Experimental Investigate on Pre-combustion Characteristic and Flame Shape of an Adjustable Axial Swirl Burner for Pulverized Coal Combustion

Pengzhong Liu

China Coal Research Institute Company of Energy Conservation <https://orcid.org/0000-0003-1971-5914>

Fang Niu (✉ nf37@163.com)

China Coal Research Institute Company of Energy Conservation, Beijing 100013, China

Pengtao Wang

China Coal Research Institute Company of Energy Conservation

Nan Jia

China Coal Research Institute Company of Energy Conservation

Jianming Zhou

China Coal Research Institute Company of Energy Conservation

Wei Luo

China Coal Research Institute Company of Energy Conservation

Naiji Wang

China Coal Research Institute Company of Energy Conservation

Research

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Experimental investigate on pre-combustion characteristic and flame shape of an adjustable axial swirl burner for pulverized coal combustion

Pengzhong Liu^{1,2}, Fang Niu^{1*}, Pengtao Wang¹, Nan Jia¹, Jianming Zhou¹, Wei Luo¹, Naiji Wang¹

1 China Coal Research Institute Company of Energy Conservation, Beijing 100013, China

2 China Coal Research Institute, Beijing 100013, China

Abstract: The 14 MW pilot-scale pulverized coal experiment system was built, pre-combustion characteristic and flame shape of adjustable axial swirl burner was investigation, and influence of swirl number also was discussed. The temperature and species concentration distribution in pre-combustion chamber showed that a high temperature oxygen-free and high CO concentration zone appeared around central pulverized coal, which enhanced burnout and inhibiting or reduction NO_x. The pre-combustion characteristic belonged to high temperature preheating combustion technology. The captured flame image showed that flame shape beyond pre-combustion chamber outlet belonged to turbulent diffusion flame. Then flame shape scales were obtained. For different swirl numbers, ignition, wall temperature, mean maximum temperature, oxygen-free boundary and CO concentration was discussed, the results indicated that $S=1.67$ had advantaged for burnout and reduction NO_x emission on the basis of stable ignition and avoiding high temperature corrosion. Mean flame length and diameter and divergence angle also were analyzed, the results showed that $S=1.67$ case had moderate flame length and best diameter and divergence. It was favorable for flame stability and high temperature region in furnace part, and increasing burnout and deceasing NO_x emission. Therefor the optimal selection was $S=1.67$ case under experimental condition.

Keywords: swirl burner; Pre-combustion characteristic; flame shape; swirl number.

1 Introduction

Coal still is the main primary energy (Chang et al. 2016; Guan 2017) in some area of world over a period of time. For pulverized coal (PC) combustion, NO_x emission in pollution control is considered continuously. A great quantity of low nitrogen combustion technologies have been researched and applied, such as air staging and fuel staging (Yang et al. 2014 and 2015), fuel rich/lean combustion (Li et al. 2014), flue gas recirculation (Kim et al. 2007), preheating-combustion (Ouyang et al. 2013) et al. But combustion efficiency and NO_x emission of PC gradually face on variable operating load and PC type conditions in boiler. The PC preheating-combustion technology displays great suitable for different PC types on the basic of guarantee high efficient and low pollutions emission (Ouyang et al. 2014; Liu et al. 2015). And adjustable swirl burner also is considered and researched as a method to satisfy variable conditions (Luo et al. 2016; Zhang et al. 2018). Thus, the investigation of preheating-

combustion processing for adjustable swirl burner is necessary.

For PC preheating-combustion technology, the preheating mothed included individual preheating device (circulating fluidized bed or preheating chamber), increasing air temperature (air preheater) and pre-combustion equipment (pre-combustion chamber burner). Ouyang et al. (2013; 2014) experimentally discussed the effect of limestone on pollution emissions of lignite, bituminous, anthracite, semi-coke by circulating fluidized bed preheating. And preheating and combustion characteristic of individual anthracite also was studied. Bituminous and ultra-low volatile coal based fuel was researched on NO_x emission and preheating combustion characteristic by Zhu et al (2019). The influence of air distribution and burner type on NO_x emission of two kinds bituminous and low volatile was investigated in down preheating chamber and down tube furnace system by Liu et al. (2015). And Li et al. (2012) researched the effect of

air temperature on combustion characteristic and NO_x emission in experimental furnace. The above results indicated that preheating-combustion technology was suitable for different PC types. For pre-combustion equipment, Jiang et al. (2014) numerically discussed the combustion characteristic of middle volatile coal in industrial boiler, which double cone pre-combustion chamber swirl burner was adopted. And the pre-combustion characteristic of coal water slurry in chamber also was studied by Mo et al. (2018). But, the experimental data in different shape chamber was deletion. To fully understand the function of pre-combustion chamber, the experimental investigation on pre-combustion chamber needed to be developed.

For swirl burner, adjustable structure can be divided into three parts: (i) adjustable burner outlet (length and angle of cone or flaring et al.); (ii) adjustable fuel rich/lean (concentrator type or fuel rich/lean duct); (iii) adjustable swirl intensity (swirl vane angle or position). Luo et al. (2016) experimental and numerically studied the effect of the adjustable inner secondary air-flaring angle of swirl burner on Coal-Opposed Combustion, where temperature distribution, ignition, flame characteristic, wall temperature, combustion loss and NO_x emission were analyzed. And combined control of flaring angle and air distribution also was investigated (2015). Zhang et al. (2018) discussed the effective of flaring angle on combustion characteristic and NO_x emission with different fuel rich/lean, loads and PC types. The cone length of different ducts was researched numerically in central fuel rich swirl burner by Ti et al. (2016). The above results showed that optimized burner outlet structure was selected with different conditions, evidenced that adjustable swirl burner was a great method. Chen et al. (2011) researched and optimized the influence of a conical rings concentrator on the gas/particle flow characteristics in central fuel rich swirl burner outlet region, and reasonable levels, distances between adjacent rings and cover ratios were obtained in specific condition. Li et al. (2014) studied the influence of fuel rich/lean on combustion characteristic and NO_x emission by speeding rate of inner and outer primary air duct. The research showed that reasonable fuel rich/lean needed to be adjusted. The investigation of literature also included the effect of swirl number, which was achieved

by adjustable axial swirler (Luo et al. 2016). The influence of tangential swirl vane angles were discussed on flow and combustion characteristic and NO_x emission for central fuel rich swirl burner (Ti et al. 2017; Li et al. 2017). Effectiveness between swirl intensity and air staging was studied on burnout characteristic and NO_x emission by Sung et al. (2015). The above literatures about swirl intensity indicated that reasonable swirl intensity or swirl number needed to be selected with different conditions. Although the adjustable structure was not used in some investigations of three parts, the all results showed that adjustable swirl burner had advantage in boiler variable conditions.

In this paper, an adjustable axial swirl burner was selected to research pre-combustion characteristic in pre-combustion chamber and flame shape beyond pre-combustion chamber outlet. And the influence of swirl intensity also was discussed, which was achieved by position of axial swirler. The investigation of different PC types and operating loads will be considered in future.

2. Experiment

2.1 Experiment system

14MW pilot-scale pulverized coal experiment system

1, 2, 4- blower; 3- Roots fan; 5- storage facilities; 6-feeding device; 7- mass flowmeter; 8-valve; 9- ignition device; 10- thermocouple; 11- air compressor; 12- Signal exchanger;13- desktop computer; 14- sampling device; 15- filter unit; 16- flue gas analyzer 17- high speed camera;18- notebook computer;19- protective wall; 20-adjustable axial swirl burner.

Fig. 1 schematic diagram of the experiment system.

1-primary air duct; 2-isolate duct; 3-inner secondary air duct; 4-outer secondary air duct; 5-tertiary air duct; 6- axial movable swirl vanes; 7- combustion stabilizing device; 8-expanding cone shape pre-chamber; 9- location of measuring points.

Fig. 2 schematic diagram of the adjustable axial swirl burner

was built, Fig. 1 showed the schematic diagram of experiment system. The PC in storage facilities was fed to mix with primary air by feeding devices, the speed was controlled by frequency of feeding devices. During each case, three times of 10 min feeding speed calibration were carried out, and error was maintained at $\pm 8\%$. A Roots fan and three blowers respectively provided primary air, inner and outer secondary air, tertiary air. The flow rate of mass flowmeter was adjusted by valve. The diesel oil was used to help PC ignition and stable combustion, then was stopped. The control system was responsible for start and stop of the whole experiment system.

The 1.5m-length stainless steel K-type thermocouple was adopted in temperature measurement. It could achieve temperature online display by signal converter. The measurement range of the thermocouple was 0-1300 °C with an error of 0.5%. When fluctuation range of temperature was ± 10 °C, it was recorded as the measurement value.

Flue gas was sampled and quickly cooled by a water-cooled sucking probe, and samples through unit and were filtered then analyzed online by a MRU VARIO PLUS flue gas analyzer to obtain the species concentrations. The water-cooled sucking probe were consisted by a centrally-located sampling pipe and double-deck stainless steel tube with cooling water. Flue gas species concentration had an accuracy consisting of $\pm 2\%$ for measurement values. In this processing, 60 group data were measured at each

Fig. 3 the vanes of adjustable axial swirler

measuring point for 120s, and the mean value of data with 30s stability was selected as the flue gas species concentrations value of this point

The flame capture mainly depended to the high-speed camera, which used its supporting application software (PCC 3.1) to select camera parameters with 1280×504 resolution, 200μs exposure time, 1100fps sampling rate etc. The scale was arranged at the same section with the burner axis, then 8337 flame pictures was obtained to analysis flame shape.

2.2 Swirl burner and experimental conditions

The schematic diagram of the burner was shown in Fig. 2, which had flame stabilizing device, isolated area of PA and ISA, ISA adjustable axial swirler, expanding cone shape pre-combustion chamber et al.. Fig. 3 showed the axial swirl vane on adjustable swirler. Axial distance of burner outlet section and the radial distance of central axis was defined as X and R respectively. Four sections X=268, 536, 670, and 804 mm were selected. Measurement points of each section were respectively 10, 60, 110, 160, 210, 260 mm from the wall surface of pre-chamber and the last

Table1 The basic characteristics of experimental coal

Proximate analysis (as received wt %)	
Volatiles	33.60
Ash	7.02
Moisture	5.62
Fixed carbon	53.76
Net heating value(kJ/kg)	27200
Ultimate analysis (as received wt %)	
Carbon	61.54
Hydrogen	4.16
Oxygen	11.64
Nitrogen	0.82
Sulfur	0.43

Table 2 Experimental conditions and parameters

ISA swirl number(S)	1.67	0.49	0.28
Feeding speed (kg/h)	1140	1140	1140
Primary air (kg/h)	900	900	900
Primary air speed (m/s)	26.3	26.3	26.3
Inner secondary air (kg/h)	1945	1945	1945
Inner secondary air speed (m/s)	11.1	11.1	11.1
Outer secondary air (kg/h)	3889	3889	3889
Outer secondary air speed (m/s)	28.0	28.0	28.0
Tertiary air (kg/h)	1955	1955	1955
Tertiary air speed (m/s)	4.5	4.5	4.5
Excess air ratio (λ)	1.0	1.0	1.0
All air temperature (°C)	20	20	20

point was the central axis.

In this combustion experiment, Shenfu long flame coal in China was used, and its basic characteristics were shown in Table1. As a kind of high volatile coal, it could ensure the smooth ignition and stable combustion of experiment processing. Table2 showed the experimental conditions and specific parameters. Swirl intensity of swirl burner was an important factor on flow and combustion characteristic. And different ISA swirl number cases were selected as experimental variables to characterize swirl level. For fixed axial swirl vane and angle, the swirl number(S) was calculated using following formula (Sung et al. 2015):

$$S = \frac{2}{3} * \left[\frac{1-(d_i/d_o)^3}{1-(d_i/d_o)^2} \right] * \tan(\theta) \quad (1)$$

where d_i was the inner diameter of swirl duct, d_o was the outer diameter of swirl duct, and θ was the special swirl vane angle. But the original swirl number formula needed

Fig. 4 adjustable axial swirler moveable conditions

to be used for adjustable axial swirler (Ti et al. 2017):

$$S = \frac{G_\theta}{RG_\chi} = \frac{\int_{R_1}^{R_2} \rho U W r^2 dr}{R(\int_{R_1}^{R_2} \rho U^2 r dr + \int_{R_2}^{R_3} \rho u^2 r dr)} \quad (2)$$

where G_θ was axial flux of swirl duct tangential momentum, G_χ was all axial flux of swirl duct axial momentum, R was swirl duct outlet outer radius, ρ was air density, U and W were axial and tangential velocities of swirler outlet position, u was axial velocities of direct flow at the position, R_1 , R_2 and R_3 respectively were inner and outer radius of swirler outlet, swirl duct outer radius at the position. In our experimental process, the moveable conditions was illustrated in Fig4, swirl number calculated of ISA duct respectively were 1.67, 0.49 and 0.28. Because of ISA/OSA=1:2, secondary air swirl number was lower, only ISA swirl number was considered at present work.

3. Results and discussion

Pre-combustion characteristic and flame shape of adjustable axial swirl burner were researched by above experiment section. Influence of swirl number also was considered to select reasonable case under the condition

Fig. 5 gas temperature distribution with different S in pre-combustion chamber

Fig. 6 O₂ concentration distribution with different S in pre-combustion chamber

Fig. 7 CO concentration distribution with different S in pre-combustion chamber

of 63% load and ISA/OSA=1:2.

3.1 Pre-combustion characteristic

Fig. 5 showed gas temperature distribution with different S in pre-combustion chamber. At four measuring cross-sections, temperature profiles slightly rose then fell rapidly along radial direction. The reasons were that PC ignition and combustion increased temperature and wall air decreased temperature. The area of $T > 800$ °C was defined as high temperature zone (HTZ). The area and position of HTZ gradually reduced and faded away from central axis along axial direction. The reasons were incomplete PC combustion and divergence ability of swirl. At $X=536-804$ mm area, a significant low temperature zone could be seen around central axis, indicated that PC underwent pyrolysis processing.

Fig. 6 showed O₂ concentrations distribution with

different S in pre-combustion chamber. At four measuring cross-sections, O₂ concentrations profiles along radial direction kept low concentration then rose rapidly. Because it was continuous oxygen consumption and gradual mixing of combustion products for near wall secondary air injection. The area of $O_2 < 1\%$ was defined as oxygen-free zone (OFZ) to provide an inhibiting NO_x generation region. The boundary difference of OFZ was slight along axial direction, indicated that heat recirculation zone was formed between PA and ISA. Because radial diffusion of high speed PA and PC particles was weak.

Fig. 7 showed CO concentrations distribution with different S in pre-combustion chamber. At four measuring cross-sections, CO concentrations profiles along radial direction fell rapidly then kept stable. The reason was that O₂ concentrations caused PC incomplete and complete combustion. The area of high CO concentrations was

defined as reduction atmosphere zone (RAZ) to provide environment and reactant of NO_x reduction. The boundary and value of RAZ were slightly increased or decreased alone axial direction, which reflected mixing of swirl ISA and high speeding PA at burner outlet region. In pre-combustion chamber, the temperature, O₂ and CO concentrations distribution showed that high temperature, oxygen-free and strong reduction atmosphere region surrounded central PC. This finding demonstrated that PC underwent the process of preheating and inhibiting or reduction NO_x. It was indicated that pre-combustion chamber also was a method of PC preheating-combustion, and had high temperature preheating characteristic.

3.2 Flame shape

Fig. 8 showed flame shape image with different S beyond pre-combustion chamber outlet. Long and slender flame shape could be seen in all images, and the flame divergence also was weak. It was typical diffusion flame. The phenomenon was caused by high speeding PA and PC. The wrinkle of flame surface was typical turbulence flame characteristic, which were favorable for flame propagation

Fig. 8 flame shape image with different S

and mass and heat diffusion. Because pre-combustion chamber retarded air decaying, long low speeding region was formed to stably the turbulence diffusion flame beyond pre-combustion chamber outlet. The flame shape indicated that adjustable axial swirl burner might be used on opposed or tangential circle combustion.

Fig. 9 flame processing sets and shape scale obtained

To obtain specific data of flame shape, the original flame image was processed by method of literature (Katz et al 2017). The sets of flame processing was shown in Fig. 9. Original image was converted to gray image and the brightness of each pixel point could be obtained. Then brightness profiles of different vertical lines was shown and brightness limit line was selected to use. The vertical line needed to be selected in area of flame appearing. Finally, the original image was converted to monochrome image with selected limit. According to pixel value (0 or 1) distribution of monochrome image, flame pixel length (l) and diameter (d) were obtained and real divergence angle (α) was calculated. The flame real length (L) and diameter (D) were translated using following formulas:

$$L/L_R = l/l_R \quad (3)$$

$$D/D_R = d/d_R \quad (4)$$

where L_R and D_R were reference objection real length and height, l_R and d_R were reference objection pixel length and height. To decrease errors of flame shape, 1000 images in 8337 images of each case were processed to obtain mean value. The specific data will be shown in Section 3.3.

Flame shape pixel scale was depended on limit ratio in image processing. For length example, Fig. 10 showed influence and selection of limit ratio on flame pixel length. The length decreased alone limit ratio increasing with different S . Relative horizontal region was selected as arrange used of limit ratio, such as 20-60%. But $S=1.14$ case appeared two regions due to unstable flame wake,

Fig. 10 influence and selection of limit ratio

later region was used to select limit ratio. Finally 50% limit ratio was adopted in all image processing.

3.3 Influence of swirl number

Influence of swirl number was discussed to select optimizing S by temperature and species concentration and flame shape scale. Ignition, central and wall region and specific flame shape scale were analyzed.

The maximum temperature of $X=256\text{mm}$ cross-section was considered as ignition temperature to discuss influence of S . Heat recirculation of isolate duct area and stable flame device ignited PC, the heat recirculation processing was reflected by ignition temperature. Ignition temperature profiles in Fig. 11 indicated that heat recirculation processing for $S=1.14$ case was stronger than others. But temperature more than 1000°C was able to

Fig. 11 influence of S on ignition and mean maximum temperature

Fig. 12 influence of S on mean NOx boundary and maximum CO concentration

produce high temperature corrosion.

For central region, the mean maximum temperature and CO concentration and NO₂ boundary was shown in Fig. 11 and Fig. 12. The profiles indicated that mean maximum CO concentration and NO₂ boundary for S=1.67 case were higher than others, and mean maximum temperature also was moderate. There were beneficial for increasing burnout and inhibiting or reducing NO_x comparing with others in pre-combustion processing.

The temperature of measuring point from wall 10mm was defined as wall temperature to reflect high temperature corrosion of pre-combustion chamber. Fig. 13 illustrated wall mean and maximum temperature with decreasing S. the wall maximum temperature was lower than 400°C for each S, high temperature corrosion no occurred on pre-combustion chamber. The temperature for S=1.67 case were lower than others, indicated that the case avoided

Fig. 13 influence of S on wall mean and maximum temperature

Fig. 14 influence of S on mean and maximum flame length

Fig. 15 influence of S on mean diameter and divergence angle

easily high temperature corrosion. Fig. 14 illustrated influence of S on mean and maximum flame length. The variation trend of flame length was opposite between mean and maximum. Maximum flame length increased slightly with decreasing S, and mean flame length decreased slightly. When OSA was mainstream, decreasing S of ISA increased slightly flame length. The reason was that axial velocity of air flow enhanced slightly. But the stability of air flow was fell, indicated that flame fluctuation increased and mean flame length decreased.

Fig. 15 illustrated influence of S on mean flame diameter and divergence angle. For S=1.14 case, A minimum value could be seen both diameter and divergence angle. It was indicated that the rigidity of air flow was weak and was broken easily. On the basic of flame length slight variation, moderate flame diameter and lager divergence angle were selected in S=1.67 case. The results showed that rigidity of air flow and high temperature region in furnace increased, and indicated that mixing of over-fire air was inhibited to decrease NO_x emission and increase PC burnout.

4. Conclusions

Pre-combustion characteristic and flame shape and influence of S were experimental investigation for an adjustable axial swirl burner, the conclusions were as follow:

1. For the adjustable axial swirl burner, a high temperature, oxygen-free and high CO concentration zone was formed in pre-combustion chamber. It was enhanced to increase pulverized coal burnout and inhibit or reduction

NO_x in pre-combustion processing.

2. For the adjustable axial swirl burner, typical turbulence diffusion flame appeared beyond pre-combustion chamber outlet. Pre-combustion chamber had the ability of stable flame.

3. For the adjustable axial swirl burner, influence of S was discussed and analyzed on ignition, temperature of central and wall region, atmosphere and flame shape scale. And S=1.67 case was optimal selection under 63% loads, ISA/OSA=1:2 and $\lambda=1.0$ experimental condition.

Declarations

Data Availability: No data were used to support this study. The burn of the experiment is available from the authors.

Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Figures

1, 2, 4- blower; 3- Roots fan; 5- storage facilities; 6-feeding device; 7- mass flowmeter; 8-valve; 9- ignition device; 10- thermocouple; 11- air compressor; 12- Signal exchanger;13- desktop computer; 14- sampling device; 15- filter unit; 16- flue gas analyzer 17- high speed camera;18- notebook computer;19- protective wall; 20-adjustable axial swirl burner.

Figure 1

schematic diagram of the experiment system.

1, 2, 4- blower; 3- Roots fan; 5- storage facilities; 6-feeding device; 7- mass flowmeter; 8-valve; 9- ignition device; 10- thermocouple; 11- air compressor; 12- Signal exchanger;13- desktop computer; 14- sampling device; 15- filter unit; 16- flue gas analyzer 17- high speed camera;18- notebook computer;19- protective wall; 20-adjustable axial swirl burner.

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Figure 2

schematic diagram of the adjustable axial swirl burner

1-primary air duct; 2-isolate duct; 3-inner secondary air duct; 4-outer secondary air duct; 5-tertiary air duct; 6- axial movable swirl vanes; 7-combustion stabilizing device; 8-expanding cone shape pre-chamber; 9-location of measuring points.

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Figure 2

schematic diagram of the adjustable axial swirl burner

Figure 3

the vanes of adjustable axial swirler

Figure 3

the vanes of adjustable axial swirler

Figure 3

the vanes of adjustable axial swirler

Figure 4

adjustable axial swirler moveable conditions

Figure 4

adjustable axial swirler moveable conditions

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Figure 5
gas temperature distribution with different S in pre-combustion chamber

Figure 5
gas temperature distribution with different S in pre-combustion chamber

Figure 5

gas temperature distribution with different S in pre-combustion chamber

Figure 6

O_2 concentration distribution with different S in pre-combustion chamber

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O_2 concentration distribution with different S in pre-combustion chamber

Figure 6

O_2 concentration distribution with different S in pre-combustion chamber

Figure 7

CO concentration distribution with different S in pre-combustion chamber

Figure 7

CO concentration distribution with different S in pre-combustion chamber

Figure 7

CO concentration distribution with different S in pre-combustion chamber

Figure 8

flame shape image with different S

Figure 8

flame shape image with different S

Figure 8

flame shape image with different S

(a): Image of pulverized coal flame

(b): Image in grayscale with vertical line to analysis the flame brightness

(c): Graph of the brightness of pixels for different vertical lines

(d): Image (a) converted with selected limit from diagram (c)

Figure 9

flame processing sets and shape scale obtained

(a): Image of pulverized coal flame

(b): Image in grayscale with vertical line to analysis the flame brightness

(c): Graph of the brightness of pixels for different vertical lines

(d): Image (a) converted with selected limit from diagram (c)

Figure 9

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(a): Image of pulverized coal flame

(b): Image in grayscale with vertical line to analysis the flame brightness

(c): Graph of the brightness of pixels for different vertical lines

(d): Image (a) converted with selected limit from diagram (c)

Figure 9

flame processing sets and shape scale obtained

Figure 10

influence and selection of limit ratio

Figure 10

influence and selection of limit ratio

Figure 10

influence and selection of limit ratio

Figure 11

influence of S on ignition and mean maximum temperature

Figure 11

influence of S on ignition and mean maximum temperature

Figure 11

influence of S on ignition and mean maximum temperature

Figure 12

influence of S on mean NOZ boundary and maximum CO concentration

Figure 12

influence of S on mean NOZ boundary and maximum CO concentration

Figure 12

influence of S on mean NOZ boundary and maximum CO concentration

Figure 13

influence of S on wall mean and maximum temperature

Figure 13

influence of S on wall mean and maximum temperature

Figure 13

influence of S on wall mean and maximum temperature

Figure 14

influence of S on mean and maximum flame length

Figure 14

influence of S on mean and maximum flame length

Figure 14

influence of S on mean and maximum flame length

Figure 15

influence of S on mean diameter and divergence angle

Figure 15

influence of S on mean diameter and divergence angle

Figure 15

influence of S on mean diameter and divergence angle