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# Simulation on an optimal combustion control strategy for 3-D temperature distributions in tangentially pc-fired utility boiler furnaces

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**Abstract:** The control of 3-D temperature distribution in a utility boiler furnace is essential for the safe, economic and clean operation of pc-fired furnace with multi-burner system. The development of the visualization of 3-D temperature distributions in pc-fired furnaces makes it possible for a new combustion control strategy directly with the furnace temperature as its goal to improve the control quality for the combustion processes. Studied in this paper is such a new strategy that the whole furnace is divided into several parts in the vertical direction, and the average temperature and its bias from the center in every cross section can be extracted from the visualization results of the 3-D temperature distributions. In the simulation stage, a computational fluid dynamics (CFD) code served to calculate the 3-D temperature distributions in a furnace, then a linear model was set up to relate the features of the temperature distributions with the input of the combustion processes, such as the flow rates of fuel and air fed into the furnaces through all the burners. The adaptive genetic algorithm was adopted to find the optimal combination of the whole input parameters which ensure to form an optimal 3-D temperature field in the furnace desired for the operation of boiler. Simulation results showed that the strategy could soon find the factors making the temperature distribution apart from the optimal state and give correct adjusting suggestions.

**Keywords:** tangentially-fired boilers; combustion control; three-dimensional temperature distributions; adaptive genetic algorithm

## Introduction

On-line optimal combustion control techniques are essential for the safe, economic and clean operation of fossil-fuel-fired utility and industrial boilers. At present, the input variables of the combustion system in a pulverized-coal-fired boiler, including the mass flow rates of fuels, primary airs, secondary airs and tertiary airs of all burners, always be controlled via the bias of the main steam pressure with respect to the preset value and the oxygen, CO contents and the NO<sub>x</sub> emissions in the flue gas (John, 1997; Vavak, 1997; Liu, 1999). In facts, as the steam parameters (Ptscheider, 1996) are used as input parameters, the delay is too long compared with the time scales of the combustion reactions.

Recently, the authors have done theoretical and experimental work to visualize the 2-D and 3-D temperature distributions inside large-scale furnaces (Zhou, 2004). The temperature distributions contain many information which reflect the factor influencing the NO<sub>x</sub> formation. The NO<sub>x</sub> emission of the combustion from boilers can be reduced significantly by modification of the combustion process. Through changing the input parameters, the highest temperature in furnace can be decreased and the distribution uniformity of temperature can be improved, and so decrease the formation of NO<sub>x</sub>. The optimum 3-D temperature distributions in a furnace under different loads can be determined by the balance between the combustion efficiency and NO<sub>x</sub> emission in flue gas as proposed by John (John, 1997), and regarded as preset value for discrete load points. So, it will be a good choice to monitor simultaneously the temperature distributions and the intermediate products (Obertacke, 1996) inside furnaces to improve the combustion control systems.

So, the ideal temperature distributions under different loads can be preset before the control, and this will be discussed in another work.

In the past two decades, the CFD (computational fluid dynamics) codes for modeling utility boilers is becoming a useful tool to predict the performance of boilers, which has the potential to become an important design tool (Boyd, 1986). Unfortunately, CFD modeling is time consuming, and could not be used in real-time for combustion control.

In this paper, a furnace combustion control strategy using a group of new characteristic parameters featuring the 3-D temperature distributions inside the furnaces was studied by simulation. A linear model relating the 3-D temperature distributions and the input of the combustion process such as the mass flow rates of fuel and air for the every burner was obtained off-line by a CFD code. In the control strategy the adaptive Genetic Algorithm is adopted to search for the optimal control input.

## 1 Model of 3-D temperature distribution

### 1.1 Establishing a linear model

As shown in Fig. 1, the 3-D temperature distribution in a furnace is discretized into  $n$  planes along the flow direction of the flue gas. We define a group of area average cross-section temperatures varied in the vertical direction of the furnace labeled as  $T_k$  and their position coordinates  $x_k, y_k$ , defined as coordinates of the cross-section temperature centers, calculated from the gravity center formulas of cross-section temperature, where  $k = 1, \Delta, n$  refers the discrete points.  $x_k, y_k$  should be in the geometrical center of the furnace cross-section if the aerodynamic field and the combustion condition inside a furnace are reasonable. If not,

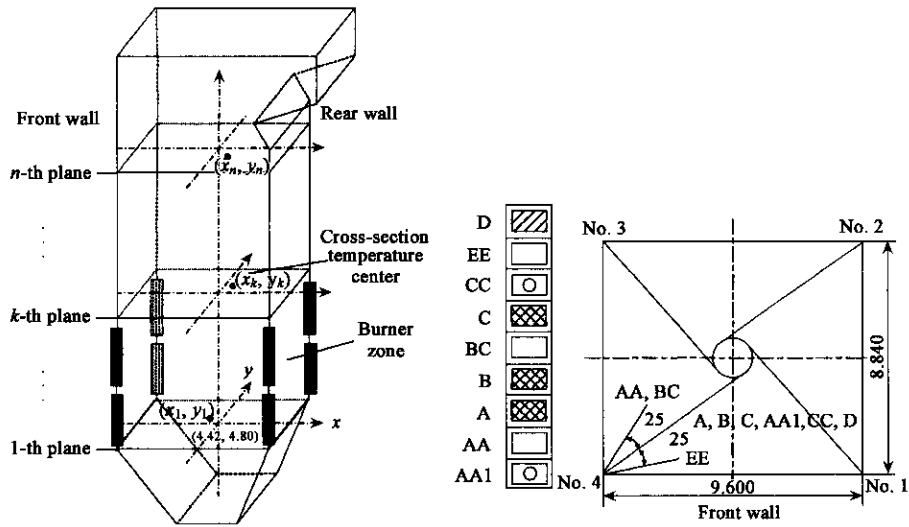


Fig.1 The schematic of the tangentially fired furnace and the burner arrangement

A, B, C: the primary air ports; AA, AA1, BC, CC, EE: the secondary air port; D: the tertiary air port

the waterwall surface will suffer slagging or deposition.

The fourth power of the average cross-section temperatures,  $T_k^4$ , indicating the radiation energy levels of the flame, and  $x_k, y_k$ , can represent the 3-D characteristics of the whole combustion process inside the furnace, and can be obtained either from flame image processing techniques (Zhou, 2004) or from combustion simulation (Boyd, 1986).

So, the output parameter vector of the combustion control objective is represented as follows:

$$\begin{aligned} \mathbf{S} &= (T_1^4, \Delta, T_n^4, x_1, \Delta, x_n, y_1, \Delta, y_n)^T \\ &= (T^4, \mathbf{X}, \mathbf{Y})^T, \end{aligned} \quad (1)$$

where  $\mathbf{S} = (S_i, i = 1, \Delta, 3n)^T$ . The input parameter vector of the tangentially fired boiler studied in the paper is composed of every nominal fuel flow rate,  $F_i$ , primary and secondary airs,  $A_i^1$  and  $A_i^2$  respectively, of all burners, and the tertiary air,  $A_i^3$ , and is written as:

$$\begin{aligned} \mathbf{U} &= (F_1, \Delta, F_m, A_1^1, \Delta, A_m^1, A_1^2, \Delta, A_m^2, A_1^3, \Delta, A_4^3)^T \\ &= (\mathbf{F}, \mathbf{A}^1, \mathbf{A}^2, \mathbf{A}^3)^T, \end{aligned} \quad (2)$$

where,  $\mathbf{U} = (u_j, j = 1, \Delta, 3m + 12)^T$ ,  $m$  refers to the number of the layers of burner.  $F_i = F_{0,i} \times Q_{\text{net.ar}} / Q_{\text{net.ar}}^0$ ,  $F_{0,i}$  is one of fuel flow rate,  $Q_{\text{net.ar}}$  and  $Q_{\text{net.ar}}^0$  are heating value of present coal and the design coal, respectively.

By the first approximation, we can have the mathematic model relating the 3-D temperature distribution of flames,  $\mathbf{S}$ , with the input parameter vector,  $\mathbf{U}$ , in furnace are written as,

$$\mathbf{S} = \mathbf{D}\mathbf{U} + \mathbf{B}, \quad (3)$$

where  $\mathbf{D} = (d_{i,j})$  represents a coefficient matrix with dimensions of  $3n \times (3m + 12)$ , and  $d_{i,j} = \frac{\Delta S_i}{\Delta u_j}$  represents

the influence coefficient of the  $j$ th input parameter on  $i$ th output parameter.  $\mathbf{B}$  is a constant matrix with dimensions of  $3n \times 1$ , and  $\mathbf{B} = \mathbf{S}_0 - \mathbf{D}\mathbf{U}_0$  is defined under the condition desired,  $\mathbf{S}_0, \mathbf{U}_0$  is the set of output and input parameters corresponding to the basic condition desired, respectively.

In application, due to the nonlinear features of the

combustion process, we can set different matrixes  $\mathbf{B}, \mathbf{D}$  for different loads. In the near future, with the visualization technique for 3-D temperature distribution applied in on-line operation in fossil-fuel-fired power generation plants (Zhou, 2004), the matrixes  $\mathbf{D}$  and  $\mathbf{B}$  can be estimated from experiments. At the simulation stage now, they were determined by a CFD code described below.

## 1.2 Coefficient matrix D

The control object was a tangentially fired boiler (125 MWe power generation unit, 420 t steam/h) with a furnace of 9.6 m  $\times$  8.84 m in horizontal section and 37.7 m high. Wide rang burners are equipped in the furnace. Here  $m = 3$ . Five secondary air ports, three primary air ports and one tertiary air ports are arranged on each corner of the furnace. A CFD code (Boyd, 1986) is used to model flow, combustion and heat transfer inside the furnace in various operational conditions. In this study, the computation domain was discretized using  $25 \times 27 \times 69$  grid nodes while the radiative heat transfer equation was solved on a coarser grid with  $14 \times 21 \times 39$  control volumes. For the purpose of model establishment, the furnace was discretized into 13 characteristic planes along the vertical direction.

The rated load was regarded as the basic operational condition. The method of single factor taking turns was adopted to set the simulation cases. A post processor was employed to obtain the cross section average temperature and the coordinates of the cross section temperature centers in any characteristic plane. Then the elements in the influence coefficient matrix  $\mathbf{D}$  in Eq.(3) were calculated.

The verification of linear model will not be described in detail here.

## 2 Optimal combustion control based on adaptive genetic algorithm

### 2.1 Adaptive genetic algorithm

The genetic algorithm (GA) is robust search and optimization techniques based on the Darwinian theory (Vavak, 1997). But Standard GA is difficult to converge to

global optimum solution and ease to occur premature convergence on complex optimal problem and nontrivial multimodal functions. For the tangentially fired boiler, the furnace temperature distribution is proposed to be controlled based on adaptive genetic algorithm in this paper. At first, the input parameters of the model in Eq. (3) were discretized and coded with binary system. In practical AGA based control program, the binary system codes all the input parameters by 10-bit. They together consist the chromosome code of one burner. A data structure including chromosomes of all burners and that of the other secondary and tertiary air is an individual of AGA. Evaluating above structure repeatedly with stochastic method can create a randomly-distributed initial colony with a scale of 100.

The objective function,  $V(U)$ , for the AGA method, is given as follows:

$$V(U) = \sum_{i=1}^n \lambda_i (T_i - T_{0i})^2 + \sum_{i=1}^n \lambda_{i+n} (x_i - x_{0i})^2 + \sum_{i=1}^n \lambda_{i+2n} (y_i - y_{0i})^2, \quad (4)$$

where,  $T_{0k}, (x_{0k}, y_{0k})$  are the vectors of optimized cross-section average temperatures and the coordinates of the cross section temperature centers in the planes, respectively;  $\lambda_i$  are weight coefficients to balance the different magnitudes of the biases of the temperatures and the coordinates ( $\lambda_i > 0, i = 1, \Delta, 3n$ ).

The function of fitness is written as:

$$f(U) = \begin{cases} C_{\max} - V(U), & V(U) < C_{\max} \\ 0, & V(U) \geq C_{\max} \end{cases}, \quad (5)$$

where,  $C_{\max}$  is the maximum value of  $V(U)$  so far evolutionary process.

Then the optimization problem for this study can be simply stated as follows:

$$\begin{aligned} & \max f(U) \\ & \text{s.t. } 1.0 < \\ & \sum_{i=1}^{2m+12} u_{i+m} \left/ \left( (0.2627 Q_{\text{net,ar}} + 0.007 M_{\text{ad}} - 0.06) \cdot \right. \right. \\ & \left. \left. (1 - q_4) \cdot \sum_{i=1}^m u_i \right) \leq 1.3, \right. \\ & U \in D, \end{aligned} \quad (6)$$

where the set of  $D$  might typically include lower and upper bounds on the variables, which is checked by the CFD code to obtain the entire operating envelope of the combustor.  $M_{\text{ad}}$  is moisture content of coal in air-dry basis,  $q_4$  is the heat loss due to unburned carbon. During the simulation,  $q_4$  is kept constant and equal to the value of design condition.

The AGA algorithm can be found in Chen's report (Chen, 1996) and will not be described in detail.

## 2.2 Simulation and analysis

As this control strategy is applied in practice, the temperature condition in all sections,  $S$ , will be compared with the corresponding basic temperature distribution  $S_0$ . When the difference exceeded the tolerance for the operation, the control program begins to run. The resulted input parameter vector  $\Delta U$ , quantified by the change ratio to the basic value,

obtained by using the AGA method, will lead to create a change in temperature distribution  $\Delta S$  in the furnace, making the temperature distribution back to its basic condition.

To validate the control strategy, the algorithm program was tested under many kinds of disturbances of boiler combustion conditions. In simulation, the ratio of fuel to primary air in every burner and the coal properties were kept constant.

### 2.2.1 Optimization results under disturbance of load

When the load increased from 90% to 100%, Fig. 2 shows the optimization results of the temperatures of the flame. The optimized temperature distribution was coincidence with the prescribed ideal one. Fig. 2 also shows the optimization result which is simulated by adding noisy readings to intermediate parameters with a Gaussian distribution with zero average value and mean square deviation 3%, the algorithm obtained the optimum control signals. As shown in Fig. 3, the total fuel and air flow rates entering the furnace would increase by approximately 10% as before. Fig. 4 shows the optimized results of the change ratios of the mass flow rates of the fuels, primary and secondary airs of each burner. Each burner will receive an instruction of increasing the mass flow rates of fuel, primary and secondary air accordingly. Results revealed that the AGA based control strategy can rapidly respond to the requirement of changing boiler load and adjust the fuel and air mass flow rates of each burner. The adjustment made the temperature distribution agreed well with the basic temperature distribution under the new boiler load level. Simultaneously, the x- and y-coordinates of the horizontal cross-section temperature centers were maintained well.

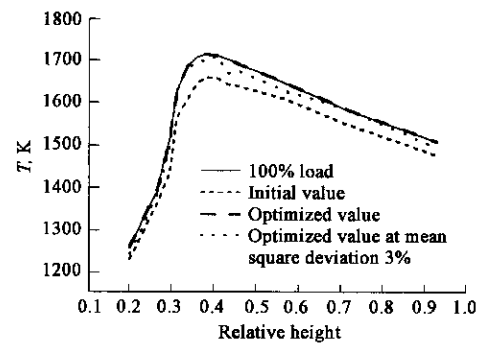


Fig. 2 Optimized temperatures under boiler load increasing

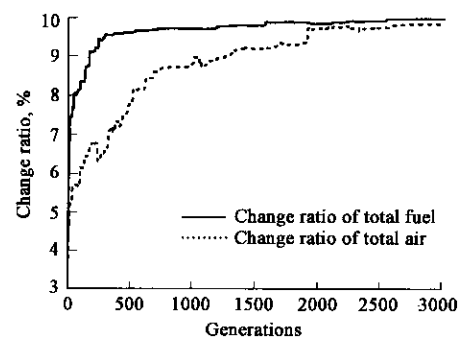


Fig. 3 Searching process under boiler load increasing

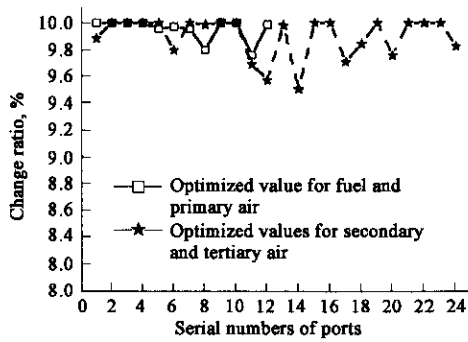


Fig. 4 Optimized change ratio of the mass flow rates of every fuel and air ports

### 2.2.2 Optimization results under disturbance of burner failure

Fig. 5—7 represent the simulation results when the burner of the 2nd corner in the first layer was out of service. When the controller was given an instruction that the burner could be resumed, the optimization result was that the fuel and the primary air mass flow rates of the burner should be forced back to the normal ones, as shown in Fig. 7, and the other burners input parameters did not change obviously. Fig. 5 shows that the optimized temperature distribution was consistent with the ideal one. The biases of cross-section temperature centers were corrected accordingly, as shown in Fig. 6. If the controller was given an instruction that this burner could not be resumed, the algorithm program then fixed the fuel and primary air mass flow rates of that burner to zero, and during the course of optimization, the mass flow rates of fuel and primary air of the burners near the failed one increased, and the second air flow rates were optimized correspondingly. Limited by the space, the results were not presented. This adjustment can compensate the influence on the temperatures and the biases of cross-section temperature centers due to the failure of one burner. So, the results have revealed that the control strategy can rapidly diagnose the disturbance of the burner failure and optimize the combustion state in the furnace.

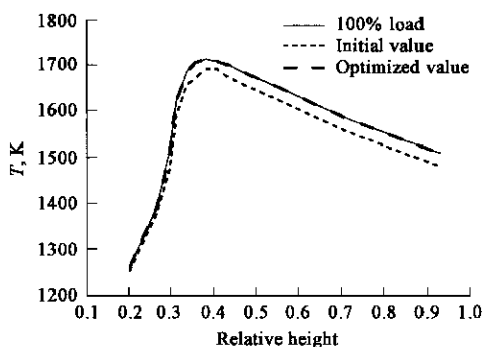


Fig. 5 Optimized temperature under burner failure

## 3 Conclusions

The adaptive genetic algorithm was introduced into an optimal control method for pulverized coal combustion in multi-burner tangentially fired furnaces. The three-dimensional temperature distribution was used as a set of

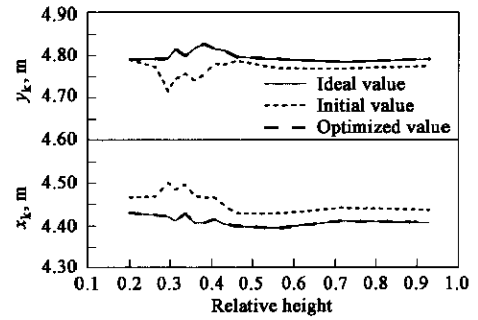


Fig. 6 Optimized coordinate of section temperature center as one burner fails

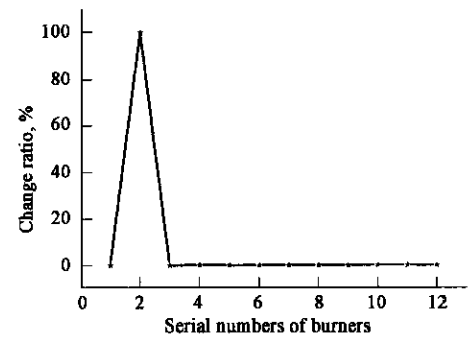


Fig. 7 Optimized change ratio of the mass flow rate of fuel and primary air as one burner fails

intermediate variables, and its optimization was taken as a basic aim. The simulation has been done with a furnace combustion model, and the results showed that the control method could provide suitable control signals for the fuel and air mass flow rates to change the load level, estimate the failure of individual burner and give correct control signals to deal with it. At present, we are developing a system to visualize the 3-D combustion temperature distributions in furnaces (Zhou, 2004). The work is expected to establish a firm basis for the application of the optimal control strategy.

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