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Investigation on the energy conversion and load control of supercritical circulating fluidized bed boiler units

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ABSTRACT

Load control is the core of the operation control system on power plant units. The energy conversion process is complicated in the supercritical circulating fluidized bed (SCFB) boiler due to the special fluidized combustion type, which also results in the large thermal inertia. So the control performances of conventional load control scheme without the consideration of carbon storage are poor in SCFB units. To reveal and monitor the energy storage in the boiler, the control model of burning carbon is established. Through the analysis on energy conversion process, the signal of advanced dynamic heat is structured to characterize the variation trend of energy. Based on the combination of the burning carbon control model and the dynamic heat signal, the boiler main control and feed-water control schemes are designed to optimal the control performance. Finally, the verification and application on the 600 MW SCFB unit prove the effectiveness of advanced dynamic heat signal and feasibility of the proposed control scheme.

1. Introduction

The circulating fluidized bed (CFB) boilers have been widely commercialized in power generation applications owing to the advantages in fuel flexibility [1,2] and lower cost of emission control [3,4] compared to the pulverized coal (PC) boilers. However, the thermal efficiency of the CFB unit is relatively low. So it is necessary to develop SCFB boiler units to overcome this disadvantage.

The heat distribution along the furnace height direction in the supercritical PC boilers is inhomogeneous due to the combustion of coal powders with small particle size [5]. Thus the cooling capacity of the water wall is one of the key challenges. With the characteristic of fluidized combustion, the temperature and heat distributions in the CFB furnace are much more uniform than that in the PC boiler. Besides, in the CFB furnace, the heat flux decreases with increasing height of furnace and the maximum heat flux occurs at the bottom part, which is just the position with lowest temperature of the water in water wall. This is beneficial to control the metal temperature of water wall. On the other hand, the combustion temperature in the boiler is lower than general ash melting point and the intensive solid particles are conducive to the heat absorption of the water wall. So it is suitable for the combination with the fluidized combustion technology and the supercritical steam parameters [6].

Load control is the core of the operational management for the units [7,8]. Attributed to the fluidized combustion mode and wide-size range of the coal feed particles, the thermal inertia of CFB boilers is quite large and the energy conversion process is fairly complicated [9,10]. Moreover, the supercritical units adopt the once-through furnace rather than the traditional drum one, making the higher requirements for feed-water control. Usually, the CFB power plant unit can operate at a fixed load stably, while the control performances will turn worse during the adjustment of load. In fact, the load variation is almost inevitable and the current requirement for the speed of load changes is becoming stricter due to the rapid development of new energy power generation [11]. All these characteristics lead to the great difficulty in the load control of SCFB units [12,13].

The key to the load control schemes is to regulate the combustion intensity in the boiler and govern the heat transformation in the unit precisely based on energy and mass balance principles, especially during the dynamic process. The intensive material and heat transfer [14], and complex chemical reaction in the furnace [15] bring about the challenges in analyzing the energy conversion of CFB unit. There is little systematic research on the energy conversion process and effective load control theory in SCFB units.

In this paper, it was concluded that the accumulated carbon could reveal the huge thermal inertia and the complicated heat balance in the CFB boiler. The dynamic heat signal was structured

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Abbreviations: CFB, circulating fluidized bed; SCFB, supercritical circulating fluidized bed; EHE, external heat exchanger; HTS, high temperature superheater; ITS, intermediate temperature superheater; LTS, low temperature superheater; PA, primary air; PC, pulverized coal; SA, secondary air.

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Nomenclature

A_{ir}	Total air flow rate
A_I	Instruction of total air volume
B	Amount of burning carbon
C_{ar}	Net carbon as received basis
C_{arL}	Carbon content of fly ash
C_{arS}	Carbon content of slag
C_h	Coefficient of enthalpy differential
Co_2	Oxygen concentration
d_c	Average diameter of particles
F	Coal-feed rate into the furnace
F_I	Instruction of coal-feed rate
F_L	Rate of fly ash
F_S	Rate of slag
h_{gr}	Final super heater outlet steam enthalpy
h_{gs}	Enthalpy of feed-water
H_0	Calorific value of carbon unit
P_{pr}	Predictive power
P_T	Main steam pressure
P_{TS}	Set point of main steam pressure
Q_B	Released energy
Q_{car}	Heat released in carbon combustion
Q_F	Energy of coal combustion
Q_L	Energy required for target load
Q_o	Effective output energy
Q_r	Boiler heat absorption
Q_{vol}	Heat released in volatile combustion
R_c	Combustion rate of burning carbon
R_{WF}	Ratio of water to fuel
u_T	Valve opening of turbine
W_{SI}	Feed water flow
Yo_2	Practical oxygen content
$Y'o_2$	Set value of the oxygen content
Greeks	
H_F	Calorific value of coal unit
k_{AF}	Coefficient of the air flow instruction
k_{AO}	Coefficient of the air flow instruction
k_c	Combustion rate constant of granule
k_{FL}	Coefficient of the coal quantity instruction
k_{FQ}	Coefficient of dynamic energy deviation
k_{FP}	Coefficient of the coal quantity instruction
k_L	Coefficient of load
ko_2	Oxygen concentration coefficient
k_{Wh}	Coefficient of the enthalpy deviation
k_{WQ}	Coefficient of the released energy
K	Overall coefficient
L	Load instruction
Mc	Molar mass of carbon
Ne	Power
η_b	Boiler efficiency
η_t	Turbine efficiency
ρ_c	Density of carbon particle
Δh_{so}	Enthalpy deviation

to monitor the combustion intensity and the trend of heat transformation. This paper mainly investigates the coal-fired SCFB unit and the main contributions are consisted of the following aspects.

- The control model of burning carbon is established to monitor the amount of reactive carbon that participating in the combustion in CFB boilers.
- The balance model in the energy conversion of the SCFB unit has been set up to reflect the heat transfer process.
- The designed boiler main control and feed-water control schemes are validated to optimal the control performance in SCFB units by engineering verification.

The rest of paper is organized as follows. In Section 2, the combustion and energy conversion process are analyzed, laying a foundation for the control model of the burning carbon. Section 3 presents the designed load control scheme of SCFB units, then the verifications and applications on the 600 MW SCFB units are shown in Section 4. Finally, Section 5 concludes the work.

2. The energy conversion process in the SCFB boiler unit

2.1. Plant description

This study mainly investigates a 600 MW coal-fired SCFB unit of Baima power plant in Sichuan Province, China, which has been successfully put into commercial operation since April 14, 2013. It is characterized with once-through boiler, single furnace with double air distributors, H-type symmetric layout, balanced draft and single reheat system. Six high temperature steam-cooled cyclones are adopted for gas-solid separation and six external heat exchangers (EHEs) are equipped to adjust the bed temperature and reheated steam temperature.

The general layout of the CFB boiler is shown in Fig. 1. The raw coal are dried and smashed without mill to particles of the diameter in a very wide range of 1–10 mm. In general, the coal are mixed with limestone through fluidization, which can capture SOx produced in the combustion. The primary air enters the furnace from the bottom of two legs and plays a vital role in keeping the bed inventory in fluidized state and enhancing the fully mixing of bed inventory with the newly-added fuel. Secondary air nozzles are installed at various levels of the furnace walls to supply sufficient air for complete combustion. Mixed particles consisting of partly burned coal, limestone and ash are carried to the upper region of the furnace with flue gasses. Subsequently, the particles are sent to six cyclone separators, in which the heavy particles are separated from the gasses and returned to the furnace for recirculation. The gasses pass through the cyclones and flow to the heat transfer surface for heat exchange. The coal particles experience multiple circulations in the furnace accompanied by the low temperature combustion of 850–950 °C. The special combustion mode leads to the considerable energy storage at fuel side and a large amount of residue chars are accumulated in the furnace. Thus the combustion process in a CFB boiler is more complicated than that in a PC boiler, in which small coal particles with size of 0.05–0.1 mm burn out one time pass within a few seconds.

Rather than natural circulation, supercritical boilers use the once through circulation for the water wall. The water wall system consists of headers, inlet tubes, tube panels, outlet tubes, elbows and other elements for the absorption of heat flux on the furnace side. Saturated steam is drawn off the top of the steam separator and re-enters the furnace in through the reheat system. Then the steam with supercritical parameters is sent to turbine to generate electrical power combined with a generator.

2.2. The combustion in the CFB boiler

The energy of the coal is given off instantly in a PC boiler and the released heat can be calculated by Eq. (1).

$$Q_F(t) = F(t)H_F(t) \tag{1}$$