Supporting Information for
Reducing NO_x emissions for a 600 MW_e down-fired pulverized-coal utility boiler by applying a novel combustion system

Lun Ma[†], Qingyan Fang[†※], Dangzhen Lv[‡※], Cheng Zhang[†], Yiping Chen[‡], Gang Chen[†], Xuenong Duan[‡], Xihuan Wang[††]

[†] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, P R China

[‡] Electric Power Research Institute, Hunan Power Company, Changsha 410000, P R China

[††] Jinzhushan thermal power company, Datang Huayin electric power Limited by Share Ltd, Loudi 417500, P R China

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[*] to whom all correspondence should be addressed

Qingyan Fang

Address: State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, P R China

Tel.:+86 27-87540249; fax: +86-27-87540249; e-mail: qyfang@hust.edu.cn.

Dangzhen Lv

Address: Electric Power Research Institute, Hunan Power Company, Changsha 410000, P R China

Tel.:+86 731-85605384; fax: +86 731-85605384; e-mail: dangzhenlv@163.com.

Figure Caption

Figure S1. Schematics of the original combustion system of the down-fired boiler (dimensions in mm).

Figure S2. Schematics of the combustion system of the down-fired boiler with the novel combustion system.

Figure S3. Detailed schematics of the novel combustion system

Figure S4. CFD model and grid division of the novel combustion system

Table Caption

Table S1. Reaction kinetic data of devolatilization and char combustion

1. Brief Introduction of Utility Boiler

Figure S1 shows the schematics of the original combustion system of the down-fired boiler. Seventy-two direct-flow burner nozzles with double cyclone separators are arranged symmetrically on the arches. Primary air under the centrifugal effect of cyclone separators is divided into two parts: the fuel-rich coal/air streaming in dense phase region and the fuel-lean coal/air streaming (i.e., named the vent coal/air) in the dilute region. The main purpose of the burner design is to reduce NO_x emissions by decreasing the air stoichiometric ratio and to promote ignition by raising the fuel concentration in the burner zone. The fuel-rich coal/air nozzles are installed near the back-fire side, while the fuel-lean coal/air nozzles are arranged over the back-fire side. Secondary air is gradually injected into the furnace and is separated into seven layers in the bellows (i.e., named A, B, C, D, E, F_1 and F_2). The first three secondary air nozzles (A, B and C) are arranged on the arches, while the remaining four secondary air nozzles (D, E, F_1 and F_2) are below the arches. Around the fuel-lean and fuel-rich coal/air nozzles, the A- and B-layer secondary air is transported through annular ports to cool the burner nozzles and strengthen the downward coal/air mixture. The C-layer secondary air was provided through a total of 36 ports, which is close to the pulverized coal burner, and is supplied for the oil igniter. The remaining four layers of secondary air (i.e., D-, E-, F_1- and F_2) are below the arches and account for the major share of the combustion air in the furnace. The air mixes gradually with the ignited coal/air flow, thereby forming air-staging combustion to lower NO_x emissions and regulate the flame penetration depth. The designed temperatures of main-steam and re-heat steam are both 814 K.

The schematics of the novel combustion system is shown in Figure S2, and Figure S3 displays the detailed schematic of the novel combustion system.

In addition, the designed parameters of the another similar modified FW down-fired boiler are similar to the studied boiler in this paper.

2. CFD Model, Grid Division, Numerical Simulation, and other Important Settings in the Simulations

A geometric model was created and divided into several sections to accurately characterize the physical furnace. The different sections were meshed together with hexahedral mesh and coupled at the interface to improve the quality of the mesh. In order to minimize the numerical error, the mesh was refined in the burner zone with intense combustion and was consistent with the airflow direction in the furnace. Grid independence tests were carried out under the cells at 2800000, 3260000, 3820000 and 4270000. The mesh consisting of 3820000 cells (shown in Figure S4) was adopted for the calculations. The size distribution of the pulverized-coal particles followed Rosin-Rammler, with a minimum and maximum diameter of 5 μm and 250 μm, respectively. The average particle diameter was 54 μm with a spread parameter of 1.05.

Coal devolatilization was simulated by the two-competing-rate mode [29-31]. The parameters about the two-competing-rate model and the diffusion/kinetics model are shown in Table S1.

devolatilization-1 at low temperature:

$$coal(s) \xrightarrow{K_{v1}} \alpha_1 Volatitle(g) + (1-\alpha_1) char(s) \tag{1}$$

devolatilization-2 at high temperature:

$$coal(s) \xrightarrow{K_{v2}} \alpha_2 Volatitle(g) + (1-\alpha_2) char(s) \tag{2}$$

3. Full-Scale Industrial Measurements

The coal characteristics were analyzed by Vario EL-2 for proximate analysis, and TGA-2000 for ultimate analysis. During the full-scale industrial experiments, the following measurements were made: (1) temperature distributions along the axis of one primary-air burner. These were carried out with a fine-wire thermocouple device through inserting along the burner axis. And the mean gas temperature measurements were performed with a 0.3 mm-diameter nickel-chromium/nickel-silicon thermocouple. Heavy deposition of ash can be avoided as far as possible because of the high velocity of primary flow. (2) the method of measuring mean gas temperatures near observing ports 1-4. It was carried out with the above thermocouple device through observing ports 1-4, and the device was kept in the furnace (near the right-side wall about 1.5 m) less than 1 min to protect the thermocouple from depositing seriously ash. (3) O_2 , CO, and NO_x were sampled at the inlet of the air pre-heater. An MSI EURO-type flue gas analyzer, with the measuring accuracy of more than 99%, was employed with grid-based method to measure the components of flue gas (including O_2, CO and NO_x concentrations). Then, the data of measured points are averaged. The measurement error were about $\pm$1% for O_2, $\pm$50 ppm for CO, and $\pm$20 ppm for NO_x. (4) The collected fly ash is mixed, and the carbon content in ash is measured by using a proximate analyzer. The collected bottom ash is also mixed, and the carbon content in ash is measured by using a proximate analyzer.

3. NOMENCLATURE

MBEL	Mitsui Babcock Energy Limited
B&W	Babcock & Wilcox
FW	Foster Wheeler
MIMSC	multiple-injection and multiple-staging concept
CHELNO	combined high-efficiency and low-NO_x technique
OFA	overfire air
SOFA	separated overfire air

WSGG weighted sum of gray gases

CPD chemical percolation devolatilization

Table S1. Reaction kinetic data of devolatilization and char combustion [29-31]

reaction	A (pre-exponential factor)	E (activation energy)
devolatilization-1 ($\alpha_1 = 0.3$)	3.75×10^{5} s^{-1}	7.366×10^{4} J/mol
devolatilization-2 ($\alpha_2 = 1$)	1.46×10^{13} s^{-1}	2.511×10^{5} J/mol
Char combustion	0.0016 kg •(m^2 • s •Pa)$^{-1}$	83,700 J • (mol)$^{-1}$

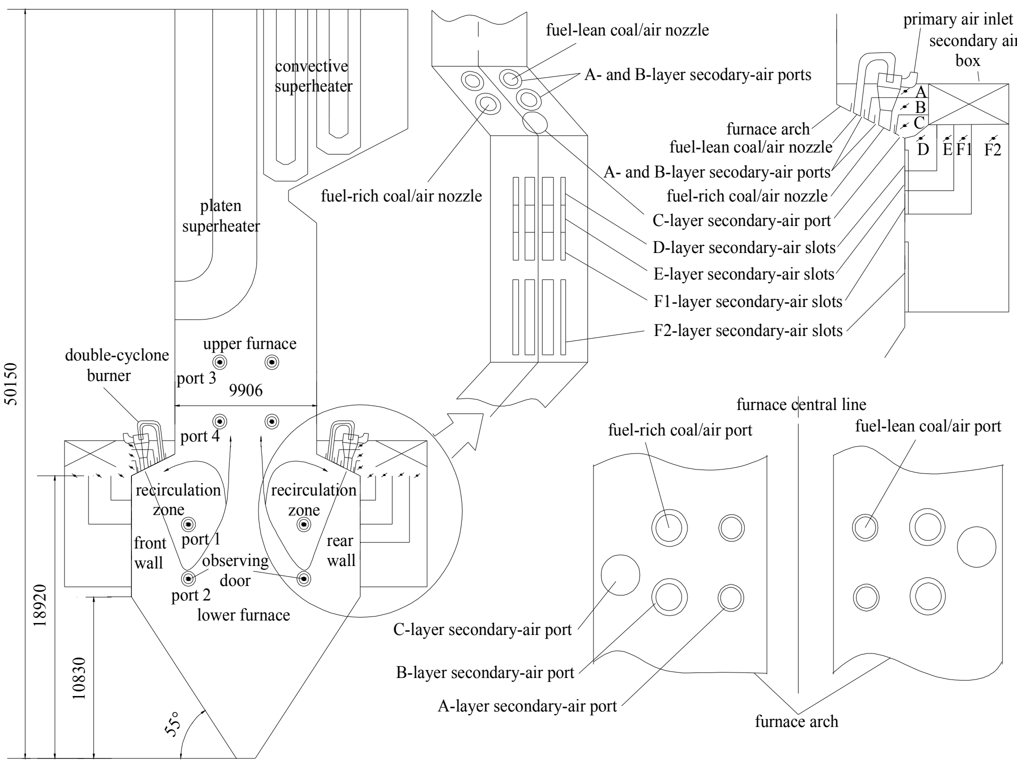

Figure S1. Schematics of the original combustion system of the down-fired boiler (dimensions in mm).

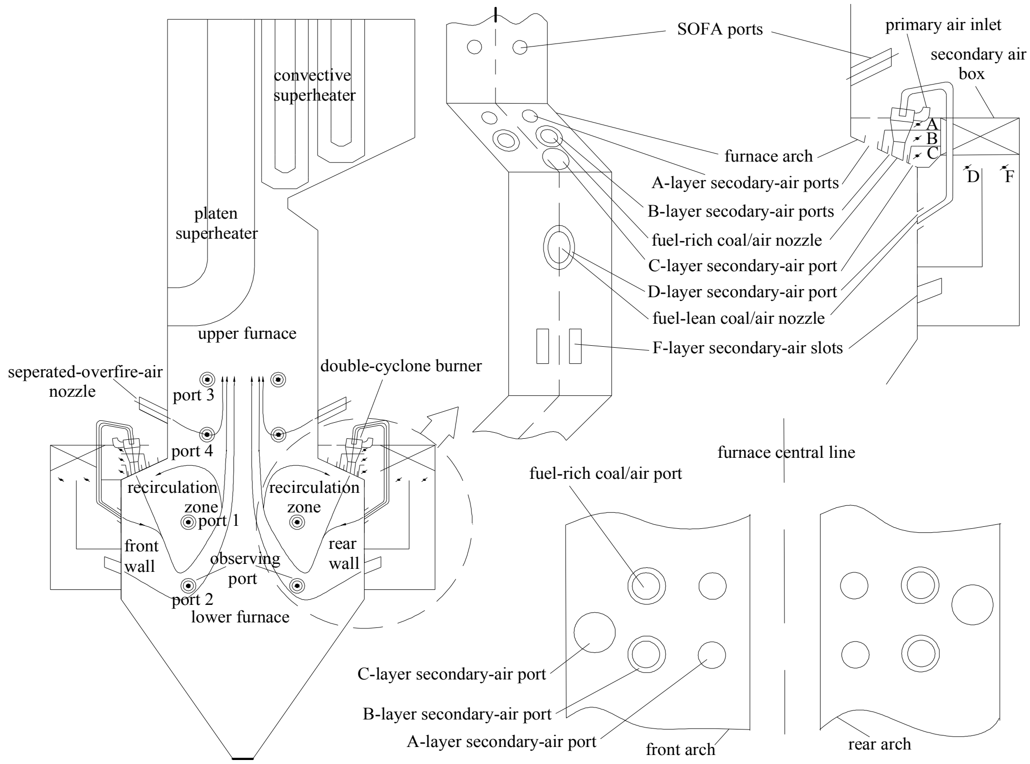

Figure S2. Schematics of the combustion system of the down-fired boiler with the novel combustion system.

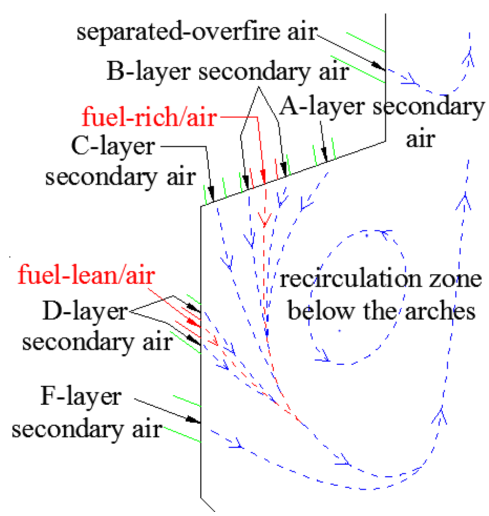

Figure S3. Detailed schematics of the novel combustion system

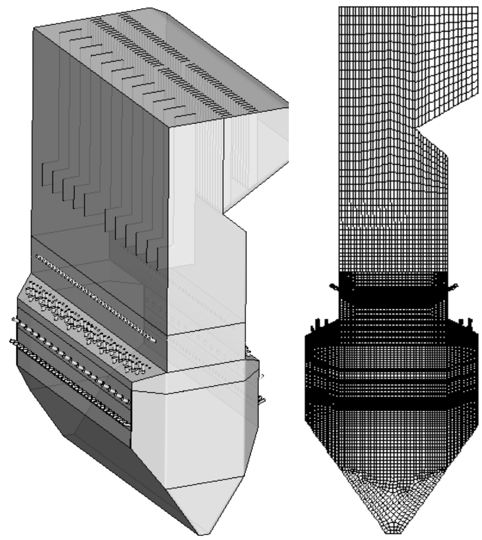

Figure S4. CFD model and grid division of the novel combustion system