extracted some features from the flames that were used to represent the combustion state,

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but did not specially focus on the direct relationships between each other. Single flame diagnosing detects radical distribution during the combustion process. Third, the purpose of the two is different. Combustion diagnosis for coal-fired boilers aimed to obtain information about the stability, economic and environment impacts of the combustion process in the chamber, and the conclusions are used to guide the operators to enhance the efficiency of the operating unit and to reduce NOx, SO_x and particles emissions. Single flame diagnosis aimed to obtain ignition mechanism, chemical reactions and products evolution characteristics.

In current study, a brief review on engineering applications of combustion diagnosis techniques in coal fired boilers for power plants in China has been presented. The aim was to reveal problems still remained to be solved as well as to attract more focus to prompt the development of these methods. Diagnosing techniques are generally based on detection of flame radiation intensity, flame image analysis, acoustic pyrometry and furnace pressure measurement. The basic working procedure and application state of all these techniques and a summary with critics are presented.

II. COMBUSTION DIAGNOSING TECHNIQUES FOR BOILERS IN POWER PLANTS

A. FLAME RADIATION INTENSITY METHOD

A direct reflection of the combustion process is the presence of a flame, which is characterized by sensors that detect the spectral response in the ultraviolet, visible and infrared regions or the combination of all of them [5]–[10]. The characteristics of different sensors applied in engineering are presented in Table 1.

TABLE 1. Characteristics of different sensors used in the boilers of power plants.

Sensors	Characteristics
Ultraviolet type	Requires high flame intensity and low particle concentration in the furnace. Appropriate for gas-fired and oil-fired boilers.
Infrared ray and visible light type	The sensitivity is superior to the ultraviolet type flame monitoring device. Appropriate for gas-fired, oil-fired and coal-fired boilers.

Based on the flame radiation intensity and some appropriate mathematical processing, combustion stability analysis is conducted by many researchers. Zhou and Han [11] investigated the spectrum distribution characteristics of the coal-fired flame as shown in Figure 1. They conducted fast Fourier transformation to the sequential signal of the combustion flame and analyzed the energy distribution characteristic in the frequency domain. It is qualitatively suggested that the low-frequency fluctuation energy of the flame and the peak of the low-frequency spectrum increases when the stability of the combustion process becomes worse.

B. FLAME IMAGE ANALYSIS METHOD

Digital flame image recorded by CCD cameras contains meaningful information about the combustion process. Based on image analysis, goals of the flame stability evaluation and temperature measurement could be achieved. Zhou and his team [12]–[15] had investigated two methods to obtain the temperature field in the furnace based on the flame image analysis. The first one was to integrate the analysis of a monochromatic flame image with the measurement of a reference temperature detected by thermocouple. The radiation intensity calculated by the detected temperature was regarded as a reference, temperature calculating at other places could be achieved by comparing the radiation intensity of each pixel in the flame image to the reference intensity. It is important to confirm the accurate position of the reference temperature in the flame image. The second method was to extract the quantitative color information of red, green and blue from the flame image recorded by a color CCD camera and to restructure the temperature field in the furnace by using two-color method, which is applied in a 300 MW coal-fired power unit. The schematic of the temperature measuring principle based on the two-color method is shown in Figure 2. Lu and his colleagues [16]–[18] achieved 3-D temperature measurement of a flame by using a single monochromatic CCD camera which have basic principle also the two-color method.

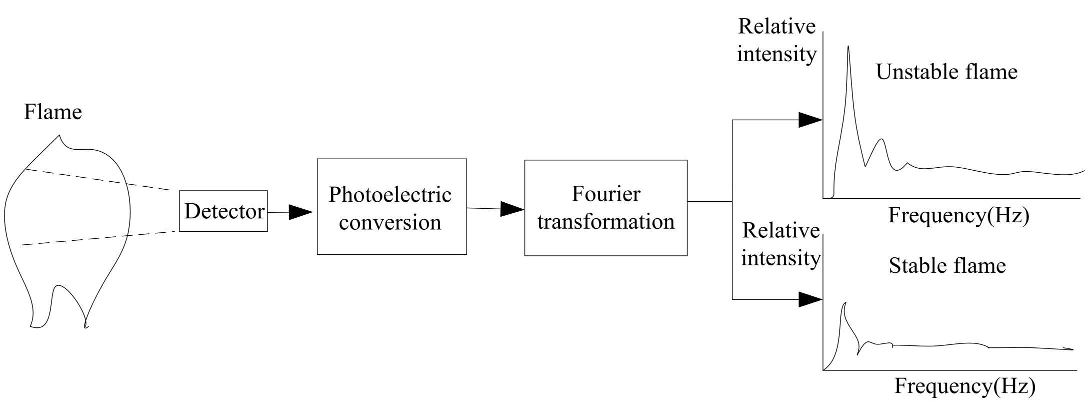

FIGURE 1. The schematic of the combustion diagnosing procedure based on the analysis of the radiation intensity of a flame.

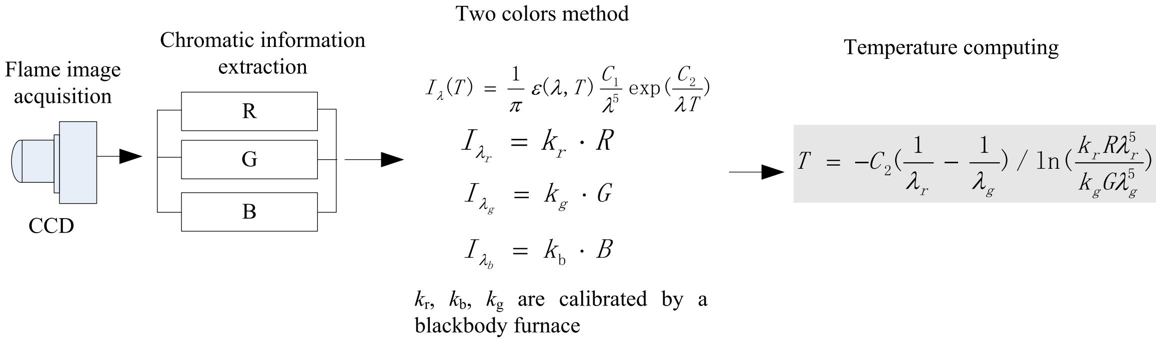

FIGURE 2. The schematic of the principle for temperature reconstruction based on the two-color method.

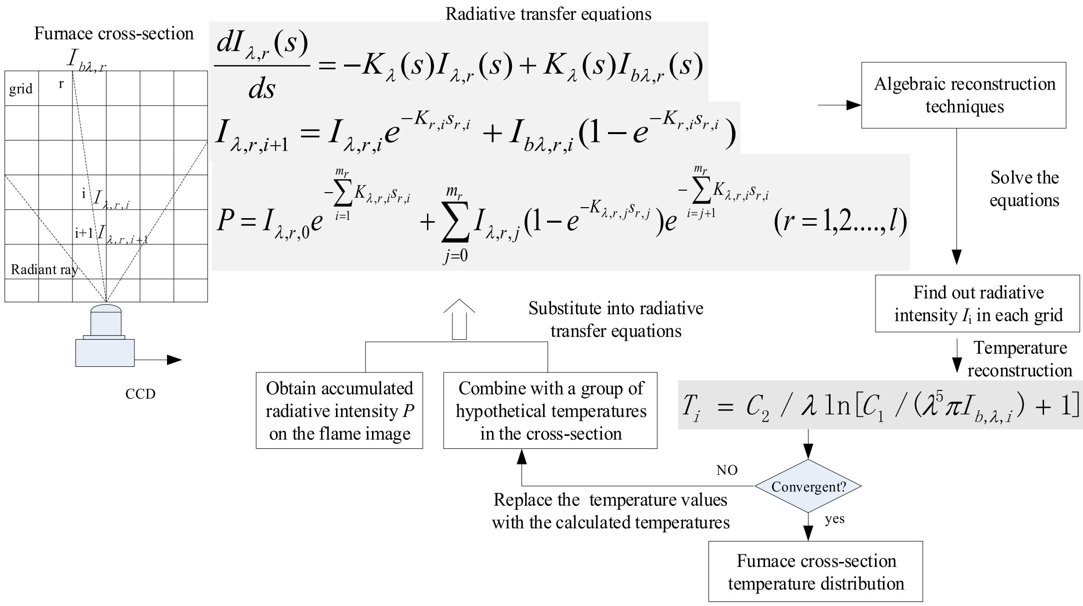

FIGURE 3. The schematic of the principle for temperature field calculating based on the algebraic reconstruction technique.

Wang and his team [19]–[28] proposed a method to restructure the temperature field of a cross section in the furnace based on the radiation law and the optics response characteristics of a color CCD camera as shown in Figure 3. A cross section was chosen and divided into many grids. According to the radiation attenuation law, equations of radiation transfer were built. Based on some boundary conditions, substituted a group of hypothetical temperatures into the equations, solved the equations by using the algebraic reconstruction technique to obtain the radiation intensity in each grid. Calculated the temperature in the grids according to the Planck's law by using the calculated intensities. The process was terminated upon convergence of obtained temperature. The convergent temperatures were regarded as the measurement results.

C. ACOUSTIC PYROMETRY

Acoustic pyrometry has been developed since 1990s [29]. According to the gas equation and the propagation equation of acoustic wave, the relationship between the speed of the wave and the gas temperature can be obtained. Since the distance between an acoustic transmitter and a receiver is easily measured, the speed of the sound wave can be calculated by recording the time of flight (TOF), based on which the temperature calculation of the measured path is achieved, as shown in Figure 4. Moreover, if one want to measure the

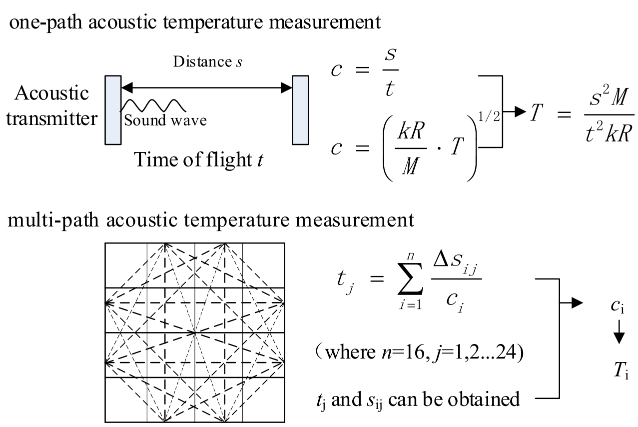

FIGURE 4. The schematic of the principle of acoustic pyrometry.

TABLE 2. Temperature measurement methods for combustion flames.

Methods	Characteristics	State
Integration of a monochromatic flame image with a reference temperature [12]	It is important to confirm the accurate position of the reference temperature in the flame image. The lifespan of the reference temperature detector may be a hinder for commercial use of the method.	Engineering application
Two-color method [13]	Flame image is the projection of a 3-D flame on the 2-D plane. There are errors in the color information extracted from the 2-D images because of the radiation accumulation. In the range of 1100~1500 ℃, the error is less than 5% [13].	Engineering application
Integration of the radiation decaying law and an algebraic reconstruction technique [19-28]	The calculating cost is great during the iteration process. The performance of the method depends on the number of grids. Measurement error will increase at high temperature (above 1273 ℃) [22].	Engineering application
Acoustic pyrometry [30]	The mean temperature of the path between an acoustic transmitter and a receiver is easily calculated. Precise temperature measurement of each point in the section would increase the difficulty of the iteration process. The accuracy of the measured temperature is affected by thermal noise and particles in the furnace.	Engineering Application

TABLE 3. Characteristics of different diagnosing method in engineering application.

Methods	Advantage	Disadvantage
Flame radiation intensity method	Direct information about the combustion intensity of a flame; Low cost and easy maintenance.	Single kind information only.
Flame image analysis method	Abundant information contained; Quantitative information about the flame could be achieved.	Complex image collecting and analyzing system is needed; Extra routine maintenance cost.

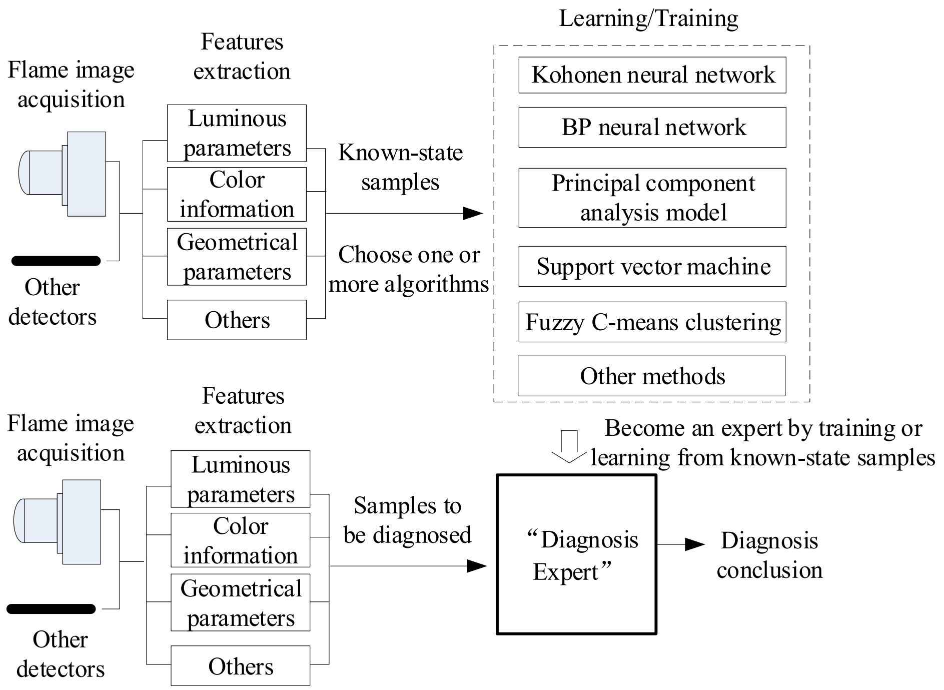

FIGURE 5. The procedure of the diagnosing method using artificial intelligence.

temperature filed of a furnace cross section, distribute many acoustic transceivers around the perimeter of the furnace cross section to form a multiple path array. Each transceiver is commanded to send a sound signal in sequence, and the TOF of all paths are acquired. Therefore, the two-dimensional temperature distribution through the furnace cross section can

TABLE 4. Characteristics of features group for coal-fired flame diagnosing.

Classification	Features group	Characteristics
Based on the combustion character parameters monitoring	Mean value, standard deviation, peak, and uniformity of the pressure in the furnace; Mean value, standard deviation, peak, and uniformity of the flame radiation intensity signal [40, 41]	The features group is a statistic anslysis of the pressure signals and the flame radiation intensity. The synchronization of the two is very important. The pressure signals cover the full furnace and the flame radiation intensity signal aims at an individual burner. The D-S evidence theory should be used to integrate the diagnositic conclusions obtained based on each other.
	Variance, measure of skewness, kurtosis, shape factor, singular spectrum entropy, power spectral entropy and wavelet energy entropy of the flame radiation intensity signal [50]	No more hardware cost is needed. Diagnosing object is an individual burner.
Based on the flame image processing	Luminous region area, flame brightness, uniformity of flame brightness, average brightness of the nonluminous area, average color of the whole flame image, average color of the flame luminous region, total number of colors appearing in the luminous region [47]	CCD camera is needed. Brightness threshold is needed, which is not a theoretical one, but obtained based on experiences. The performance is affected by the installation of the camera.
	Average brightness in the effective region, flame front position, distance between the flame front positions in two adjacent images and average color index of the luminous region [52]	CCD camera is needed. Brightness threshold is needed, which is not a theoretical one, but obtained based on experiences. The performance is affected by the operating condition.
	Effective area ratio, high-temperature area ratio, average brightness in the effective region, standard deviation of the brightness in the effective region, histogram entropy of the brightness in the effective region, row coordinate of the centroid, line coordinate of the centroid, row coordinate of the geometrical center, line coordinate of the geometrical center [38] Average brightness in the effective region, average brightness in the high-temperature region, effective region area, high-temperature region area, high-temperature area ratio, offset of the centroid and circularity [39]	CCD camera is needed. Brightness threshold is needed, which maybe affected by coal quality. Flame shape changes with load, which may affect the geometrical parameters.

be calculated by using a reconstruction algorithm. An and his team [30]–[33] developed one-path, multi-path acoustic temperature measurement systems and acoustic computed tomography (CT) technology and applied them in 300 MW, 200 MW and 600 MW thermal power plants, respectively. The practical application indicated that the acoustic pyrometry is accurate and reliable. The challenge is that, as shown in Figure 4, the accuracy of the measured temperature is affected by the particles in the furnace.

Above mentioned temperature measurement techniques have provided quantitative information about the combustion process, which appears be convicted for combustion diagnosis and optimization. The characteristics of the temperature measurement methods are summarized in Table 2. Based on the furnace temperature measurement and some further mathematical fitting, unburned carbon prediction and NOx concentration calculation could be achieved [34].

The difference between the flame radiation intensity method and flame image analysis method is shown in table 3.

D. COMBINED WITH ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) systems are widely applied in many areas because it offers an alternative way to tackle complex and un-defined problems by learning from examples [35]. It is used as a combustion diagnosing technique for coal-fired boilers in power plants since 1990s. The brief procedure of the method is illustrated in Figure 5. One should extract features that could be used as combustion indicators. The featured group usually are different in values when the combustion state is practically different. After repeated trial-and-error searches using known-state samples (called training stage), the chosen algorithm, e.g., artificial neural network [36], [37], principal component analysis model [38]–[40], fuzzy C-means clustering [41], [42], obtained the ability to recognize the state of a sample to be evaluated.

1) FEATURES EXTRACTION

Combustion theory does not provide a theoretical definition for a stable combustion state but illustrate some properties

TABLE 5. Application of the algorithms in the combustion diagnosing for coal-fired boilers in power plants.

Methods	Diagnosing procedure	Characteristics	Applications
Kohonen self-organizing neural network [20]	Extract features group from the stable coal-fired flame images and the unstable ones to act as training samples. After training, flame images that belong to the same classification are clustered, and the nodes in the topology map of the neural network become sensitive to features group that is same as or similar to themselves. This function is achieved by the adjusted connection weights. Input the features group of a flame to be diagnosed into the trained neural network, the state is then identified according to the cluster that the features group belongs to.	Self-organizing cluster is an unsupervised learning model. It is required that the features group of a same kind flame should have obvious common characteristics. Flames whose state are different should be easily distinguished from each other by the features group. The cluster performance relies on the difference of the input samples, which makes the reliability of the method is inferior to the supervised learning model.	Engineering application
Back propagation (BP) neural network [37]	Set a network structure and define expected output signals as a training tutor. Input the features group extracted from the stable and unstable coal-fired flame images to make the network export values that represent the corresponding flame state as expected. Repeat the process many times and the connection weights of the neural nodes are well trained. Input the features group of a flame to be diagnosed into the trained network, the state of the flame could be determined according to the output value. When the output value is not equal to either of the values that represents stable and unstable flames, the state of the flame is then determined by calculating the distances between the output value and the tutor signals.	Back propagation neural network is a supervised learning model. The accuracy of the method for flame state recognition increases as the capacity of the known-state training samples increases. Error function is very important to the performance of this method.	Engineering application
Principal component analysis (PCA) [38, 39]	Extract features group from the coal-fired flame images with certain state to constitute an initial matrix with size of $m \times n$. Conduct mathematical processing to the initial matrix and obtain the principal component space matrix with size of $m \times k$ ($k < n$) that is comprised of linearly independent vectors. The remained dimensions make up the residual space matrix. Define two statistics that can be calculated based on the principal component space and residual space, respectively. Set control limits to the two statistics. Calculate the values of the two statistics at every moment. The flame state supervisory is achieved by checking if either of the two statistics exceed the limit values.	The method is used to check whether the state of a flame is changed rather than identify the flame state directly. The accuracy of the method could be enhanced when the capacity of the training sample is increased.	Engineering application
Support vector machine (SVM) [40]	Extract features group from the stable coal-fired flame images and the unstable ones. Each features group acts as a feature vector that represents a certain flame state. Find out the optimal classification surface (classification function) for the feature vectors that represent stable and unstable flames. Substitute the features group of a flame to be diagnosed into the classification function and compare the function value to a critical value for classification (usually equals to 0), based on which determine the state of the tested flame.	As to sample classification, the performance of SVM is better than other methods. This method is able to classify any group of samples into two classifications. Each sample in the group belongs to either of the two. Increase the capacity of the sample that is used to find out the classification function could improve the performance of the method.	Experimental research.
Fuzzy C-means cluster [41,42]	Choose a group of features group extracted from stable, unstable flames and these between them. Find out the cluster centers of each state, respectively. Calculate the membership between the features group of a flame to be diagnosed and the cluster centers. Identify the state of the tested flame according to the values of the membership.	It is required that the features group of the known-state sample should differs obviously from each other when the flame state is different. The membership could describe the flame state of stable, unstable and this between the two. It is a description that very close to the practical combustion process.	Engineering application

TABLE 5. ***(Continued.)*** **Application of the algorithms in the combustion diagnosing for coal-fired boilers in power plants.**

D-S evidence theory [50]	Integrate two uncertain conclusions obtained based on different criterions or methods to form a conclusion that is more accurate.	Usually combine with other methods, i.e. self-organizing neural network and support vector machine.	Experimental research.

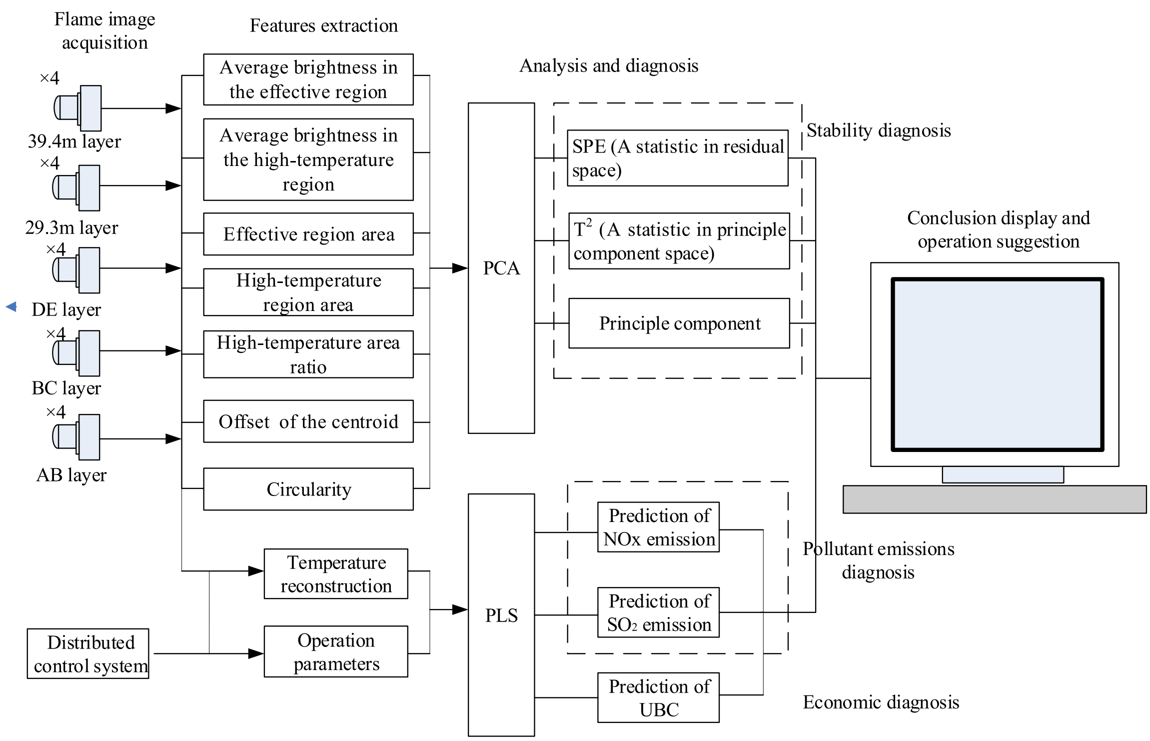

FIGURE 6. **The schematic of the working principle of the CSDS.**

for a stable flame. These properties are used as features for combustion diagnosing. The features consist of geometrical parameters [43]–[45], luminous parameters [46], [47], color information [47]–[49], pressure signals in the furnace and spectrum of the flame intensity [50].

Features are proposed according to experimental investigations and engineering operation experiences. They are chosen for the reason that the values of them in an image of stable flame are different from that in an image of unstable one. In order to accurately supervise the variation of the combustion state, usually a group of features are combined. Features group for coal-fired flame diagnosing and their characteristics are shown in Table 4. Features extraction combination is different from one researcher to another. Generally, the features group should meet the requirements as follows. a) contain information that reflects the combustion state as much as possible. b) should be easily distinguished from one to each other when the combustion state is practically different. c) the geometrical parameters used as features should be out of the influence of the installation angle of the detector and the position of the burner. The luminous and thermodynamics parameters should be out of the influence of the coal quality.

2) ALGORITHMS

There are number of algorithms including neural network (including self-organizing network [36] and back propagation neural network [37]), principal component analysis [38]–[40], support vector machine [40], and fuzzy C-means cluster algorithm [41], [42] has been employed. Characteristics of the algorithms in diagnosing the coal-fired flames in power plants are shown in Table 5. Application and comprehensive performance of these methods are also presented.

III. ENGINEERING APPLICATIONS

The schematic of a combustion supervising and diagnosing system (CSDS) applied in a 300 MW coal-fired power unit [52] and the schematic of a temperature supervising system applied in a 300 MW coal-fired power unit are shown in Figure 6 and 7, respectively.

The information of the two engineering application cases is summarized in Table 6. The operating experience results that there are some weak points that needs to be improved. The performance of the flame image collecting system which is not stable. There is high need to improve the reliability of

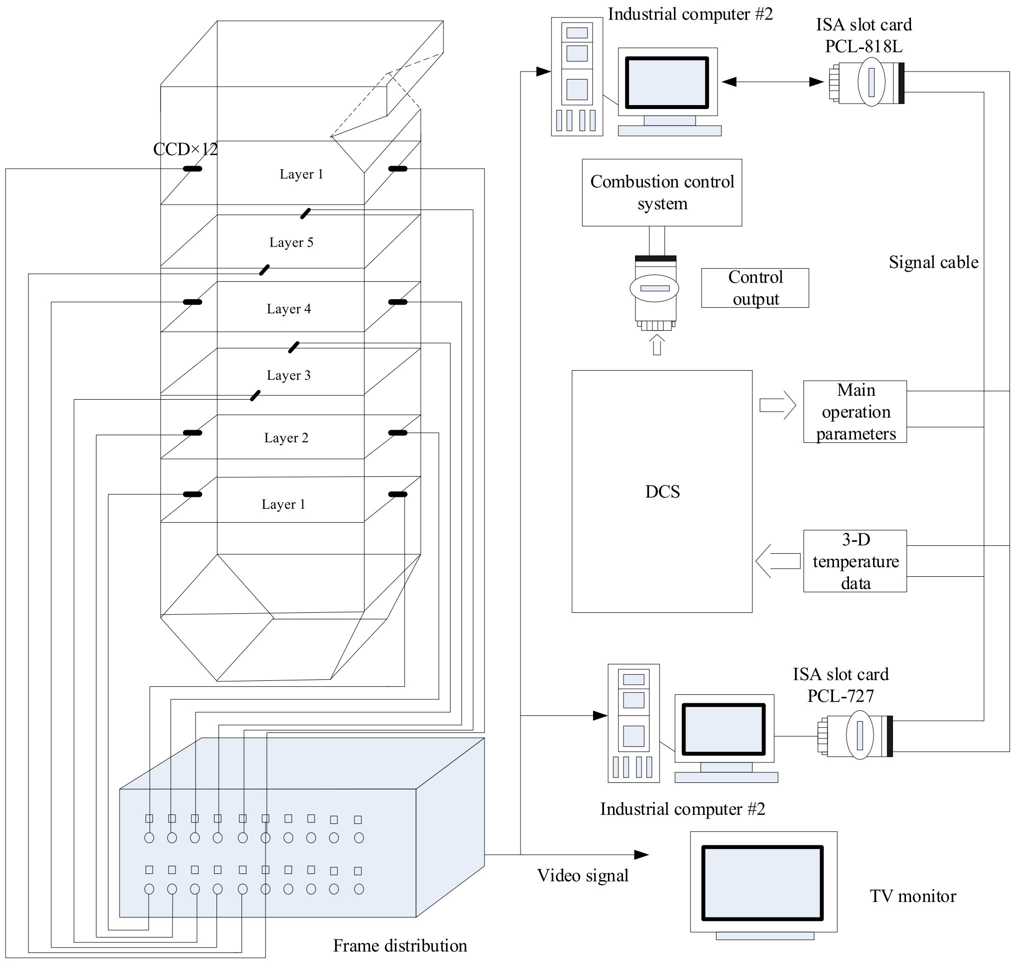

FIGURE 7. A 3-D temperature supervisory system applied in a 300 MW coal-fired power unit [12].

TABLE 6. The information about the two engineering application cases.

Boiler type	Methods	Functions	Economic benefits
Tangentially coal-fired boiler [53]	Principal component analysis (PCA); partial least square (PLS); algebraic reconstruction technique.	Temperature field measuring in the furnace, combustion stability diagnosing, unburnt carbon and pollutant emissions predicting and operation guiding of the unit	The unburnt carbon concentration is the exhaust gas decreases by 4.1%, the total efficiency of the boiler increases by 1.7% and the response speed to the load variation increases by 10%.
Tangentially coal-fired boiler[12]	Two-color method	Visualization of the 3-D temperature in the furnace.	--

the hardware system that being used to collect and transmit information.

IV. CONCLUSION AND EXPECTATION

The combustion diagnosing method for coal-fired boilers in power plants is briefly reviewed and following conclusion and expectation are drawn.

1. Temperature measurement inside the furnace based on the flame image analysis is useful for the operators to obtain quantitative information of the combustion process. It is also possible to achieve the goal of automatic and real-time optimization based on the measured temperature field. The reliability of the image collecting and analyzing system should be improved. The particles and thermal noise produced in the furnace affects the accuracy of the acoustic pyrometry that applied in coal-fired boilers. Since the radiation intensity is easy to measure and the features extracted from the radiation intensity performs good distinguishing ability for stable and unstable flame, it is

recommended to adopt artificial intelligence algorithm combining with the flame radiation intensity signals for combustion stability diagnosing.

2. There are at least two steps for intelligent control of combustion process which should be the hot spot area for future studies. Foremost is to develop methods that automatically analyze the formation regularity of a poor-quality combustion state, based on which optimized operation guidelines could be provided. Another important is to develop intelligent learning algorithms to accumulate experiences from the practical operation, which can lead to control the combustion process without or with least supervisory of the operation personnel.

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