Data-driven control for combustion process of circulating fluidised bed boiler

Fang Fang1,2*, Songyuan Yu1, Le Wei1, Yajuan Liu1,2, Jizhen Liu1

1School of Control and Computer Engineering, North China Electric Power University, Beinong Road No. 2, Changping District, Beijing, People’s Republic of China
2Key Laboratory of Condition Monitoring and Control for Power Plant Equipment, Ministry of Education, North China Electric Power University, Beinong Road No. 2, Changping District, Beijing, People’s Republic of China

E-mail: ffang@ncepu.edu.cn

Abstract: Owing to the advantages of burning low-quality coal (coal slime and coal gangue), furnace desulphurisation, low NOx emission and deep load adjustment, the circulating fluidised bed (CFB) combustion technology becomes one of the few fossil fuel utilisation technologies funded continuously by the Chinese government. However, compared with the pulverised coal boiler, the combustion process of CFB boiler is more complicated because of the larger time delay, significant uncertainty and more coupled variables. In this study, a data-driven proportional–integral-derivative (DD-PID) control strategy is presented for the combustion control of CFB boiler to improve the operating performance under full operating conditions. By analysing the running mechanism of combustion process, an inverse decoupler is introduced to transfer the combustion object to the generalised controlled object, which has relatively independent input–output relationship. After that, a normative procedure of DD-PID, including PID-parameter database establishment, information-vector neighbourhood selection, active PID-parameter determination, database update, and redundant vector deletion, is given. Finally, a series of case study, including numerical tests applied to the proposed combustion model and application test employed on 330 MW CFB simulation platform proves the feasibility of DD-PID control strategy.

1 Introduction

Facing the deep adjustment of the energy structure and the increasingly severe constraints from climate and environment, as the world’s largest energy producer and consumer, China will increase the proportion of installed capacity of non-fossil power generation from 35 to 39%, while decrease the proportion of installed capacity of coal-fired power generation from 59 to 55% by 2020 according to ‘The 13th Five-Year Plan of Electric Power Development (2016–2020)’ [1]. To achieve this goal, the Chinese government has stopped or postponed the construction of traditional coal-fired power plants in a planned way and has demolished a large number of the small coal-fired generation units with high energy consumption and high pollution emissions since 2016. It seems that the winter of coal-fired power generation is coming. However, circulating fluidised bed (CFB) power units, which also belong to the coal-fired power generation, became more and more popular in recent years in China, and are regarded as the representative of clean and efficient utilisation of traditional fossil fuels. More than eight supercritical CFB units, distributed in several provinces, have already been put into operation only for one year in 2018.

A typical structure and dynamic responses of a CFB boiler are shown in Fig. 1. The most distinctive equipment is a ‘bed’ at the bottom of the boiler furnace. The bed is a place where the coal or fuel spreads. High-pressure air is supplied from under the bed to

Nomenclature

| Symbol | Description |
|--------|-------------|
| \(x_v\) | proportion of volatile in fuel |
| \(\mu\) | valve opening of the control valve of the turbine |
| \(\tau_i (i = 1, \ldots, 4)\) | transmission delay in a certain process |
| \(\theta_b\) | bed temperature |
| \(C\) | specific heat capacity of bed material |
| \(C_{ad}\) | specific heat capacity of primary air |
| \(C_{ai}\) | specific heat capacity of air leaving the dense-phase zone |
| \(C_i\) | specific heat capacity of materials entering the dense-phase zone |
| \(C_o\) | specific heat capacity of materials leaving the dense-phase zone |
| \(D_\theta\) | effective heat-absorbing of boiler |
| \(D_t\) | main steam flow |
| \(F_i\) | quality of materials entering the dense-phase zone |
| \(F_o\) | quality of materials leaving the dense-phase zone |
| \(F_{a1}\) | amount of the primary air |
| \(F_{a2}\) | amount of the air leaving the dense-phase zone |
| \(F_c\) | coal feed |
| \(H_c\) | calorific value of carbon |
| \(H_v\) | calorific value of volatile |
| \(k_i (i = 1, \ldots, 7)\) | proportionality coefficient |
| \(M_b\) | total mass of bed material in dense-phase zone |
| \(P_t\) | main steam pressure |
| \(Q_{c1}\) | heat released by fuel combustion in the dense-phase zone under disturbance of fuel flow |
| \(Q_{c2}\) | heat released by fuel combustion in the dense-phase zone under disturbance of primary air |
| \(Q_v\) | heat released from volatile combustion in dense-phase zone |
| \(T_{a1}\) | temperature of air leaving the dense-phase zone |
| \(T_{c1}\) | inertia time of combustion process in the furnace under disturbance of fuel flow |
| \(T_{c2}\) | inertia time of heat release process in the furnace under disturbance of fuel flow |
| \(T_{d1}\) | inertia time of heat transfer process in the furnace under disturbance of fuel flow |
| \(T_{q1}\) | inertia time of heat transfer process in the furnace under disturbance of primary air |
| \(V_1\) | primary air flow |
lift the bed material and the coal particles. The coal combustion takes place in a suspended condition.

With the aid of bed, the CFB boiler can burn all types of coal and a wide range of other fuels efficiently, which includes low-grade and difficult-to-burn fuels [2]. The combustion temperature of CFB boiler is controlled between 850 – 950°C to reduce emissions of NOx. With the limestone injected into the furnace, majority of the formed SO2 during coal combustion can also be captured [3].

However, the wide operation range, strong fuel adaptability and complex combustion equipments of CFB boilers make it difficult for the traditional control systems to work normally, and to maintain good performance [4, 5]. More and more application examples show that the reason for restricting the further popularisation of CFB boilers is not equipment manufacturing technology, but operation control technology. In recent years, many researchers focused on the modelling, control and optimisation of CFB boilers. Based on real operation data, Lv et al. [6] built a dynamic model for predicting the bed temperature of a 300 MW CFB boiler by adopting least squares support vector machine method. Hu et al. [7] combined the advantages of zone method and Aspen Plus to develop a detailed radiation model coupled process simulation of fluidised beds. Gao et al. [8] designed a double-feedforward self-balance feed water instruction for a 350 MW CFB boiler, which can accelerate the control action of water feeding and speedup the tuning process. Liu and Wang [9] proposed a technical route for CFB boiler unit control by combining with non-linear function approximation of BP neural network, predictive control and real-time feedback revision. Niva et al. [10] presented a self-optimising control structure, which decouples fluidisation and oxygen-carrying tasks and introduces new degrees of freedom and alternatives for control. From the control point of view, fixed-parameter PID controllers are simple and easy to implement, but the load adaptability is poor, it is hard to meet the requirements of variable operating conditions. Neural network control has some intelligent characteristics, but it is difficult to complete the experiential learning process in practical applications. Predictive control requires low accuracy of the model and can handle all kinds of constraints, but the calculation of the optimal value of the objective function is relatively large. Therefore, effective use of mass real data and appropriate complexity of the control algorithm are the two key factors to improve the control performance of CFB boilers.

At present, the data-driven (DD) control has been a hot topic in control theory and applications. Kusiak et al. [11] developed a DD approach to minimise energy consumption of a heating, ventilating, and air conditioning (HVAC) system while maintaining the thermal comfort of a building with uncertain occupancy level. Lautenschlager and Lichtenberg [12] introduced DD iterative learning into model predictive control and approved its applicability by simulations of a heating system. Renani et al. [13] investigated and compared two different approaches in wind power forecasting which are indirect and direct prediction methods using DD method. DD control is also used in a class of non-affine non-linear systems with output saturation only depending on the control input data and the saturated output data [14]. An adaptive dynamic programming problem for non-affine non-linear systems based on the DD control is identified in [15], which is solved by adopting the alternating direction method of multipliers. A hybrid optimisation algorithm is proposed to solve non-linear or non-convex DD models involved in DD predictive control [16]. The remarkable advantage of DD control is that it has active adaptability to the change of working conditions, and the design process has low requirement for the accuracy of the model. With the gradual deepening and enrichment of DD control research, it is possible to introduce it into the CFB boiler control, and the improvement of the operation performance will be worthy of expectation.

In this paper, a DD control strategy applied to the CFB combustion process has been established for the first time. The core of the control strategy is to automatically generate and renew PID parameters online with the change of working condition, and to obtain good tracking performance, variable load adaptability and anti-disturbance ability. The main contributions consist of the following aspects:

- Coupling model of CFB unit combustion system is established.
- A normative procedure of DD PID controller is designed, including PID-parameter database establishment, information-vector neighbourhood selection, active PID-parameter determination, database update, and redundant vector deletion.
- The control strategy based on the DD technique is used for the CFB combustion process. And numerical and application tests are applied to the established CFB combustion model and a 330 MW CFB simulation platform of the Ningdong Power Plant, respectively.

The rest of the paper is organised as follows. The coupling relationship, dynamic mathematical model and control task of CFB combustion process are summarised in Section 2. The control structure and detailed design steps of DD-PID are presented for the CFB combustion control in Section 3. Comprehensive performance of the proposed control system is tested systematically in Section 4, and the conclusion of this work is listed in Section 5.

2 Mathematical model of combustion system

2.1 Characteristics of combustion system

A CFB unit is a kind of controlled plant with parameter coupling, as shown in Table 1. If we regard the weak coupling relationship between the variables as an independent system, a CFB boiler can be divided into three relatively independent parts: the superheat steam temperature sub-system, the water supply sub-system and
the combustion sub-system. The control-system design of the first two sub-systems is similar to that of the pulverised coal boilers. However, there are some significant differences between combustion sub-systems of the CFB boiler and the pulverised coal boiler. So the design of combustion control system will be the key problem.

According to the interaction relationship shown in Table 1, there are four tasks that must be done: (i) keep the energy balance of supply of boiler and demand of turbine by stabilising the steam pressure, (ii) control the discharge of pollutants reaching the standard by tuning the bed temperature within limitation, (iii) guarantee the safety of combustion process by keeping the hearth negative pressure, (iv) realise economic combustion by controlling oxygen content in optimal value. Generally, the hearth negative pressure guarantees the safety of combustion process by keeping the hearth temperature and preventing materials carried with high-temperature gas from being carried out. The economic combustion depends on the air-coal ratio which can be optimised by tuning the secondary air. The economic combustion is mainly used for the fluidisation of material in dense phase zone. It changes in proportion to the fuel flow and accelerates the heat release of fuel. This relation can be expressed as

$$\frac{\theta_{b}(s)}{F_{c}(s)} = \frac{K_{p1}(T_{s} + 1)}{(T_{a} + 1)(T_{s} + 1)} e^{-T_{s}s} \quad (4)$$

with

$$K_{p1} = \frac{\chi_{c} H_{c} + k_{1}}{F_{c} C_{a} - F_{c} C_{1}} T_{1} = \frac{\chi_{c} H_{c} + k_{1}}{\chi_{c} H_{c} + k_{1}} T_{2} = \frac{M_{0} C}{F_{c} C_{a} - F_{c} C_{1}}$$

2.2.2 Bed temperature to primary air model: Taking the primary air as input variable, and utilising the law of energy conservation in dense phase zone, we can obtain

$$\dot{M}_{0} C \frac{d\theta_{b}(t)}{dt} = (F_{c} C_{c} - F_{c} C_{b}) \theta_{b}(t) + \left(\dot{Q}_{c}(t) + Q_{b}(t)\right) e^{-T_{s}s} \quad (5)$$

The primary air is mainly used for the fluidisation of materials in furnace. It changes in proportion to the fuel flow and accelerates the heat release of fuel. This relation can be expressed as

$$Q_{b}(s) = H_{c} F_{c}(s) = k_{1} H_{c} V_{l}(s) \quad (6)$$

Combining (5) and (6), and in order to better express a negative correlation between the primary air and bed temperature, the transfer function of bed temperature to primary air is written as

$$\frac{\theta_{b}(s)}{V_{l}(s)} = - \frac{K_{p2}}{T_{s} + 1} e^{-T_{s}s} \quad (7)$$

where

$$K_{p2} = \frac{C_{a} T_{s} - C_{a} T_{s}}{F_{c} C_{a} - F_{c} C_{1}} T_{3} = \frac{M_{0} C}{F_{c} C_{a} - F_{c} C_{1}}$$

2.2.3 Main steam pressure to fuel model: The combustion and heat transfer process in the furnace can be simplified to a second-order system [18], whose transfer function is

$$D_{q}(s) = \frac{k_{1}}{(T_{a} + 1)(T_{a} + 1)} F_{c}(s) e^{-T_{s}s} \quad (8)$$

Taking into account the energy storage of the boiler drum and steam pipes [19], the energy balance equation can be written as

$$D_{q}(t) - \dot{D}_{q}(t) = C_{a} \frac{dP_{h}(t)}{dt} \quad (9)$$

The non-linear characteristics of the dynamic process in boiler are mainly reflected in two parts:

- The pressure drop from the drum pressure, $P_{h}$, to the main steam pressure, $P_{s}$, has a square root relationship with the main steam flow rate, $D_{q}$. $C_{a}$ is coefficient of thermal storage in the steam drum.

### Table 1 Coupling relationships of the parameters of a CFB unit

|                      | Main steam pressure | Bed temperature | Hearth negative pressure | Oxygen content in flue gas | Superheat steam temperature | Drum level |
|----------------------|---------------------|-----------------|--------------------------|---------------------------|----------------------------|------------|
| fuel                 | S                   | S               | M                        | S                         | M                         | S          |
| primary air          | S                   | S               | M                        | M                         | M                         | M          |
| secondary air        | M                   | M               | S                        | S                         | M                         | M          |
| induced air          | W                   | W               | W                        | W                         | W                         | W          |
| slagging             | W                   | W               | W                        | W                         | W                         | W          |
| water supply         | M                   | —               | —                        | —                         | —                         | S          |

M, middle coupling; S, strong coupling; W, week coupling; —, none.
• $D_i$ is proportional to the product of the opening of the turbine control valve, $\mu$, and the main steam pressure, $P_t$.

The above two processes can be described as

$$P_b(t) - P_i(t) = k_bD_i(t)$$  \hspace{1cm} (10)

$$D_i(t) = k_bP_b(t)$$  \hspace{1cm} (11)

Suppose the combustion process is in an equilibrium state with a stable operating point $[\overline{P}_b, \overline{P}_i, \overline{D}_i, \mu]$. Then a small range linear approximation for (10) and (11) can be obtained

$$\Delta P_b(t) - \Delta P_i(t) = \chi \Delta D_i(t)$$  \hspace{1cm} (12)

$$\Delta D_i(t) = k_b \Delta P_b(t)$$  \hspace{1cm} (13)

where $\Delta P_b$, $\Delta P_i$ and $\Delta D_i$ are small deviations from the stable operating point, and $\chi = 2k_bD_i^\alpha$.

Combining (8), (9), (12) and (13), and considering the value of $T_{ci}$ is much smaller than those of other inertia times, the transfer function of main steam pressure to fuel can be deduced as

$$\frac{P_i(s)}{F_i(s)} = \frac{K_{P\delta}}{(T_{s\delta} + 1)(T_\delta + 1)e^{-s\tau}}$$  \hspace{1cm} (14)

where

$$K_{P\delta} = \frac{k_1}{k_b\mu}$$

2.2.4 Main steam pressure to primary air model: The heat transfer process under the disturbance of primary air in the furnace can be simplified as

$$\frac{D_i(s)}{V_i(s)} = \frac{k_i(T_{s\delta} + 1)}{(T_{q\delta} + 1)e^{-s\tau}}$$  \hspace{1cm} (15)

Combining (8), (14) and (15), the transfer function of main steam pressure to primary air can be obtained

$$\frac{P_i(s)}{V_i(s)} = \frac{K_{P\delta}}{(T_{q\delta} + 1)e^{-s\tau}}$$  \hspace{1cm} (16)

where $K_{P\delta} = k_b/(k_b\mu)$.

2.2.5 Overall core coupling model: From (4)–(16), we can see that the CFB combustion process is a two-input and two-output process. Let $u_1 = F_i$ and $u_2 = V_i$ be the inputs, and $y_1 = \theta_b$ and $y_2 = P_i$ be the outputs, then the controlled object of the CFB boiler combustion process can be expressed as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$  \hspace{1cm} (17)

with

$$g_{11} = \frac{K_{P\delta}(T_{s\delta} + 1)}{(T_{s\delta} + 1)(T_\delta + 1)e^{-s\tau}}, \quad g_{12} = -\frac{K_{P\delta}}{T_\delta + 1}e^{-s\tau}$$

$$g_{21} = \frac{K_{P\delta}}{(T_{s\delta} + 1)(T_\delta + 1)e^{-s\tau}}, \quad g_{22} = \frac{K_{P\delta}}{T_{q\delta} + 1}e^{-s\tau}$$

3 DD control of the core coupling part for CFB boiler combustion system

In this section, in order to show the design process of the DD control strategy, a practical system of 300 MW CFB unit in Sichuan Province with the structure of (17) is employed. And the parameters, which are derived under the condition of 50, 75 and 100% load, are given in Table 2.

| Table 2 | Model parameters of the CFB combustion system under typical working conditions of the load |
|---------|---------------------------------|
| Item    | 50% load | 75% load | 100% load |
| $K_{P\delta}$ | 12 | 10.5 | 9.7 |
| $K_{P\delta}$ | 0.078 | 0.07 | 0.057 |
| $K_{P\delta}$ | 0.35 | 0.31 | 0.27 |
| $T_1$ | 120 | 133 | 140 |
| $T_2$ | 140 | 135 | 145 |
| $T_3$ | 120 | 128 | 130 |
| $T_4$ | 160 | 167 | 165 |
| $T_{ci}$ | 130 | 121 | 120 |
| $T_{ci}$ | 151 | 154 | 159 |
| $T_{ci}$ | 150 | 156 | 166 |
| $T_{ci}$ | 120 | 115 | 110 |
| $T_{ci}$ | 90 | 85 | 80 |
| $T_{ci}$ | 130 | 125 | 120 |
| $T_{ci}$ | 108 | 105 | 100 |

3.1 Decoupling of core coupling model

Before designing a controller, the coupled degree of a coupling system should be introduced first. The Bristol [20] first defined a relative gain matrix to measure the coupling properties of multivariable systems. The information reflected by the relative gain matrix [21] can be summed up as follows

(i) When the relative gain of a channel is less than or close to 0, it indicates that the input variable of this channel is not or weakly related to the output variable, and this channel should not be chosen as a control channel.

(ii) When the relative gain of the channel is close to 1, it indicates that other channels have less correlation on the channel, and do not need to take any decoupling measure.

(iii) When the relative gain of the channel is $<0.8$ or $>1.2$, it indicates that there is a serious coupling relationship between input and output variables.

For the core coupling model (17) of CFB boiler, the relative gain matrix can be deduced as

$$\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} = \begin{bmatrix} K_{P\delta}K_{P\delta} & K_{P\delta}K_{P\delta} \\ K_{P\delta}K_{P\delta} & K_{P\delta}K_{P\delta} \end{bmatrix}$$  \hspace{1cm} (18)

where $\lambda_{11}, \lambda_{12}, \lambda_{21}$ and $\lambda_{22}$ refer to relative gains of $\theta_b - F_i$ channel, $\theta_b - V_i$ channel, $P_i - F_i$ channel and $P_i - V_i$ channel, respectively.

According to (18), we notice that $\lambda_{12} = \lambda_{22}$, $\lambda_{11} = 1$ and $\lambda_{21} = 1$. Then, using values shown in Table 2, relative gains under three typical working conditions are calculated and listed in Table 3. It is obvious that channel $\theta_b - F_i$ and channel $P_i - V_i$ should be selected as control channels, and the coupling relationships of channel $\theta_b - V_i$ and channel $P_i - F_i$ should be further weakened by decoupler. Hence an inverse decoupling method proposed by Shinseky [22] is adopted here. The superiorities of inverse decoupling method are the simple formulation, the clear structure, and the convenience for application.

Let $c_1$ and $c_2$ be the input of the inverse decoupler, the block diagram of the inverse decoupling structure is shown in Fig. 2 [23, 24]. And the transfer function of the inverse decoupler, $D(s)$, is...


\[
D(s) = \frac{1 - \frac{g_2(s)}{g_1(s)}}{\frac{g_2(s)}{g_1(s)}} \quad (19)
\]

Select 75% load as nominal working condition, according to (19) and Table 2, we can get the quantitative inverse decoupler \(D(s)\), which contains a prediction item \(e^{30t}\). Taking into account the physical realisability, a compensator matrix, \(N_i(s) = \text{diag}(1, e^{-30t})\), with time delay is selected to counteract the prediction item. Let \(D'(s) = D(s) \cdot N_i(s)\), the compensated inverse decoupler is obtained (see (20)). The decoupled relative gain \(\Lambda\) of the CFB core coupling combustion process under three typical working loads are re-calculated, respectively, and the value of each item is enriched into Table 3. It can be seen that the decoupled \(\lambda_{i1}\) and \(\lambda_{i2}\) are all close to 1, which means that the decoupler (20) works well.

### 3.2 Design of DD-PID controller

With the rapid development of computing power, data storage capacity and transmission speed, the basic quality of industrial control system is greatly improved. It makes high control performance based on real-time data possible. DD PID (DD-PID) control is a real-time parameter adjustment control technology [25]. The key to this technology is that, whether a large number of typical I/O data (the reference input \(y_r\) and the system output \(y_s\)), the control signal for the object's dynamic features and avoid the unlimited expansion of the real-time data possible. DD-PID parameter modifier (DD-PID) controller is designed to let the bed temperature, steam pressure, and the main combustion process under three typical working loads are all close to 1, which means that the decoupler (20) works well.

### References

1. [IET Cyber-Phys. Syst., Theory Appl., 2020, Vol. 5 Iss. 1, pp. 39-48](http://creativecommons.org/licenses/by/3.0/)

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**Table 3** Relative gains under different loads

| Item | 50% load | 75% load | 100% load |
|------|----------|----------|-----------|
| \(\lambda_{i1}\) original | 0.7709 | 0.7818 | 0.7899 |
| decoupled | 1.0002 | 1.0000 | 1.0002 |
| \(\lambda_{i2}\) original | 0.2291 | 0.2182 | 0.2101 |
| decoupled | −0.0002 | 0 | −0.0002 |
| \(\lambda_{i3}\) original | 0.2291 | 0.2182 | 0.2101 |
| decoupled | −0.0002 | 0 | −0.0002 |
| \(\lambda_{i4}\) original | 0.7709 | 0.7818 | 0.7899 |
| decoupled | 1.0002 | 1.0000 | 1.0002 |

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**Image 1**

Inverse decoupling device

- **Controlled object**
- **C1**
- **C2**
- **U1**
- **U2**
- **Y1**
- **Y2**

**Image 2**

Block diagram of the inverse decoupling structure

- **Reference Model**
- **Parameter Selector**
- **Database**
- **K^\text{opt}**
- **Parameter Modifier**

**Image 3**

Structure of DD-PID control system

- **Reference Object**
- **Controller Object of CFB Combustion Process**
- **DD PID Controller 1**
- **DD PID Controller 2**
- **Inverse Decoupling Device**

**Image 4**

Overall structure diagram of the CFB combustion control system

\[\hat{y}_d(t) = 0.271\hat{y}_d(t-1) - 0.0183\hat{y}_d(t-2) + 0.7473y_c(t-1)\] (23)

The PID controller 1 is described as

\[c_1(t) = c_1(t) + K^p_1[y_c(t) - y_r(t)]
- K^i_1\Delta y_r(t) - K^d_1\Delta \hat{y}_d(t)\] (24)
where $\Delta y(t) = y_{r}(t) - y_{c}(t)$, $K_{P1}^{ed}$, $K_{I1}^{ed}$ and $K_{D1}^{ed}$ are the proportional coefficient, the integral coefficient and the differential coefficient.

The design procedure of DD-PID controller 1 is shown as follows:

**Step 1: Establishing initial database**

It is necessary to build a database based on the historical data collected from the generalised control object before the system starts running.

The initial database $\Phi(t)$ is defined as

$$\Phi(t) = [\phi_1(t), \phi_2(t), \ldots, \phi_n(t)]$$

where $n$ is the number of information vectors stored in the database.

**Step 2: Calculating distance and choose neighbours**

The $L$-norm with weight is used to determine the distance between the input at time $t$, $\phi(t)$, and the information vector $\phi_j(t)$. For $i = 1, 2, \ldots, n$, the specific formula is defined as follows

$$d(\phi_i(t), \phi_j(t)) = \sum_{j=i}^{n} \frac{\phi_i(t) - \phi_j(t)}{\max \phi_i(j) - \min \phi_j(j)}$$

where $\phi_i(t)$ is the $i$th component of the $i$th information vector, and $\phi_j(t)$ is the $j$th component of the $j$th information vector.

**Step 3: Calculating $K_{I}^{ed}$**

Based on the neighbours selected in step 2, a set of PID parameters, which corresponds to the database at the initial time, is calculated by linear-weighted average

$$K_{I}^{ed}(t) = \sum_{j=1}^{n} \omega_j K_{I1}(t)$$

where $\omega_j$ is the weight of the $j$th information vector $\phi_j(t)$ in the selected neighbours and is derived as follows

$$\omega_j = \sum_{i=1}^{n} \left[ 1 - \frac{\phi_i(t) - \phi_j(t)}{\max \phi_i(j) - \min \phi_j(j)} \right]$$

The unitary processing is carried out to achieve $\sum_{j=1}^{n} \omega_j = 1$. The $K_{I}^{ed}(t)$ can be obtained as

$$K_{I}^{ed}(t) = \sum_{j=1}^{n} \omega_j K_{I1}(t)$$

Then the parameter vector of the adjustable PID controller 1 is updated by $K_{I}^{ed}(t)$.

**Step 4: Updating $K_{e}^{ed}$**

In order to obtain better control performance, the steepest descent method is adopted to adjust the PID parameters so that the control error is reduced. The newly acquired PID parameters will be updated as

$$K_{e}^{ed}(t) = K_{e}^{ed}(t) - \frac{\partial J(t)}{\partial K_{e}(t)}$$

And $K_{e}^{ed}(t)$ is stored in the database as a set of $K_{e}$.

In step 3, the learning rate $\eta_{t} := \text{diag}(\eta_{P}, \eta_{I}, \eta_{D})$, the error criterion $J(t) := 0.5(\delta(t) - \epsilon(t) - y(t) - y_{c}(t))$ and $\epsilon(t) := y(t) - y_{c}(t)$. Here, $\eta_{P} = 0.0000001, \eta_{I} = 0.0000000003, \eta_{D} = 0.0000002$.

Then the adjusted new PID parameters [27] can be deduced as

$$K_{P1}^{ed}(t) = K_{P1}(t) + \eta_{P}[y(t) - y_{c}(t)]$$

$$K_{I1}^{ed}(t) = K_{I1}(t) + \eta_{I}[y_{r}(t) - y_{c}(t)]$$

$$K_{D1}^{ed}(t) = K_{D1}(t) + \eta_{D}[y_{r}(t) - y_{c}(t)]$$

In the same way, DD-PID controller 2 can be designed. In this paper, the reference model 2 is designed as the reference model 1. And $\eta_{P} = 0.6, \eta_{I} = 0.001, \eta_{D} = 0.45, N(0) = 6$.

**Step 5: Deleting redundant data**

From the database, extract the information vectors with short distance to the query $\phi(t)$, which meets the condition

$$d(\phi(t), \phi_i(t)) \leq \epsilon_{1}, \quad i = 1, 2, \ldots, N(t) - k$$

and remove the PID parameters that meet the following condition:

$$\sum_{i=1}^{k} \left[ \frac{K_{I1}(t) - K_{I1}^{ed}(t)}{K_{I1}(t)} \right] \leq \epsilon_{2}$$

where $\epsilon_{1}$ and $\epsilon_{2}$ are the suppression coefficients of the deleted data chosen from the redundant data, and $K_{I1}(t) = 1 - 3$ mean $K_{P1}, K_{I1}$ and $K_{D1}$, respectively. Finally, to prevent the system from crashing as a result of excessive data storage, we set a threshold $N_{max}$. When the amount of data is greater than $N_{max}$, the first data vector in the database will be deleted. In the actual system, $\epsilon_{1}$ and $\epsilon_{2}$ should be set between 0.1 and 1. The specific value needs to be set based on the performance and running time of system.

### 4. Case study

To evaluate the effectiveness of the proposed DD control strategy, the established $2 \times 2$ CFB combustion model in Section 2 and a 330 MW CFB simulation platform of Ningdong Power Plant are introduced for the numerical and application tests. In a wide load range, the comparison of performances of the DD-PID controller and the traditional PID controller will be discussed here.

#### 4.1 Tracking test

For the purpose of test the tracking ability, at $t = 300$ s, it is supposed that the set-point value of the main steam pressure keeps constant, while the set-point value of the bed temperature is changed from 800 to 850°C. At $t = 3000$ s, the set-point of the main steam pressure steps from 10 to 11 MPa. For the above two cases, the time responses of the system under the DD-PID control strategy and PID control strategy are shown in Fig. 5, where trajectories of PID parameters of the DD-PID controllers are also given. It should be noted that the traditional PID parameters are fixed under 75% while the PID values of DD-PID controllers are changing. Hence, we can get different initial PID values under these three loads (50, 75, 100%), which are shown in Table 4.
Figs. 6 and 7 show the result of tracking ability at 50% load and 100% load, respectively.

From Figs. 6 and 7, it is clear that

(i) Under the DD-PID control $\theta_b$ and $P_t$ can accurately follow the setpoint, respectively. The adjustment processes are rapid and smooth. The two control channels are well decoupled.

(ii) The parameters of DD-PID controllers vary with system information vectors and eventually converge.

(iii) The settling times $\theta_t$ and the overshoots of the system outputs $P_t$ derived by DD-PID controllers are less than those obtained by traditional PID controllers.

(iv) The variation ranges of the control variables $F_c$ and $V_1$ derived by DD-PID controllers are smaller than those obtained by traditional PID controllers.

4.2 Robustness test

In order to show the effectiveness of the proposed new control strategy, the comparison of the performance index by using the DD-PID control strategy in this paper with the ones in [28] will be given in the following part.

It is assumed that all parameters of the CFBB model vary from $-20\%$ to $+20\%$ of the nominal value, and a unit step is added in the main steam pressure loop and bed temperature loop of each generated object, respectively. Based on the data carried out of the experiments of 1000 Monte Carlo, the settling times $\theta_t$, overshoots $\sigma\%$, and the mean value of $\theta_t$ and $\sigma\%$ are summarised in Table 5. It can be seen that the mean value of each index driven by DD-PID controller is much smaller than that of the traditional PID controller, which indicates that the system with DD-PID controller has better dynamic performance.

Table 4  Initial parameters of different PID controllers

| Controller          | $K_{P1}$ | $K_{I1}$ | $K_{D1}$ | $K_{P2}$ | $K_{I2}$ | $K_{D2}$ |
|---------------------|----------|----------|----------|----------|----------|----------|
| traditional PID     | 0.0243   | 0.00033  | 0.1132   | 2.281    | 0.0103   | 130.5    |
| DD-PID for 75% load | 0.0243   | 0.00033  | 0.1132   | 2.281    | 0.0103   | 130.5    |
| DD-PID for 50% load | 0.0474   | 0.00036  | 0.2276   | 2.396    | 0.0105   | 68.7     |
| DD-PID for 100% load| 0.0550   | 0.00034  | 0.3610   | 2.860    | 0.0107   | 43.2     |

Fig. 5  System time responses and PID parameters’ curves under 75% load to 50°C in bed temperature set-point at $t = 300$ s and 1 MPa step in main steam pressure set-point at $t = 3000$ s

Fig. 6  System time responses and PID parameters’ curves under 50% load to 50°C in bed temperature set-point at $t = 300$ s and 1 MPa step in main steam pressure set-point at $t = 3000$ s
Moreover, the performance index of the main steam pressure loop and the bed temperature loop are shown in Fig. 8. It can be seen that the overshoot is larger and settling time is longer by using traditional PID control strategy, which indicates that the DD-PID control strategy can provide much better performance than the traditional PID control strategy. Furthermore, Fig. 9 shows the end value of DD-PID for bed temperature loop and main steam pressure loop.

4.3 Anti-disturbance test

Next, for the purpose of investigating the robustness to the external disturbances of output signals, 10°C step disturbance of $\theta_b$ at $t = 300$ s and a 0.2 MPa step disturbance of $P_t$ at $t = 3000$ s are added to the system output position, respectively. The control results and trajectories of PID parameters are shown in Fig. 10. From Fig. 10 it is apparent that the system outputs go back to their initial stable values quickly and accurately. DD-PID controller is better than the traditional PID controller from the point view of the variation ranges of the control variables.

Then, add a 10 t/h step disturbance of $F_c$ at $t = 300$ s and a $2 \times 10^4$ m$^3$/s step disturbance of $V_1$ at $t = 3000$ s, the control results and trajectories of PID parameters are shown in Fig. 11, which means that the system outputs go back to their initial stable values quickly and accurately. And, DD-PID controller is better than the traditional PID controller from the point view of the maximum offset.

The above simulation results are obtained on a laptop computer with an 8 GB RAM and an Intel Core i5–3230M processor at a base speed 2.6 GHz. Comparing with the computing period (10 ms) of the traditional PID controller, the period (135 ms) of DD-PID controller increased significantly. For the process control of power generation unit, the qualification computing period of distributed control system is usually ≤250 ms, so the DD-PID can meet the requirement of field operation. In the DD-PID, redundant redundancy is an important step to reduce the computing load. In the examples above, due to the application of redundant redundancy, the average utilisation of the process control unit was reduced around 8.18%.

4.4 Application test

Finally, the DD-PID control strategy is applied to the simulation platform of the 330 MW subcritical CFB unit of Guohua Ningdong thermal power plant. Due to the inability to ensure the correctness and stability of the commissioning system, and consuming a lot of manpower and resources, many advanced control methods and strategies cannot be applied. Therefore, based on the real operation data of Ningdong Power Plant, a 330 MW CFB simulation platform with a simulation accuracy of 94% was developed. Based on this platform, various thermal adjustment processes can be debugged and optimised. The boiler of this unit is a subcritical, primary reheat, natural circulation drum boiler made by Dong Fang Boiler Work. It adopts close-fitting, semi-balanced ventilation, light metal roof and all-steel suspension structure. The tail of the boiler is separated by the enclosure wall to form a double flue structure in the depth direction of the boiler. A low-temperature superheater is arranged in the front flue, and a high-temperature...
superheater and a low-temperature superheater are arranged in the rear flue from top to bottom. Table 6 shows the main design parameters of the boiler under B-MCR condition. The coal burning in Ningdong Power Plant is mainly bituminous coal. The calorific value of the coal burning is generally 3800–4200 kcal/kg, the dry ashless base volatile content is 30%, the base ash content (\(A_{ar}\)) is 35.47%, and the base sulfur content (\(S_{ar}\)) is 0.73%.

![Fig. 10 System time responses and PID parameters' curves at 75% load under measurement disturbances of output signals](image)

![Fig. 11 System time responses and PID parameters' curves at 75% load under control signals' disturbances](image)

| Parameter                          | Unit | Value  |
|-----------------------------------|------|--------|
| superheated steam flow            | t/h  | 1177   |
| outlet pressure of reheating steam | Mpa(g) | 3.94  |
| outlet pressure of superheated steam | Mpa(g) | 17.5  |
| inlet pressure of reheating steam | Mpa(g) | 4.12  |
| inlet temperature of reheating steam | °C  | 341    |
| superheated steam temperature     | °C  | 541    |
| outlet temperature of reheating steam | °C  | 541    |
| inlet water temperature of economise | °C  | 279.6  |
| reheating steam flow              | t/h  | 979.7  |
| boiler efficiency                 | %    | 91.3   |

Fig. 12 System time responses under typical day load

Table 7 Comparison of ITAE performance of two control algorithms

| Method       | \(\theta_b\) | \(P_t\)  |
|--------------|-------------|---------|
| traditional PID | 5.3867 × 10^4 | 1381.3  |
| DD PID       | 3.9799 × 10^4 | 616.2   |

5 Conclusion

Data has become an important resource for modern industries. The effective use of data can improve the control and operation performance of power generation units. In this paper, a DD-PID control strategy is presented for the combustion control of the CFB boiler to improve the operating performance under full operating conditions.

(i) The core competence of DD-PID is to automatically generate and renew PID parameters online with the change of working condition. Surrounding the use of production data, a normative procedure that includes PID-parameter database establishment, information-vector neighbourhood selection, active PID-parameter determination, database update, and redundant vector deletion, is given.

(ii) The effectiveness, dynamic performance and disturbance rejection capability of the proposed strategy were verified by a set of real CFB boiler combustion models which came from real operation data identification. Besides, DD-PID control strategy is...
tested on a 330MW CFB simulation platform of the Ningdong Power Plant to further prove its validity.

(iii) For general computer systems, there is no technical barrier to the implementation of the DD-PID. Unfortunately, considering the safety and reliability, the application modes of most power plant control systems are strict and conservative, few user-defined complex control algorithm can be applied freely. Therefore, the practical research and engineering test of the proposed control strategy will be the focus of our work in the near future.

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Table 8 Comparison of production and discharge coefficient in coal-fired boiler

| Type             | Pollutant index | Unit | Pollutant producing coefficient | Terminal treatment technology | Pollutant discharge coefficient |
|------------------|-----------------|------|---------------------------------|--------------------------------|---------------------------------|
| pulverised coal  | dust            | kg/t | 9.21Aar + 11.13                | Cottrell process              | −0.005Aar + 0.042Aar + 0.057    |
|                  |                 |      |                                 | Cottrell process +             | −0.00026Aar + 0.022Aar + 0.016  |
| CFBB             | dust            | kg/t | 6.31Aar + 7.54 + 61.94Sar       | Limestone gypsum              | −0.004Aar + 0.035Aar + 0.034 + 0.124Sar |
|                  | industrial waste| m/t  | 9713                            |                                 | 9713                            |