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Pulverized-Coal Combustion in Wall-Protecting-Jets Combustor (WPJC)

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A new type of pulverized-coal combustor, called "Wall-Protecting-Jets Combustor" (hereafter, WPJC) has been proposed, designed and studied with both CFD (Computational Fluid Dynamics) and experimental methods. The WPJC is based on a novel concept in which all inlet jets are along the combustor wall. Pilot combustion experiments were conducted to investigate the combustion performance of WPJC. Two-phase flows and pulverized-coal combustion were simulated to study the mechanism of WPJC using the commercial software FLUENT. The results show that the WPJC has many remarkable advantages: wall-protection by the cold jets without the use of refractory materials; low-temperature and three-stage combustion with low NO_x emission; negligible ash/slag-deposition; multiple functions with convenient switching between them; effective adjustment of the combustion intensity and the ignition position.

Keywords: Pulverized-coal combustion; two-phase flow; combustor; CFD (Computational Fluid Dynamics)

INTRODUCTION

Effective utilization of coal has become an important challenge in energy development worldwide (Smoot and Smith, 1985). Pulverized-coal combustion has played a key role in coal utilization. Combustion of pulverized-coal involves heating coal particles in a high-temperature environment, devolatilization, ignition and combustion of volatiles, and burning of char. The flame temperature and speed are mainly determined by the amount of volatiles in the fuel and therefore the ignition and the burning properties of fuels are directly related to this amount,

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i.e., fuels with large amounts of volatiles have good ignition and burning properties. In order to completely and efficiently burn pulverized-coal, especially low-grade coal, the flow field must be arranged so that a large recirculation zone with high temperature is formed. This is the basic principle of flame stabilization in most practical systems. The large recirculation zone with high temperature can be used as an ignition source and as a means for flame stabilization.

Previous methods developed to create the recirculation zone can be separated into two types: the mechanical method (swirl-type and bluff-body methods) and the aerodynamic method (Counter-Flow, Opposed-Jet, Co-flowing Jets with large velocity difference (hereafter CFJ), Flat Inlet Jet (hereafter FIJ), and the Eccentric Jet (hereafter EJ)).

Swirl-type combustors and bluff-body combustors have been widely used to achieve flame stabilization in aircraft engines and industrial furnaces (Beer and Chigier, 1972; Lockwood, *et al.*, 1988; Nikjooy, *et al.*, 1988). They are particularly effective for gaseous and/or liquid fuels. However, the swirl-type or bluff-body combustors have not been run successfully for low-grade coals in unpreheated air in China (Fu, *et al.*, 1986). Counter-flow (Greenberg and Goldman, 1990) or opposed-jet flame (Schaffer and Cambel, 1955) stabilizers were also developed, but they are not as practical as the swirler-type or bluff-body combustor and few applications were reported. Chen (1990) and Schefer (1989) had studied the similarities and differences between swirl-type and bluff-body combustors and between turbulent-jet and bluff-body combustors.

Over the past decades, engineers and scientists have developed some pulverized-coal combustors to solve problems in practical engineering, such as poor ignition and bad flame stability, especially for low-grade coal. The techniques of CFJ (Fu, *et al.*, 1986 and 1988), FIJ (Wei, *et al.*, 1990), and EJ (Wu, *et al.*, 1988) have contributed to the important progress in pulverized-coal combustion.

In the CFJ technique, pulverized coal and primary air enter the combustion chamber along the axis at a velocity of about 20 m/s (Fu, *et al.*, 1986 and 1988). Several small nozzles are located on the head cover at certain points with a given radius from the axis. Steam or air is injected through the small nozzles at near sonic or even supersonic speeds. Thus, a large high strength circulation zone can be produced without the use of swirlers or bluff bodies. This is of great interest for practical engineering, especially for the operational department in power plants. This aerodynamic method for creating a large recirculation zone can avoid many shortcomings of mechanical methods (swirl-type or bluff body methods) such as abrasive erosion, large pressure loss, and separation and the settling of pulverized coal and ashes due to centrifugal flow or impact with the bluff body. The construction of the combustor becomes very simple and manufacturing is easy. Above all, its flame stabilization capability for low-grade coals

is better than that of the two other types of precombustors (swirl-type and bluff-body combustor).

The FIJ combustor (Wu, *et al.*, 1988; Wei, *et al.*, 1990) was invented based on the so-called Coanda effect well known in fluids and hydrodynamics (Glaettli, 1967). This type of combustor features a flattened jet of primary air and pulverized coal. The flattened jet is located near the center of the upstream end that is usually a rectangular channel. The jet can be located at mid-plane or it can be slightly offset. Within certain ranges of Reynolds numbers, for such a configuration, the jet will deflect to one side and attach to the side wall. The flow pattern is quite similar to that of a CFJ combustor. In practical applications, a narrow slit is usually arranged at the bottom to let in an auxiliary jet of air that will enhance the flow pattern and help soot-blowing.

For a precombustion chamber with an off-axis primary jet, i.e., EJ combustion technology (Wu, *et al.*, 1988), primary air and pulverized coal enter the chamber through a pipe off the axis. Sometimes this pipe is tilted at a small angle, the velocity being about 25 m/s. A flat jet of air with a speed about 50 m/s is sometimes used near the bottom for soot blowing. This arrangement can create a flow field that is similar to that of the CFJ combustor (Fu, *et al.*, 1986 and 1988), thus meeting the needs for stable burning of low-grade coals. This precombustor is of simple geometry and of very good flame stabilizing performance.

There is no need for high-speed jets for both FIJ and EJ precombustors and combustion performances for both these precombustors are similar to the CFJ combustor.

Although the development of a pulverized-coal combustor has made such progress as mentioned above, for practical engineering purposes, further improvements are desirable such as better methods of flow-control, non-slagging technologies, simple design with multiple functions (multiple operation modes) and low emission of pollutants.

A new type of pulverized-coal combustor, called "Wall-Protecting-Jets Combustor" (WPJC), based on the new concept of all inlet jets along the combustor wall, has been proposed, and a 3-D code has been developed to study 3-D two-phase flows and combustion in this combustor (Zhou and Wu, 1997). The chief aims in developing this type of combustor are to solve the problems of slag build-up inside the combustor, reduce the emission of pollutants and to realize multiple functions (boiler startup, low-load flame stabilization and main burner operation).

In the course of this research project, the combustion set-up of the WPJC was designed and studied using experimental and CFD methods. Combustion experiments were carried out to verify the concept of multiple functions of the combustor and to test the combustion performance of the WPJC. The CFD software

FLUENT was employed to extensively investigate the WPJC combustion mechanism through studies of two-phase flows and pulverized-coal combustion in WPJC.

WALL-PROTECTING-JETS COMBUSTOR (WPJC) AND EXPERIMENTAL SYSTEM

Figure 1 shows a schematic diagram of the combustor composed of a cylindrical tube (diameter 0.3 m) with two pairs of jets, i.e., one pair of primary air jets and another pair of control jets, along the inside cylindrical surface, as shown in the figure. The air jets along the wall are expected to effectively protect the wall against overheating and erosion, to effectively solve the problem of slag build-up inside the combustor, and to control temperature and ignition position so that the emission of pollutants can be reduced. The flow field characteristics are expected to achieve a multiple of functions, which include boiler startup, low load flame stabilization and main burner operation.

FIGURE 1 Schematic diagram of Wall-Protecting-Jets Combustor (WPJC). 1, 3 primary air; 2, 4 controlling air

Figure 2 presents a schematic of the experimental combustor. Except for the two primary jets and two controlling jets, in the experimental combustor there are six holes for measurements along the combustor outlet and the side wall, and one hole on the head-wall for an oil-gun igniter. This experimental combustor is made of seamless steel tubing without refractory materials and the steel is not heat resisting alloy but medium carbon steel.

Figure 3 presents a schematic diagram of the pilot experimental combustion system. It includes one blower, six flow meters, one coal feeder, one pulverized-coal distributor, the WPJC, and corresponding tubes and valves. In the

FIGURE 2 Schematic diagram of WPJC for combustion experiments. 1, 3 primary air; 2, 4 controlling air; 5 hole for oil-gun; A, B, C, D, E, F, G, H, I: holes for measurements

experiments, air flowrates of all air inlets and coal rates can be adjusted separately.

FIGURE 3 System for combustion experiments of WPJC. 1 blower; 2 valves; 3 flowmeters; 4 pulverized-coal feeder; 5 distributor of pulverized-coal; 6 WPJC; 7, 8, 9, 10 air for feeding pulverized-coal; 11 adjusting air for primary air 1; 12 controlling air 2; 13 controlling air 4; 14 adjusting air for primary air 3; 15 excess air

PHYSICAL MODELS AND SOLUTION PROCEDURES

Two-phase flows and pulverized-coal combustion in the WPJC were conducted with the commercial CFD code FLUENT (Fluent Inc., 1999). The $k-\epsilon$ model was employed to simulate the gas-phase turbulent flow, discrete phase model with stochastic tracking technique for coal-particle phase. Species transport equations with a finite rate chemistry model were solved to predict each component species. The reaction rates that appear as source terms in the species transport equations were calculated with the eddy-dissipation model. A two competing rates

model (Kobayashi, Howard and Sarofim, 1976) was used for coal particle devolatilization, and a diffusion-limited model (Baum and Street, 1971) was used for char combustion on coal particle surfaces. The two competing rates model provides two kinetic devolatilization rate expressions in terms of different temperature ranges. The two kinetic rates are weighted to obtain an expression for devolatilization. The diffusion-limited surface reaction rate model assumes that the surface reaction proceeds at a rate which is determined by the diffusion of the gaseous oxidant to the surface of the particle. The kinetic contribution to the surface reaction rate is ignored. This model assumes that the diameter of the particles keeps constant. Since the mass of the particles is decreasing due to reactions, the effective density is reduced and the char particles become more porous.

The procedure for two-phase flow and pulverized-coal combustion in the WPJC is as follows:

1. Solve the continuous phase (gas phase) flow field.
2. Solve the discrete phase by calculating the particle trajectories for each discrete phase injection.
3. Update continuous phase source terms and recalculate the continuous phase (gas phase) flow field.
4. Repeat (1)-(3) until a reasonable cold two-phase flow result is obtained.
5. Start the pulverized-coal combustion calculation based on the reasonable cold two-phase flow result.
6. With the combustion switch on, repeat (1) to (3) until the converged result is obtained.

REALIZATION OF MULTIPLE FUNCTIONS

Tables I and II describe the combustion tests carried out to verify the realization of multi-functions with the WPJC. As shown in the two tables, a stable pulverized-coal flame can be established from a completely cold environment (cold boiler startup) within less than eight minutes, thus allowing savings on fuel oil for the igniter. Also, from the two tables, it is very obvious that, by changing the velocity (flow rate) of the controlling air, the flame position can be easily changed. That is, increasing the velocity (flow rate) of the controlling air can result in the flame moving downstream while decreasing the velocity (flow rate) of the controlling air can make the flame move upstream. The flame can be completely pushed out of the combustor (main burner mode) or the combustor can be completely or partially occupied by the flame (low-load flame stabilization). During a time of ten to twelve minutes after ignition (the controlling-jets were

off), the wall of the WPJC was red after hole D (Table II), while after the controlling-jets were turned on, the wall of the WPJC showed normal color, i.e., showed no overheating. Therefore the controlling jets play an important role in protecting the combustor-wall against overheating and erosion, and prevent slag from building up in the combustor.

TABLE I Combustion experiments for the realization of multiple functions (subscript k is for coal particle phase)

Time (min)	Coal Rate (kg/h)	Air Rate (m ³ /h)	$V_1=V_{k1}$ (m/s)	$V_2=V_4$ (m/s)	$V_{k2}=V_{k4}$ (m/s)	$V_3=V_{k3}$ (m/s)	Phenomena (RF starting from or moving to)
0	0	345	5.2	0	0	31.6	ignited by burning oil
6	130	345	5.2	0	0	31.6	oil + coal combustion; hole A
8	150	345	5.2	0	0	31.6	stable coal flame (no oil); hole A
13	150	505	5.2	11.0	0	31.6	downstream
16	150	525	5.2	13.7	0	31.6	downstream
24	150	525	5.2	13.7	0	31.6	hole E
25	150	585	5.2	16.5	0	31.6	hole F
35	150	585	5.2	16.5	0	31.6	hole F
36	150	655	5.2	21.3	0	31.6	hole H
58	150	655	5.2	21.3	0	31.6	hole H
68	150	520	19.3	0	0	36.4	hole I
73	0	0	0	0	0	0	stop; no slag

* RF----Recirculating Flame

In order to investigate the mechanism of multi-functions, the following cold two-phase flows in the WPJC were simulated by the CFD code, FLUENT (Fluent Inc., 1999).

Figure 4 and Figure 5 present the predicted velocity vectors in the x-r planes of the calculated case T1 and T2 (Table III), respectively. As shown in Figure 4, the pair of primary air jets in the combustor creates recirculation zones. The physical mechanism of the creation of this recirculation is by entrainment of the adjacent gases from the primary air jets. This creates a region of low pressure in the upstream section of the chamber, thus generating the reverse flow of gases and particles. Such features of the flow field are favourable for coal flame stabilization, and are beneficial for heat and mass transfer between two phases, coal devolatilization and combustion.

TABLE II Combustion experiments for the realization of multiple functions (subscript k is for coal particle phase)

<i>Time (min)</i>	<i>Coal Rate (kg/h)</i>	<i>Air Rate (m³/h)</i>	<i>V₁=V_{k1} (m/s)</i>	<i>V₂=V₄ (m/s)</i>	<i>V_{k2}=V_{k4} (m/s)</i>	<i>V₃=V_{k3} (m/s)</i>	<i>Phenomena (RF starting from or moving to)</i>	<i>Color of WPJC Wall</i>
0	150	360	19.2	0	0	19.2	Ignited by burning oil	normal
3	150	360	19.2	0	0	19.2	oil + coal combustion; hole A	Red after hole B
7	150	360	19.2	0	0	19.2	stable coal flame (no oil); hole A	Red after hole C
10	150	360	19.2	0	0	19.2	hole A	Red after hole D
12	150	505	18.4	0	0	35.6	hole A	Red after hole D
16	130	745	18.4	16.5	0	35.6	hole G	Normal
18	130	745	18.4	16.5	0	35.6	hole G	Normal
24	130	659	18.4	11.2	0	35.6	hole F	Normal
27	130	705	18.4	13.7	0	35.6	hole H	Normal
33	130	625	18.4	8.2	0	35.6	hole G	Normal
40	130	585	18.4	5.5	0	35.6	upstream	Normal
43	130	505	18.4	0	0	35.6	upstream	Normal
46	130	425	18.4	0	0	27.0	upstream	Normal
48	130	345	5.2	0	0	31.6	hole A	Normal
58	130	345	5.2	0	0	31.6	hole A	Normal
59	130	465	0	0	0	49.8	very strong hole A	Normal
64	130	235	0	0	0	25.18	hole A	Normal
69	130	235	8.99	0	0	16.19	hole A	Normal
74	0	0	0	0	0	0	stop; no slag	Normal

* RF----Recirculating Flame

TABLE III Calculated cases (cold two-phase flows, subscript k is for coal particle phase)

Cases	V_1 (m/s)	V_{k1} (m/s)	$V_2=V_4$ (m/s)	$V_{k2}=V_{k4}$ (m/s)	V_3 (m/s)	V_{k3} (m/s)	d_k (m)
T1	12.5	12.5	0	0	25	25	6×10^{-5}
T2	12.5	12.5	20	0	25	25	6×10^{-5}

As shown in Figure 5, when the controlling jets are turned on, there is only one small gas recirculation zone near the head of the combustor which gives the adjusting and switching role of the controlling-air. Actually, by using the controlling-jets and/or by varying the ratio of the two primary air rates, the position of the recirculation zone can be easily adjusted, i.e., this can be used to adjust the ignition position. Therefore, by using the controlling-jets, the different operation modes can be conveniently realized.

FIGURE 4 Velocity vectors (cold flow) in the x - r plane of the calculated Case T1. (a) gas ($\theta = 0^\circ, 180^\circ$); (b) gas ($\theta = 90^\circ, 270^\circ$)

COMBUSTION PERFORMANCE AND EMISSIONS CONTROL MECHANISMS

In order to understand combustion performance and the emissions control mechanism of the combustor, six cases (Table IV) were tested experimentally. Parameters measured were temperature and species concentrations (carbon dioxide, oxygen, carbon monoxide, nitric oxide, sulphur dioxide). Temperature was

measured using Ni-Cr and Ni-Al thermocouples. Carbon dioxide and oxygen were measured by the YES-II CO₂ – O₂ measurement system, and carbon monoxide, nitric oxide and sulphur dioxide were measured with sample systems.

FIGURE 5 Velocity vectors (cold flow) in the x-r plane of the calculated Case T2. (a) gas ($\theta=0^\circ$, 180°); (b) gas ($\theta=90^\circ$, 270°)

TABLE IV Cases for combustion measurements (subscript k is for coal particle phase)

Cases	Coal Rate (kg/h)	Air Rate (m ³ /h)	$V_1=V_{k1}$ (m/s)	$V_2=V_4$ (m/s)	$V_{k2}=V_{k4}$ (m/s)	$V_3=V_{k3}$ (m/s)
E1	158	465	0	0	0	50
E2	130	353	12.5	0	0	25
E3	130	355	25	0	0	12.8
E4	120	235	0	0	0	25
E5	130	550	18.8	5.5	0	31.7
E6	120	510	12.7	5.5	0	35.6

Low Temperature Combustion

Figure 6 shows the temperature contours for the six cases. From these figures, it can be seen that in the six cases, the following features characterize the temperature fields: the temperature increases with the axial distance and decreases with increasing radial position. The highest temperature in the combustor, about

FIGURE 6 Temperature contours for the six experimental cases. (a) Case E1; (b) Case E2; (c) Case E3; (d) Case E4; (e) Case E5; (f) Case E6

1500K, occurs near the outlet of the combustor, which is lower than the melting point of the coal (1600K) employed in the experiments. That is why no slag built up in the combustor. Also, the low temperature combustion is beneficial for the control of pollutants.

Three Stage Combustion (Three Sub-process Combustion)

Figure 7 shows the contours of various species for the experimental case E1.

In the zone around $x=450$ mm, the concentration of carbon dioxide is higher, while the concentrations of oxygen and carbon monoxide are lower. This indicates that in this zone, volatile combustion dominates the reactions. Meanwhile, there is a small amount of char to react with the oxygen to produce carbon monoxide and carbon dioxide. In the zone around $x > 850$ mm, the concentration of carbon dioxide decreases slightly, carbon monoxide increases and oxygen decreases further, indicating that, in this zone, the carbon dioxide reacts with char to produce carbon monoxide. Meanwhile, the char reacts with oxygen to produce carbon monoxide.

The concentration of nitric oxide in the zone of $x < 750$ mm increases with increasing axial distance and decreases with increasing radial distance, which is similar to the distribution of temperature. In the zone $750 \text{ mm} < x < 1050$ mm, the concentration of nitric oxide is lower than in the zone $x < 750$ mm. This is because, in this zone, the concentration of oxygen is lower and the concentration of the fuel is higher, thus resulting in a reduction of nitric oxide. In the zone $x > 1050$ mm, the concentration of nitric oxide increases with increasing temperature, most likely due to thermal NO production.

For the concentration of sulphur oxide, there is a peak value around $x=450$ mm because in this zone, the concentration of coal particles is lower while that of oxygen is higher. The concentration of sulphur oxide decreases with increasing radial distance in the entire combustor.

Figure 8 shows the contours of carbon dioxide, oxygen, carbon monoxide, and nitric oxide for the experimental case E2. From this figure, it can be seen that, by increasing the axial distance, the concentration of carbon dioxide and carbon monoxide increases while the concentration of oxygen decreases, since oxygen is consumed as it reacts with the coal. For the concentration of nitric oxide, there is a peak value around the zone of $x=800$ mm. When $x < 800$ mm, the concentration of nitric oxide increases with increasing axial distance while it decreases with increasing axial distance when $x > 800$ mm. This means that, in the zone $x < 800$ mm, the oxidization of nitrogen dominates the reactions related to nitrogen while the reduction of nitric oxide dominates in the zone $x > 800$ mm.

FIGURE 7 Species contours for the experimental Case E1. (a) carbon dioxide; (b) oxygen; (c) carbon monoxide (ppm); (d) nitric oxide (ppm); (e) sulphur oxide (ppm)

FIGURE 8 Species contours for the experimental Case E2. (a) carbon dioxide; (b) oxygen; (c) carbon monoxide (ppm); (d) nitric oxide (ppm)

From both Figure 7 and Figure 8, it can be seen that in the zone of a lower concentration of oxygen and a higher concentration of carbon monoxide, the concentration of nitric oxide is lower. This indicates that the higher concentration of the carbon monoxide in this kind of zone is beneficial for the reduction reactions of nitric oxide (Lee, *et al.*, 1995).

In summary, the pulverized-coal combustion in the WPJC can be roughly divided into three sub-processes (three-stage combustion). Initially, coal particles are preheated and mixed with air in the front zone of the combustor. Next, the volatiles are burned and the char particles are ignited in the middle zone of the combustor. Finally, the particles are continuously oxidized and the carbon dioxide and pollutants are reduced in the rear zone of the combustor. The sizes of the three zones can be adjusted through a proper adjustment of the jets while simultaneously allowing both stabilization of the flame and the reduction of pollutants.

STABILIZATION OF PULVERIZED-COAL COMBUSTION IN WPJC

In order to investigate the combustion mechanism of the WPJC, the commercial CFD code, FLUENT, was employed to study the two-phase flows and pulverized-coal combustion in WPJC. The calculated case for pulverized-coal combustion in WPJC is shown in Table V.

TABLE V Calculated cases (pulverized-coal combustion, subscript k is for coal particle phase)

Cases	V_1 (m/s)	V_{k1} (m/s)	$V_2=V_4$ (m/s)	$V_{k2}=V_{k4}$ (m/s)	V_3 (m/s)	V_{k3} (m/s)	d_k (m)
C1	12.5	12.5	0	0	25	25	6×10^{-5}

Comparison between Experimental and CFD Results

Figure 9 presents a comparison of temperature fields between CFD and experimental results. In general, there is a reasonable agreement for the highest temperature, but the overall distributions do not agree well. The modeled adiabatic walls resulted in an overprediction of wall temperatures, compared to temperatures measured near the uninsulated walls of the test rig.

Figure 10 gives a comparison of oxygen concentration between CFD and experimental results. The numerical results show that the oxygen in this plane is almost consumed while the experimental results illustrate that the oxygen is burned gradually along the axial direction. The overprediction of reaction rate is most likely due to the unrealistic adiabatic boundary conditions for the modeling.

FIGURE 9 Comparison of temperature fields between simulation and experiments ($\theta=90^\circ, 270^\circ$). (a) experiments for Case C1; (b) simulation for Case C1

FIGURE 10 Comparison of oxygen concentration fields between simulation and experiments. ($\theta=90^\circ, 270^\circ$). (a) experiments for Case C1; (b) simulation for Case C1

Figure 11 presents a comparison of carbon dioxide concentration between CFD and experimental results. There is a reasonable agreement between them.

(a)

(b)

FIGURE 11 Comparison of carbon dioxide concentration fields between simulation and experiments ($\theta=90^\circ, 270^\circ$); (a) experiments for Case C1; (b) simulation for Case C1

If the boundary condition of the combustor wall is set to be non-adiabatic, the numerical results should improve because the combustor wall is not adiabatic in the experiments.

(a)

(b)

FIGURE 12 Calculated velocity vectors in the x-r plane. (a) Case C1 ($\theta=0^\circ, 180^\circ$). (b) Case C1 ($\theta=90^\circ, 270^\circ$)

Mechanism of the Stabilization of Pulverized-Coal Flame in WPJC

Configuration of recirculation zones Figure 12 shows that there are large recirculation zones, both in $\theta=0^\circ$, 180° and $\theta=90^\circ$, 270° planes. The recirculation zones bring the high-temperature combustion products back from downstream. This is one of the necessary conditions for stabilizing the pulverized-coal flame.

High temperature in recirculation zones Figure 13 and Figure 9 show the temperature contours for case C1. Combining Figures 12 with 9 and 13, it can be seen that the high temperature zones are located where there is recirculation. This is another of the necessary conditions for stabilizing the pulverized-coal flame.

FIGURE 13 Calculated temperature contours (K) for Case C1 ($\theta = 0^\circ$, 180°)

In summary, Figures 9, 12 and 13 illustrate that in the combustor there are several strongly recirculating zones in which the temperature is high. Such features can be used to stabilize the coal flame since coal particles are entrained into these zones where volatiles can be released and ignited. That is the basic stabilization mechanism for the WPJC.

Prediction of Concentration for Component Species

Figure 14 shows the concentration contours for volatiles, oxygen, carbon dioxide and water vapour for case C1 ($\theta = 0^\circ$, 180°). Figure 15 presents a schematic based on the information from Figure 14. It can be seen that the combustion process in a WPJC can be divided into four zones: I, II, III, IV.

In zone I, the temperature is lower, therefore the volatile content is lower; the oxygen is higher because this zone is near the primary inlet. The medium concentration for carbon dioxide and water vapour occurs because the flow in this

FIGURE 14 Concentration contours for Case C1 ($\theta=0^\circ, 180^\circ$). (a) volatile; (b) oxygen; (c) carbon dioxide; (d) water vapor

FIGURE 15 Schematic for temperature fields and concentration fields of the component species. I: lower T and volatile, higher oxygen, medium carbon dioxide and water vapor; II: lower T, higher volatile, oxygen, carbon dioxide and water vapor; III: higher T, lower volatile and oxygen, medium carbon dioxide and water vapor; IV: medium T, higher volatile, low oxygen, higher carbon dioxide and water vapor

zone is reversed-flow and the reaction products are brought back from downstream.

In zone II, the temperature is lower and the oxygen and volatile concentrations are higher due to the primary air. The higher concentrations for carbon dioxide and water vapour are present due to the recirculation of combustion products.

Higher reaction rates and temperatures characterize zone III. Thus volatiles and oxygen concentrations are low and combustion product concentrations are high.

In zone IV, the temperature is of medium level due to mixing between primary air and reaction products. The higher volatile concentration is due to the medium temperature. The lower oxygen concentration and higher carbon dioxide and water vapour concentration are due to the reactions.

From the analysis above, it can be seen that the four-zone characteristics are quite similar to the results from the experiments (three-stage combustion).

CONCLUSIONS

(1) With the new concept, all the inlet jets enter the combustor along the inside wall. There is a characteristic two-phase flow field with large recirculating zones where coal particle concentrations and temperatures are higher. These are beneficial for ignition, stable combustion of pulverized-coal, multiple functions and low emission of pollutants.

(2) The WPJC has the following advantages: wall-protection by the cold jets without the use of refractory materials, low-temperature and three-stage combustion with negligible ash/slag deposition, low NO_x emission; multiple functions (boiler startup, low-load flame stabilization and main burner operation) and convenient switching between them and effective adjustment of both the combustion intensity and the ignition position.

(3) The CFD predictions give useful information for practical engineering purposes. The flow structures obtained from CFD simulations can be used to discover the mechanisms of flame stabilization, coal combustion and pollution control. Velocity fields, particle trajectories, concentrations of all component species, and temperature fields can be obtained avoiding costly and time consuming experiments. Thus the modelling allows for inexpensive optimization of engineering designs.

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