Chinese J. Chem. Eng., **13** (3) 318 – 323 (2005)

Numerical Simulation of NO_x Formation in Coal Combustion with Inlet Natural Gas Burning*

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Abstract A full two-fluid model of reacting gas-particle flows and coal combustion is used to simulate coal combustion with and without inlet natural gas added in the inlet. The simulation results for the case without natural gas burning is in fair agreement with the experimental results reported in references. The simulation results of different natural gas adding positions indicate that the natural gas burning can form lean oxygen combustion enviroment at the combustor inlet region and the NO_x concentration is reduced. The same result can be obtained from chemical equilibrium analysis.

Keywords coal combustion, natural gas, burning, NO_x formation, numerical simulation

1 INTRODUCTION

Coal burners are widely used in the utility boilers of power stations in China. Nowadays it is important to develop low-pollutant burners. Presently, most of studies on reducing pollutant formation are focused on chemical reactions and using the aerodynamics to form fuel rich combustion. As to the chemical method, re-burning is effective way to reduce NO_x formation. It was found that swirl coal combustion with natural gas re-burning added in the combustor side wall can reduce NO_x emission to less 30% of that without re-burning[1,2]. Due to the difficulty of tube arrangement at the side wall, injection of natural gas with the original inlet air tube may be more convenient. On the other hand, inlet natural gas burning may raise combustion temperature in the main combustion zone, and it is harmful to reducing NO_x formation.

In this paper, many inlet natural gas burning cases with different natural gas injecting positions, coal types and flow patterns are simulated by in-house procedure proposed by the authors[3,4]. The simulation results are in satisfactory agreement with experimental results in references. Simulation results indicated that, in general, inlet natural gas burning can form fuel rich combustion atmosphere in the inlet region and can reduce NO_x formation. However, inlet natural gas burning is not suitable for reducing NO_x formation in some cases.

2 THE FULL TWO-FLUID MODEL FOR REACTING GAS-PARTICLE FLOWS AND COAL COMBUSTION

For the comprehensive modeling of reacting gas-particle flows and coal combustion, a full two-fluid model, proposed by Zhou *et al.*[3] is used. The continuity, momentum, energy and turbulent kinetic energy equations for gas and particle phases are derived and solved in Eulerian coordinates. The sub-models are: k-ε-k_p two-phase turbulence model[4], EBU (eddy break up)-Arrhenius combustion model, six-flux radiation model, two-equation model of coal devolatilization, and diffusion-kinetic model of char combustion. The detailed description of this comprehensive model can be found in Ref. [3]. The simplified Solomon HCN release model[5] and AUSM (algebraic unified second order model) turbulence-chemistry model for NO_x formation are incorporated into the comprehensive model[6].

The basic equations of 3-D turbulent two-phase reacting flow and coal combustion can be expressed in the following generalized form.

Gas-phase equations:

$$\frac{\partial}{\partial x}(\rho u\varphi)+\frac{\partial}{r\partial r}(r\rho v\varphi)+\frac{\partial}{r\partial\theta}(\rho w\varphi) = \frac{\partial}{\partial x}(\Gamma_\varphi\frac{\partial\varphi}{\partial x})+\frac{\partial}{r\partial r}\left(r\Gamma_\varphi\frac{\partial\varphi}{\partial r}\right)+\frac{\partial}{r^2\partial\theta}\left(\Gamma_\varphi\frac{\partial\varphi}{\partial\theta}\right)+ S_\varphi+S_{\varphi\mathrm{p}} \qquad (1)$$

Particle-phase equations:

$$\frac{\partial}{\partial x}(\rho_\mathrm{p}u_\mathrm{p}\varphi_\mathrm{p})+\frac{\partial}{r\partial r}(r\rho_\mathrm{p}v_\mathrm{p}\varphi_\mathrm{p})+\frac{\partial}{r\partial\theta}(\rho_\mathrm{p}w_\mathrm{p}\varphi_\mathrm{p}) = \frac{\partial}{\partial x}\left(\Gamma_{\varphi\mathrm{p}}\frac{\partial\varphi_\mathrm{p}}{\partial x}\right)+\frac{\partial}{r\partial r}\left(r\Gamma_{\varphi\mathrm{p}}\frac{\partial\varphi_\mathrm{p}}{\partial r}\right)+ \frac{\partial}{r^2\partial\theta}\left(\Gamma_{\varphi\mathrm{p}}\frac{\partial\varphi_\mathrm{p}}{\partial\theta}\right)+S_{\varphi\mathrm{p}}+S_{\varphi\mathrm{pg}} \qquad (2)$$

Received 2004-07-02, accepted 2004-12-30.
* Supported by the National Natural Science Foundation of China (No. 50376068).
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where φ and φ_p are the generalized dependent variables, S_φ, $S_{\varphi p}$ and $S_{\varphi pg}$ are the source items[3].

The boundary conditions for the gas phase and particle phase are specified as in usual treatment: fully developed flow conditions at the exit; symmetrical conditions at the axis; no-slip condition for the gas velocity at the wall; the wall function approximation is used for near-wall grid nodes. The particle-phase conditions at the wall are: zero normal mean velocity and zero gradients of other variables.

3 EXPANDING COAL COMBUSTION AND NO_x FORMATION

3.1 Experimental section

The trials were conducted in an entrained flow combustion reactor (EFCR) (see Fig. 1). The electrically heated reactor has five regulated heating zones. The carrying air with pulverized coal enters the burner center, surrounded by the primary air and the secondary air. A gravimetric screw conveyor supplies a constant coal-feeding rate. The furnace (ceramic tube) has a length of 2.5 m and an internal diameter of 200 mm[7].

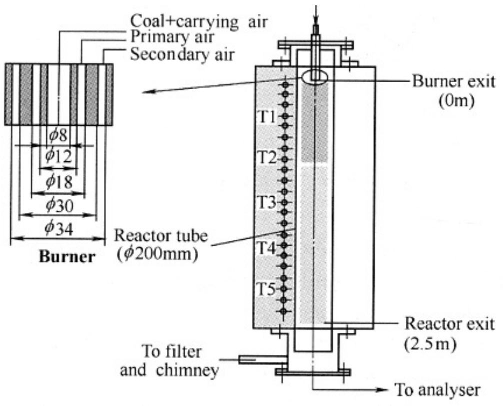


Figure 1 Scheme of the coal combustor[7]

Table 1 gives the parameters of the basic calculation. Table 2 gives the germanic soft coal analysis data. A set of in-house CFD procedure is used to simulate coal combustion and NO_x formation. A non-uniform staggered grids with $50 \times 30 \times 7$ nodes is used. Because the case is axis symmetrical, the number of grid points on the circumferential direction is less compared with the grid points number on other two directions. Running a case on a Pentium-4-(2.0G) PC takes about 4—5 d.

3.2 Results and discussion

Figures 2—4 give the experimental results and simulation results of CO_2, O_2, NO_x concentrations of the basic case. The simulation results are in good agreement with experimental results from Han *et al.*[7], suggesting that the models and procedure used in this paper are reasonable.

Table 1 Parameters of the basic calculation

Parameter	Value
coal mass flow, $kg \cdot h^{-1}$	1.0
wall temperature, ℃	1100
flow rate of coal carrying air, $nm^3 \cdot h^{-1}$	1.5
temperature of coal carrying air, ℃	200
primary air + secondary air, $nm^3 \cdot h^{-1}$	8.0
primary air: secondary air	1:2
temperature of primary air, ℃	250
temperature of secondary air, ℃	350
subgroup diameter of particle, μm	16, 52, 160, 350
%	30, 35, 25, 10
mean diameter , μm	98

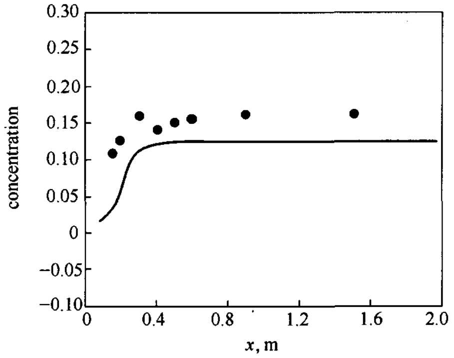


Figure 2 CO_2 concentration along the axial distance in the basic case

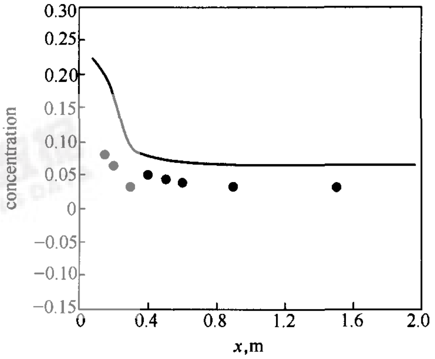


Figure 3 O_2 concentration along the axial distance in the basic case

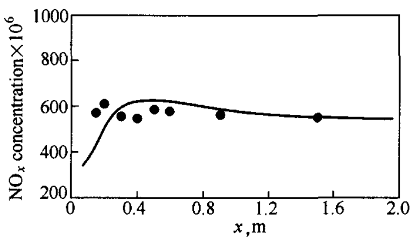


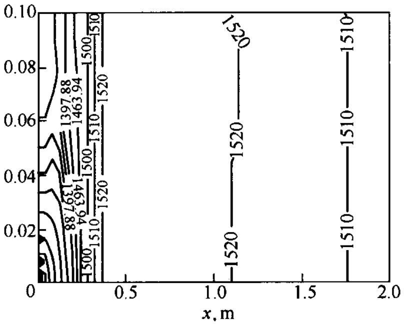
Figure 4 NO_x concentration along the axial distance in the basic case

Table 2 Coal analysis data (%, by mass)

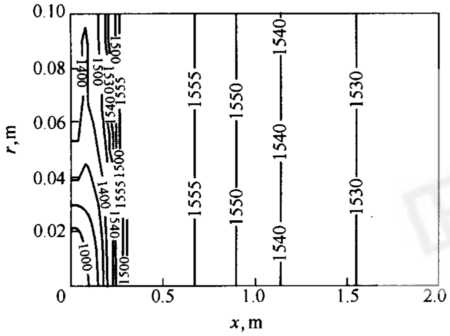
Proximate analysis (raw basis)				Ultimate analysis (raw basis)				
moisture	volatile	ash	fixed carbon	C	H	N	S	O
1.57	30.46	6.67	62.87	78.9	4.86	1.25	0.57	7.61

Cases A—D refer to different ways of inlet burning. Case A: the carrying, primary and secondary airs contain 1% natural gas by mass fraction. Case B: only the carrying air has natural gas. Case C: only the primary air has natural gas. Case D: only secondary air carries natural gas. For all cases the total injected amount of natural gas is equal.

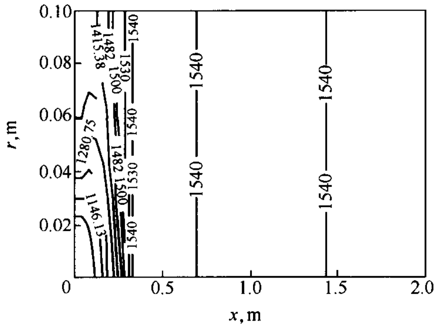
Figure 5 gives the combustion temperature of basic case without burning and other burning cases(in Kelvin). It can be seen that, the zone of high temperature for burning cases moves toward the inlet compared with that of basic case, but there is no large difference of emission gas temperature among these cases.



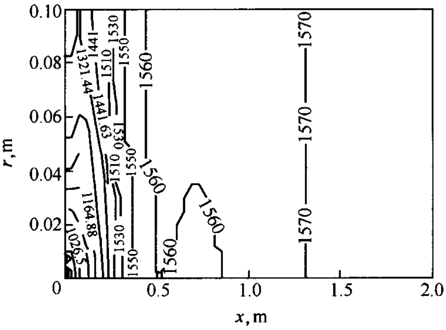
(a) Basic case



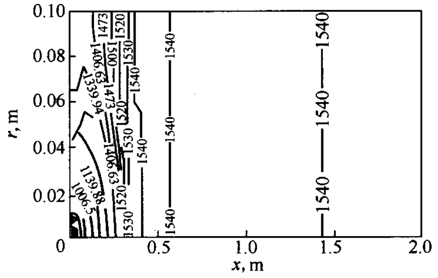
(b) Case A



(c) Case B



(d) Case C

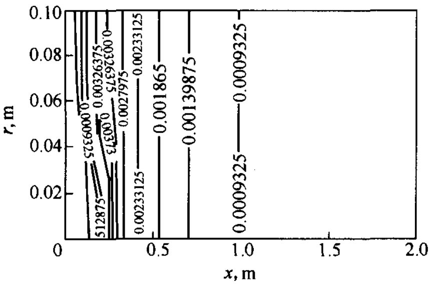


(e) Case D

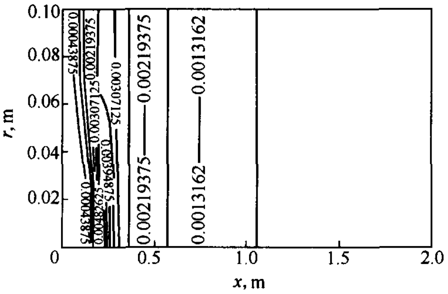
Figure 5 Temperature map

Figure 6 gives the CH_4 concentration maps of different cases. For all inlet burning cases, the inlet CH_4 concentration is higher than that in the case without burning. In the place farther than 0.8 m from the inlet, the CH_4 concentrations of all cases are similar. This means injected CH_4 is burned out in the main combustion zone, the oxygen is consumed and the lean oxygen combustion is formed. Only CH_4 concentration of Case C is relatively high even when $X > 0.8$ m, meaning that the CH_4 is not totally burned out in the main reaction zone for Case C.

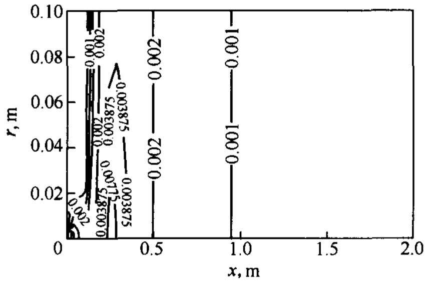
Figure 7 gives the NO_x concentration along the combustor length. The zone of high NO_x concentration for burning cases moves toward the inlet compared with the base case without burning, essentially because the high combustion temperature zone moves back toward the inlet. The highest value of NO_x concentration for burning cases is lower than that in the case without burning, except Case C. In the downstream, the NO_x concentrations of all burning cases are similar, the highest is for Case C while the lowest is for Case B. The NO_x emissions of all burning cases are lower than the base case without burning. This



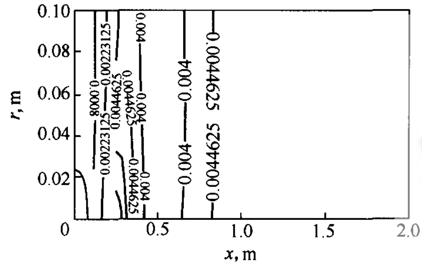
(a) Basic case



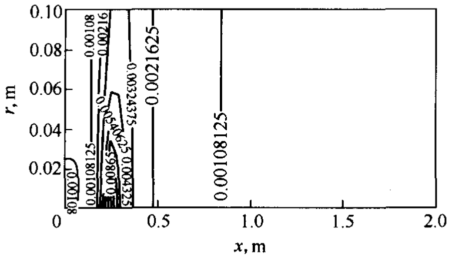
(b) Case A



(c) Case B



(d) Case C



(e) Case D

Figure 6 CH_4 concentration

means inlet natural gas burning can reduce NO_x formation, but subject to the effect of the way of burning gas injection.

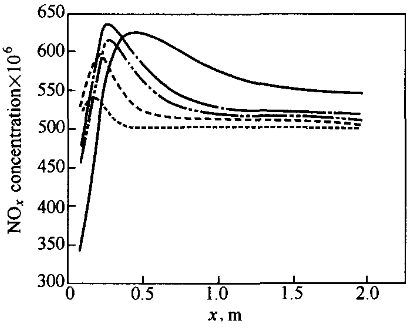


Figure 7 NO_x concentration along the combustor axis for all cases
—— without burning; - - - - burning A; ······ burning B; — · —· burning C; — · ·— burning D

Figure 8 gives the chemical equilibrium analysis result, and there is no difference among all burning cases. It shows that inlet natural gas burning can reduce NO_x formation and emission. The equilibrium NO_x concentration is higher than CFD simulation result, because the real chemical reactions do not reach equilibrium yet.

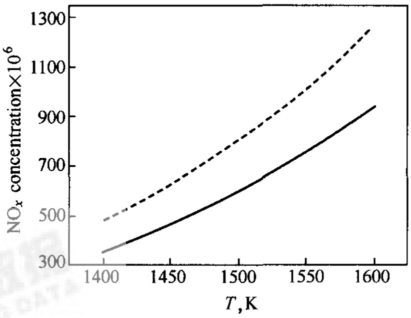


Figure 8 Chemical equilibrium analysis result
—— with burning; - - - - without burning

As to the discussed sudden expanding coal combustor, the height of which is high enough to ensure the main chemical reaction can be finished before the exit. In this situation, inlet natural gas burning can be used to reduce NO_x formation and emission. The way of natural gas injection can be optimized to get lowest NO_x emission.

4 SWIRLING COAL COMBUSTION AND NO_x FORMATION

4.1 Experimental section

Simulation of coal combustion and NO_x formation was carried out on the experiment on combustor in Fig. 9 by Abbas *et al.*[8]. The geometrical sizes and inlet-flow conditions are given in Tables 3 and 4. The coal proximate analysis is given in Table 5.

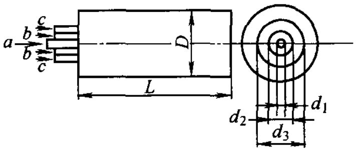


Figure 9 The coal swirl combustor[8]

Table 3 The geometrical dimension of the swirl combustor (m)

D	L	d_1	d_2	d_3
0.6	3.0	0.022	0.035	0.104

Table 4 Inlet-flow parameters of the swirl combustor

	Air flow rate kg·h^{-1}	Coal feeding rate, kg·h^{-1}	Swirl number	Temperature, K
primary air	32.8	14	0	300.0
secondary air	120.4	0	1.0	600.0

Table 5 Proximate analysis of the coal (%)

Volatile	Char	Water	Ash
35.8	53.7	6.3	4.2

The inlet condition is: the pulverized coal is fed through the annular space "*b*", the swirling secondary air is supplied through the annular space "*c*", the ratio of swirling momentum and inflow momentum for second air is 1.0. In order to enhance coal flame stability, a bluff body is located in the central orifice "*a*". The average initial size of the pulverized coal is 45 μm. A non-uniform staggered grids nodes of 55 × 45 × 11 are used. Because the case is axis symmetrical, the number of grid points on the circumferential direction is less compared with the grid points number on other two directions. Running a case in the Pentium-4(1.5G) PC takes about 4—5 d. The prediction results are compared with the experimental results from Ref. [8]. Case E is the basic case without natural gas burning. Case F is the burning case, 4% (by mass) natural gas injected into space "*b*". In the other cases with mass fraction of natural gas injected less than 4% , the NO_x reduction effects are too inconspicuous to be shown in this paper.

4.2 Results and discussion

Figures 10 and 11 give the predicted and measured temperature profiles, NO_x concentration profiles in the base case E, showing a good agreement between predictions and experiments. Figure 12 shows the O_2 profiles on the inlet for Case F, in which natural gas burning reduces obviously the O_2 concentration in the main combustion zone. Figure 13 shows the profiles of CH_4 concentration on the inlet, indicating that, CH_4 concentration of Case F is higher than what of Case E. Fig. 14 shows the NO_x concentration map of two cases, showing that, the NO_x concentrations at the outlet of two cases are quite different, suggesting that the chemical reactions continue even at the exit. The inlet burning can reduce NO_x emission but not such obviously as in Cases B—D above.

As to the swirling coal combustor, because of the coal type, combustor structure and flow pattern, the chemical reactions are not finished at exit totally enough. Although inlet natural gas rebuning can form fuel rich combustion, the overall effect of inlet natural gas burning to reduce NO_x formation is not remarkable.

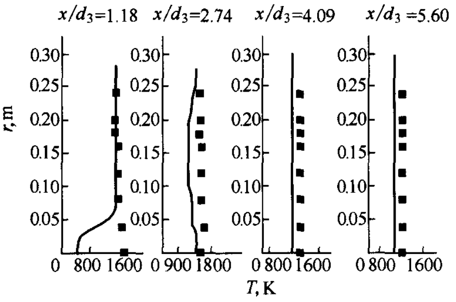


Figure 10 Temperature profiles in the base case E
—— Pred.; ■ Exp. Case E

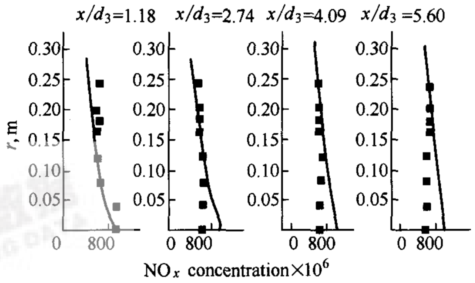


Figure 11 NO_x concentration profiles in the base case E
—— Pred.; ■ Exp. Case E

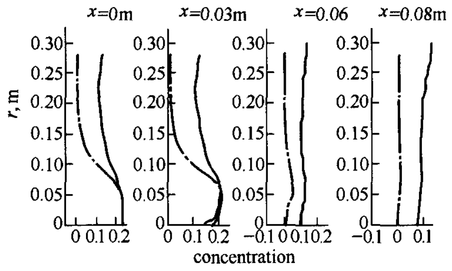


Figure 12 O_2 concentration profiles in Case F

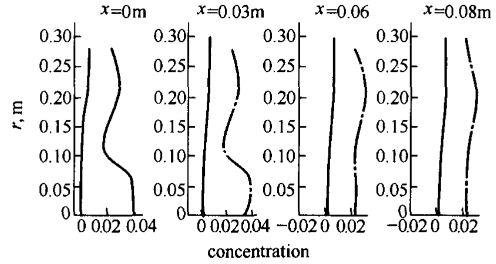
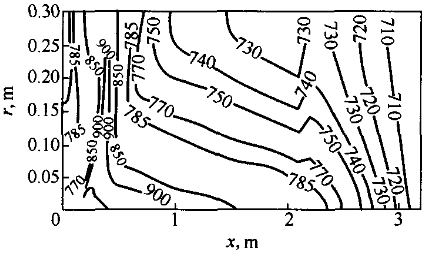
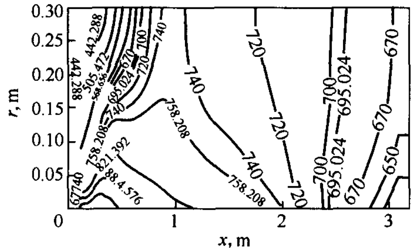


Figure 13 CH$_4$ concentration profiles in Case F



(a) Case E



(b) Case F

Figure 14 NO$_x$ concentration map

5 CONCLUSIONS

(1) Inlet natural gas burning can form a fuel rich combustion region in the main combustion zone.

(2) Inlet natural gas burning makes both the high combustion temperature zone and high NO$_x$ concentration zone move towards the inlet, but reduces the highest NO$_x$ concentration value in the combustor and NO$_x$ emission at the exit.

(3) For the cases in which chemical reactions are completed before exiting, the inlet natural gas burning can reduce NO$_x$ formation and emission remarkably. When chemical reactions are not be completed before the exit, the effect of inlet natural gas burning on NO$_x$ emission reduction is comparatively weak.

(4) Inlet natural gas injection position should be optimized to get lowest NO$_x$ emission.

NOMENCLATURE

k	turbulent kinetic energy, $m^2 \cdot s^{-2}$
R	universal gas constant
$S_\varphi, S_{\varphi p}, S_{\varphi pg}$	the source items
T	gas temperature, K
u, v, w	velocity components, $m \cdot s^{-1}$
$\overline{W}_s$	mean reaction rate, $kg \cdot s^{-1}$
Y_i	mass fraction
$\overline{Y}$	mean mass fraction
ε	TKE dissipation rate, $m^2 \cdot s^{-3}$
ρ	density, $kg \cdot m^{-3}$
φ, φ_p	the generalized dependent variables

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