Effect of O_2/CO_2 ratio on fuel-NOx formation in oxy-coal combustion

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(1) Aim of Oxy-coal combustion

(2) Experiment (NOx data)

(3) Analysis of NOx in oxy-coal combustion

(4) Clarification of formation mechanism of Fuel-NOx

Motivation : Oxy-fuel combustion

CO_2 released by combustion of coal： 1800 ~ 2410 g/kg-coal

- ·High heat value
- ·Abundant reserves
- ·Distributed throughout the world

→ **Call for new combustion methods that help reduce the environmental load**

There has been a steady increase in global environmental problems, the most serious of which is global warming caused by CO_2 emissions

↓

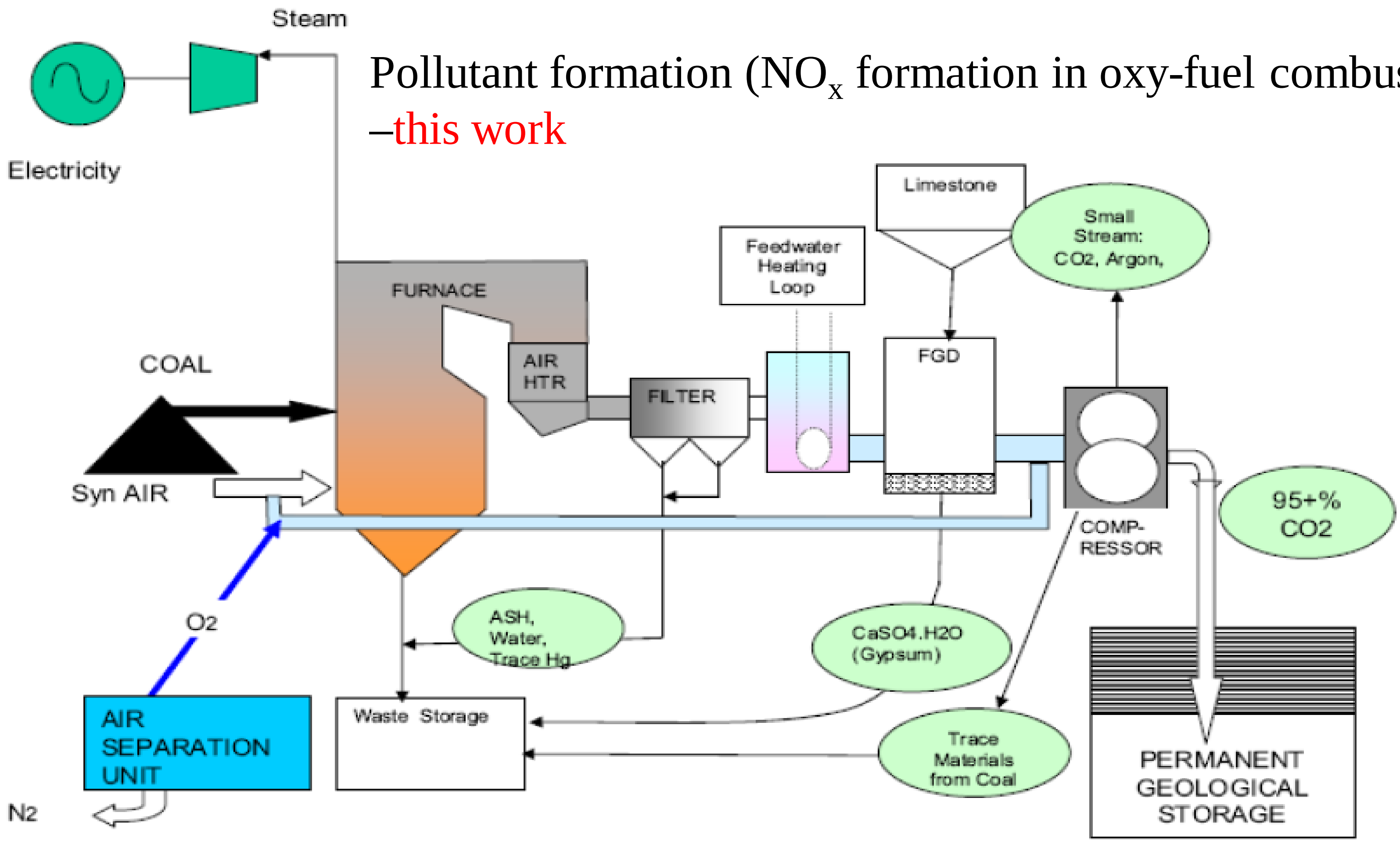
Efficient use of energy resources and development of methods for generating CO_2-emission-free energy

→

- IGCC
- Carbon capture and sequestration

Oxycoal combustion: near-term application to efficient conventional boilers. (Stobbs. 2007)

Pollutant formation (NO_x formation in oxy-fuel combustion)
–this work



SaskPower Oxyfuel Process

Ref. Jost O.L.Wendt, Presented at 2007 AIChE Annual Meeting, (2007)

Conventional research related to pure oxygen-pulverized coal combustion

<u>References in the past (recirculated exhaust gas stream)</u>

(i) Effect of O_2 concentration on the CO_2/O_2 flame stability

(ii) Characteristics of SO_x emission during combustion in a recirculated CO_2 stream

(iii) Numerical simulations of NO_x formation

(iv) combustion characteristics of the pulverized coal burner that injects pure O_2 as well as the flow structure in the burner

(v) Combustion characteristics of gaseous fuels (such as CH_4, C_3H_8) in a pure O_2 atmosphere

Very few experimental studies have been conducted on fuel-NOx formation during environment **<u>with a high O_2/CO_2 ratio</u>**. The mechanism of fuel-NOx formation in oxy-coal combustion with a high O_2/CO_2 ratio remains unexplained.

Aim of Research

Under Oxy-coal combustion

i. Effect of O_2 /CO_2 ratio on fuel-NO_x emission **(21–40 vol%)**

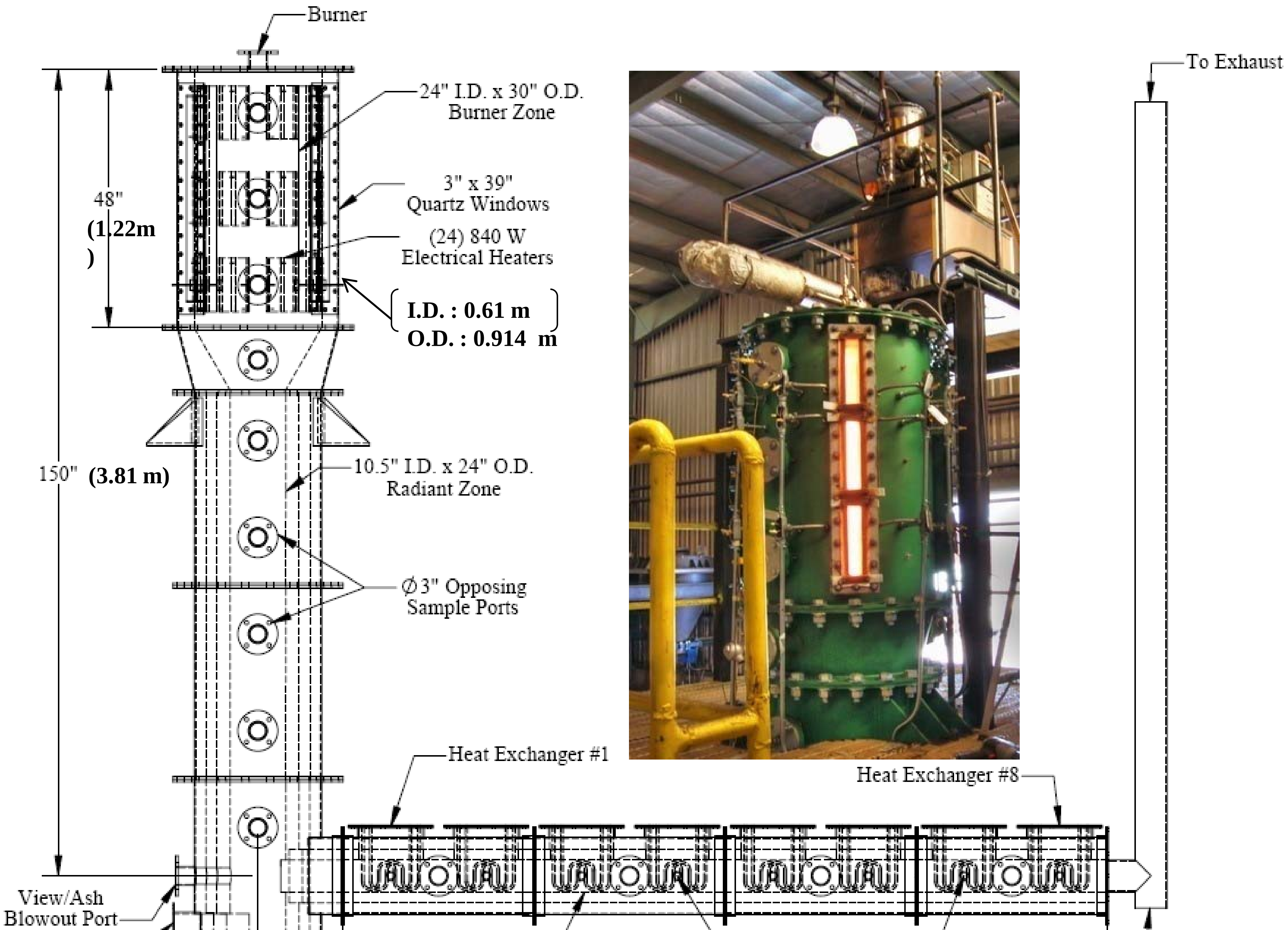
ii. Effect of flame temperature on fuel-NO_x emission

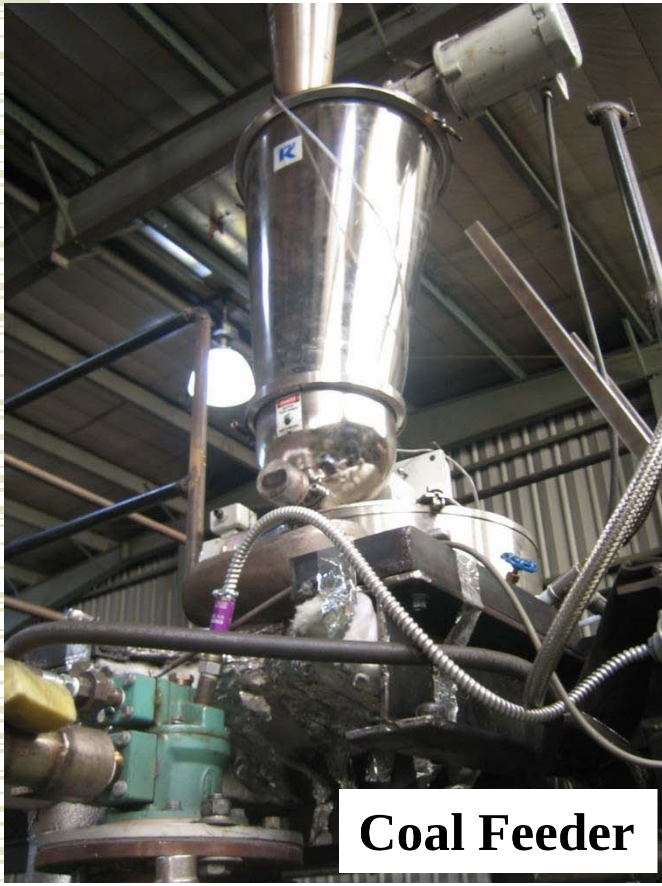
iii. Extract the solid–gas reaction

Mechanism of NO_x formation

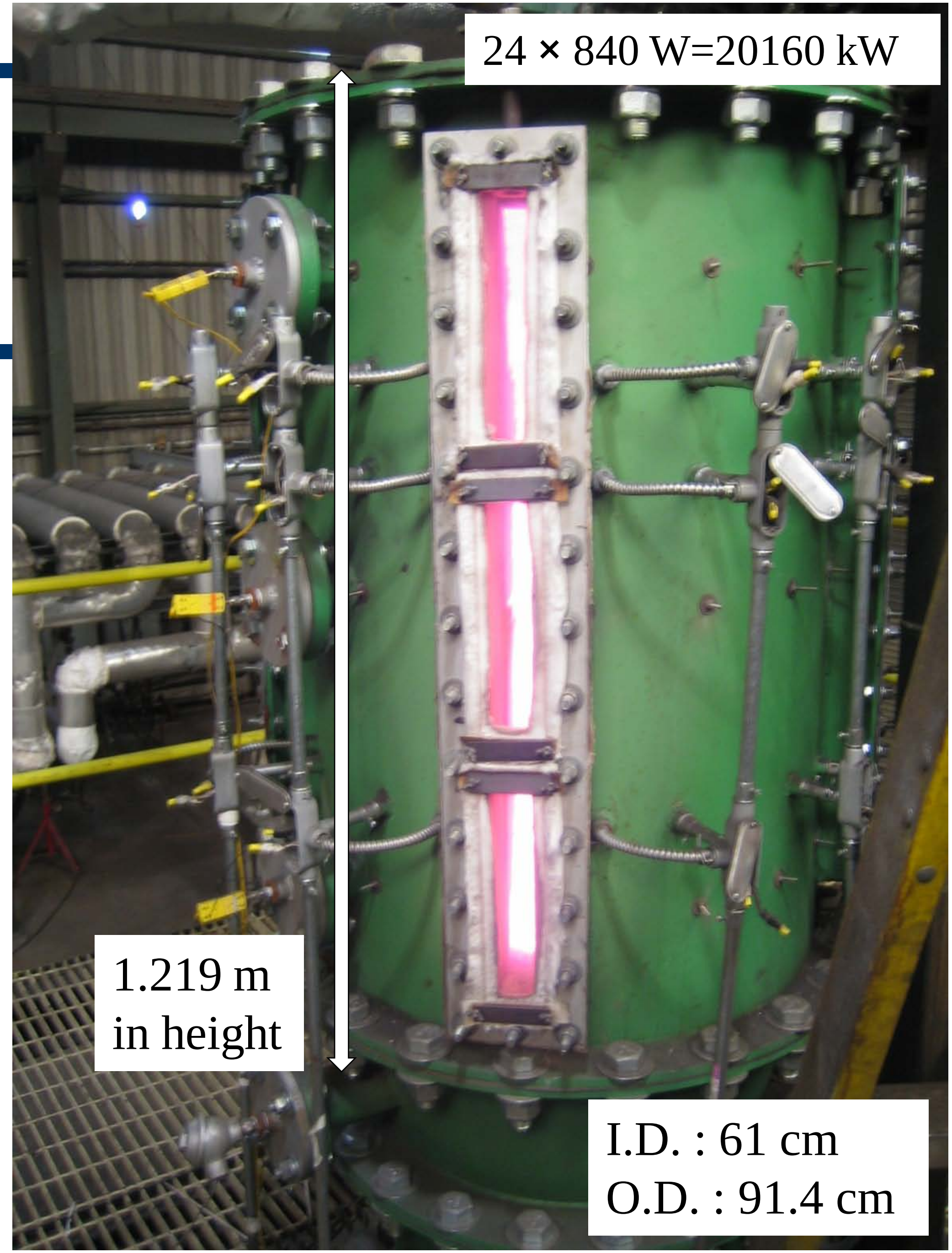
in oxy-coal combustion

Experimental setup

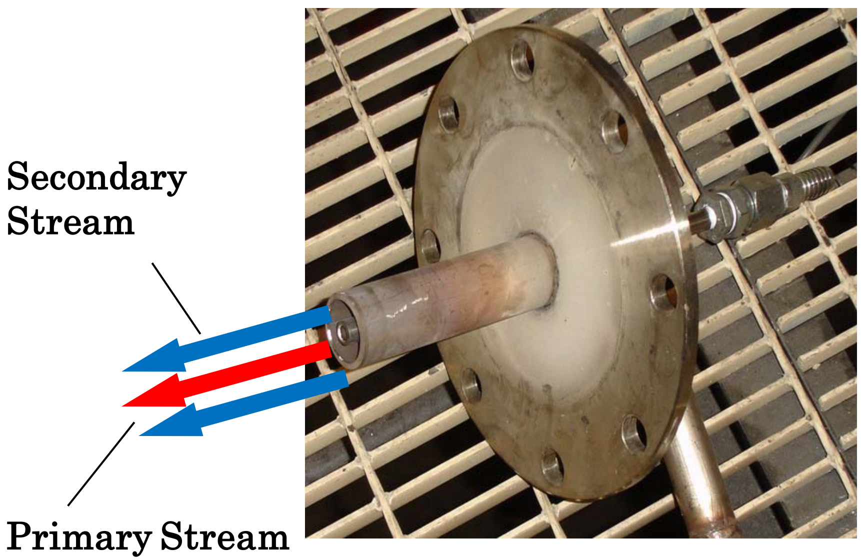



Coal Feeder


4.54 kg/h (1.26 g/s)


24 × 840 W=20160 kW
1.219 m
in height
I.D. : 61 cm
O.D. : 91.4 cm

Photograph of burner



Inner diameter of primary nozzle: 18mm,(thickness=2.0 mm)
Inner diameter of secondary nozzle: 42.2mm, (thickness =3.6mm)

We examined the once-through process of CO_2/O_2 combustion because it does not involve a swirl process and is suitable for determining the effect of various factors.

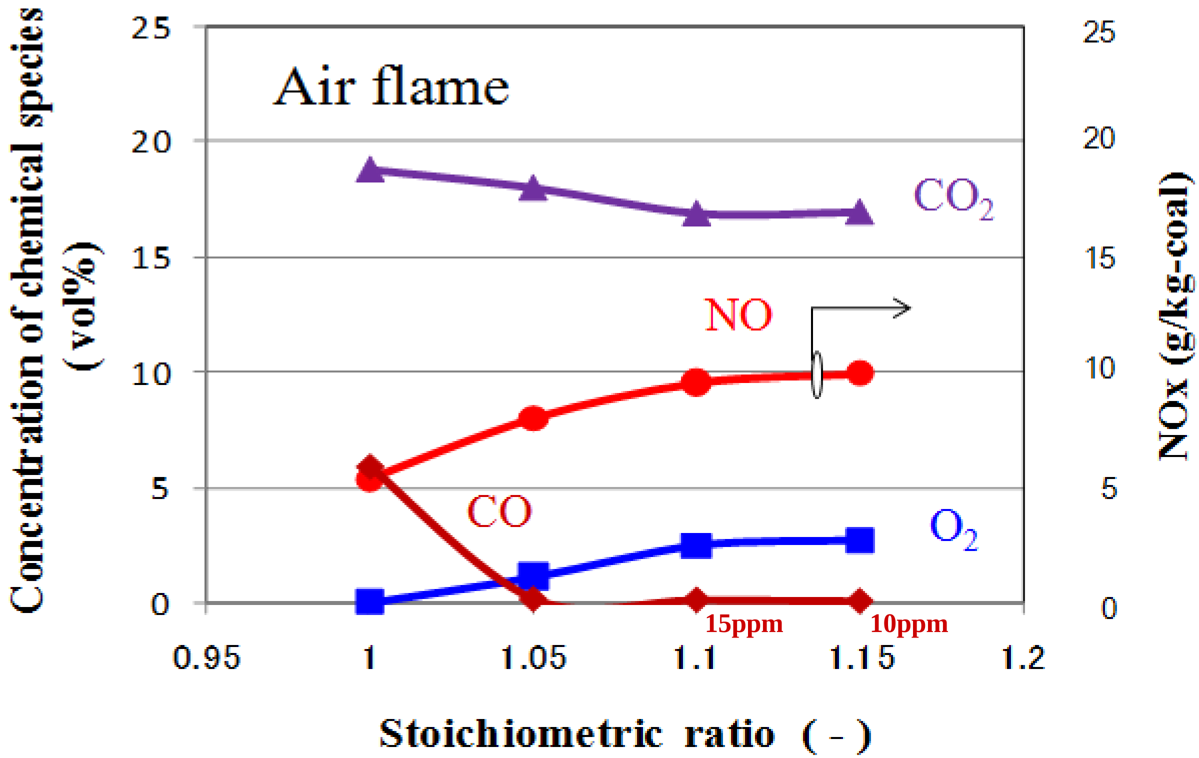
Coal Analysis and experimental condition

Proximate Analysis (wt%)	
Volatile Matter	38.81%
Fixed Carbon	46.44%
Ash	11.72%
Moisture	3.03%

Utah Coal		
	Ultimate Analysis (wt%)	Ultimate Analysis (wt%, daf)
C	66.28	77.75
H	4.29	5.03
N	1.23	1.44
S	0.38	0.45
O	13.07	15.33
Ash	11.72	0.00
Moist.	3.03	0.00

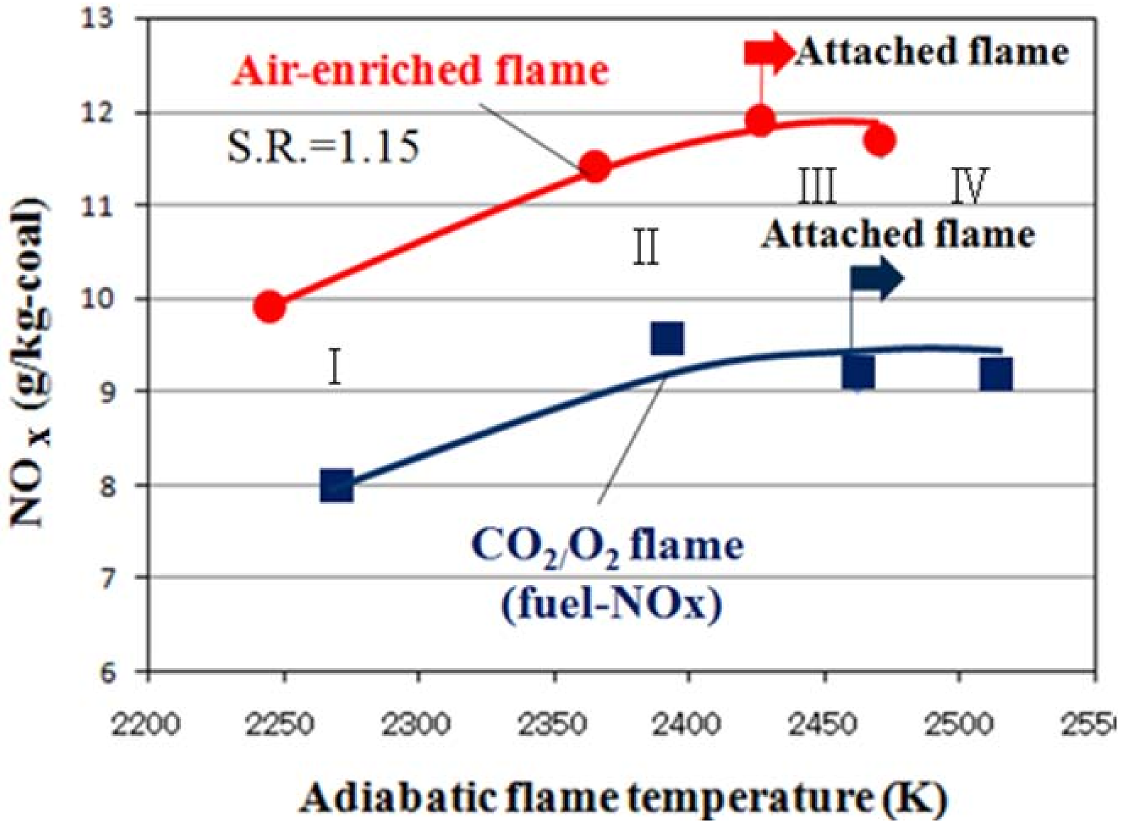
Type of flame		Experimental case			
		I	II	III	IV
CO_2/O_2 flame	Overall O_2 (vol%)	31.2	35.2	37.9	40.1
	Adiabatic temp. (K)	2270	2390	2460	2510
Air-enriched flame	Overall O_2 (vol%)	20.8	23.5	25.2	26.6
	Adiabatic temp. (K)	2240	2360	2430	2470

Experimental result



When S.R. is close to 1.15, completion of combustion can be confirmed.

Comparison of NOx level under O_2/N_2 and O_2/CO_2 environments



(Owing to no thermal NO_x formation,) NO_x emission level in the oxycoal condition is lesser than that formed in the air-enriched condition.

Detached flame

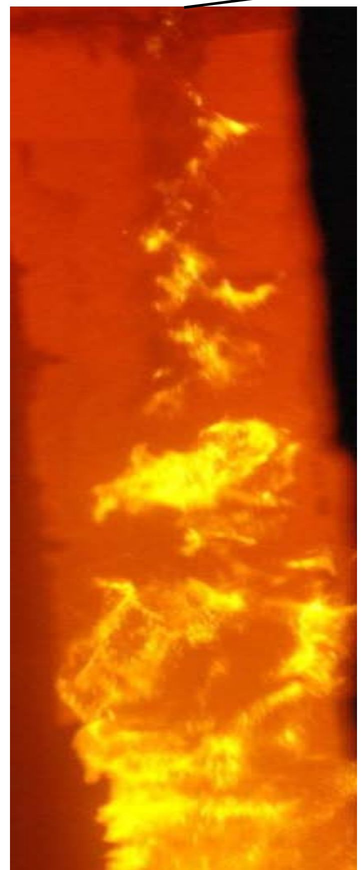
Below T = 2430 K

Mixing distance between coal and oxidant

Ignition

Attached flame

Above 2430 K

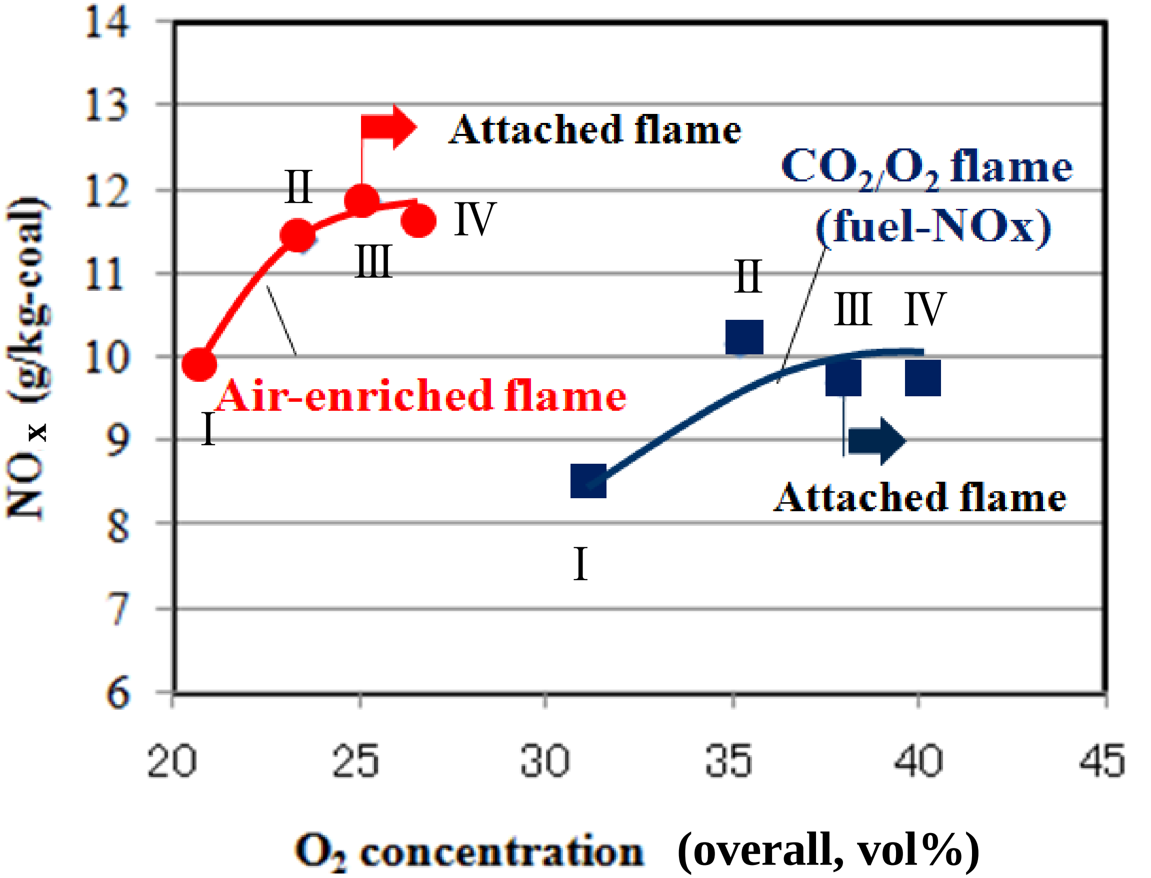


magnification

1/4000 sec exposure
Pentax (Pentax K200D)
single lens reflection

Flame temperature

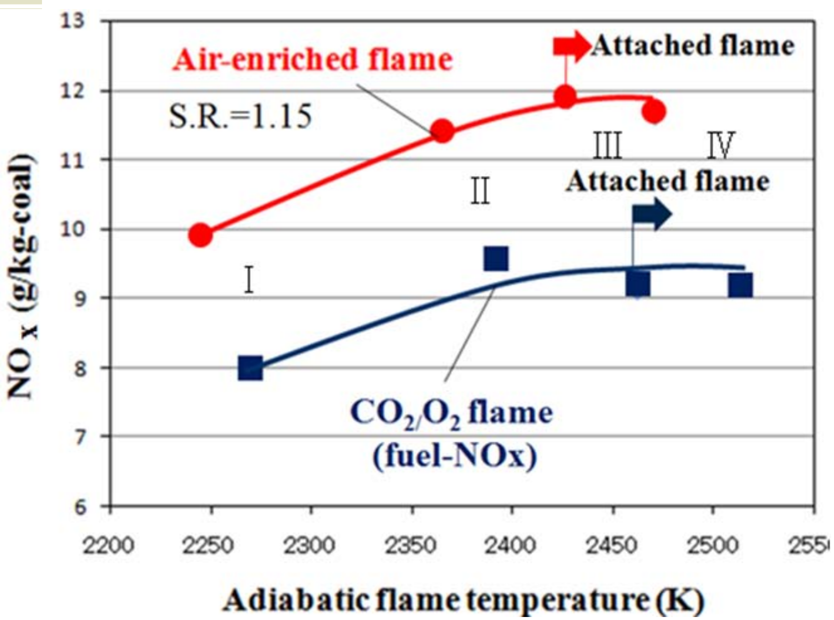
Effect of initial O_2 concentration



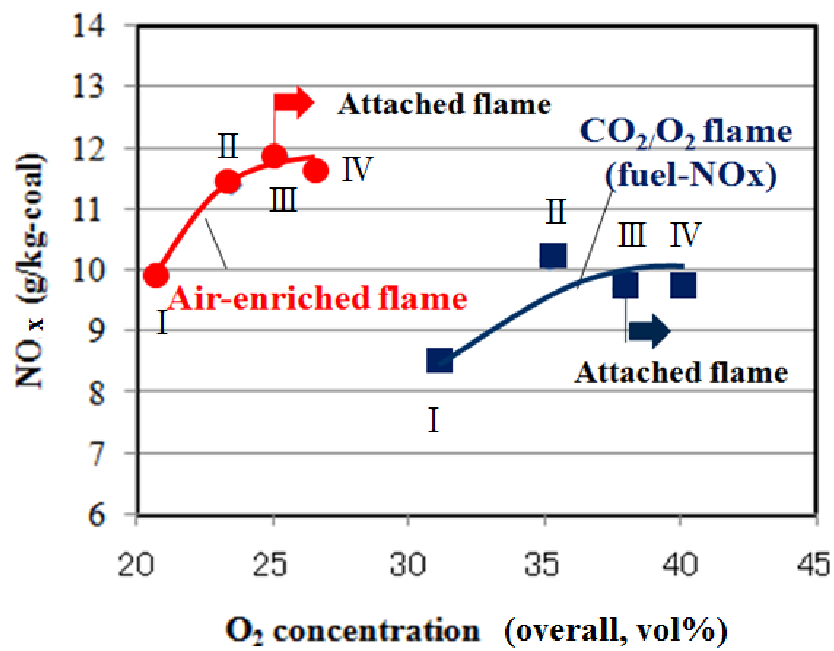
The emission level of NO_x increases with the initial O_2 concentration.

Which is dominant, the effect of flame temp. or the effect of O_2 conc. on NO_x formation in oxy-coal combustion?

Effect of flame temperature



Effect of O_2 concentration



Discussion point

The fuel NO_x formation behavior around a coal particle is theoretically analyzed.

discussion

i. Extract the **solid–gas reaction**

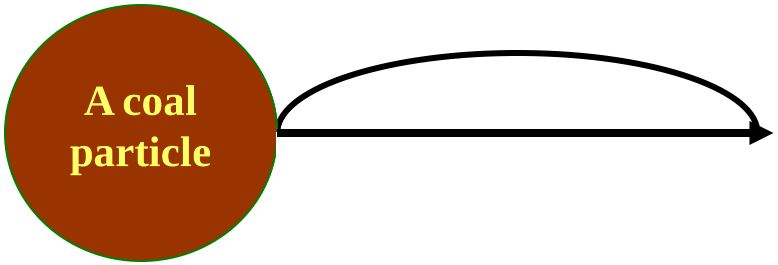
ii. Effect of **flame temperature** on fuel-NOx level

iii. Effect of **O_2 concentration** on the fuel-NOx level

Separate

Modeling

Fuel NOx formation behavior around a coal particle was analyzed.



Assumption

(1) **A coal particle is spherical and all phenomena considered are spherically symmetric.**

(2) Methane (CH_4), HCN, NH_3, and N_2 are considered to be evolved volatile matter.

(3) Fixed carbon is oxidized on the particle surface by CO_2 and O_2 (i.e., includes the solid-gas phase reaction).

(4) Particle diameter is constant during volatile matter combustion.

(5) Radical velocity is calculated from the evoluting flux of volatile matter and combustion products; then the momentum conservation equation is excluded.

(6) Gas and particle temperatures are the same and constant at the given value; then the energy conservation equation is excluded.

Basic Equation

- Continuity equation $$\frac{\partial}{\partial r}\left(r^2 \upsilon_r\right) = 0$$
- Chemical species conservation equation $$\frac{\partial Y_k}{\partial t} + \upsilon_r \frac{\partial Y_k}{\partial r} = D_k \left\{ \frac{1}{r^2} \cdot \frac{\partial}{\partial r}\left(r^2 \frac{\partial Y_k}{\partial r} \right) \right\} + \frac{1}{\rho_k} \sum_{j=1}^{n} \xi_{kj} M_k \omega_k$$
- Mass conservation Equation $$-\frac{\partial}{\partial t}\left(\frac{4}{3} \pi r_p^3 \rho_{char} \right) = \sum_{m=1}^{n} \xi_{mj} \omega_m \cdot 4\pi r_p^2$$

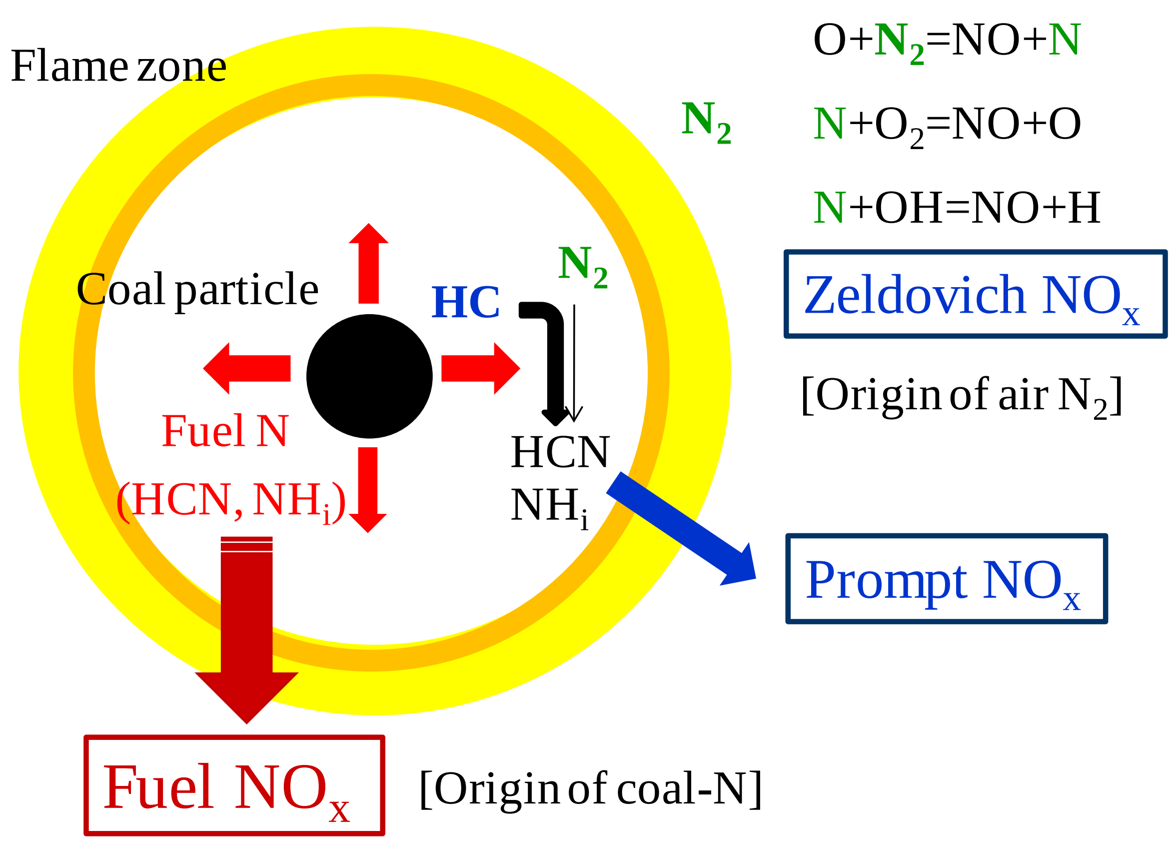
r :radius υ_r : radius velocity Y : mass fraction ∂r : discrete value of radius

D : Diffusion coefficient ∂t : discrete value of time ρ : density

ξ_{kj} : coefficient of chemical equivalent M : molecular weight ω : surface reaction

ξ_{mj} : ratio of mass equivalent k m

Outline of formation of NOx in air



Elementary reaction with N-species (38)

Element：C，O，H，N

Chemical species：O OH CHO HO_2 CH_2 CH_3 CH_4 O_2 H_2 CH_2O H_2O CO_2 H CO

(25) N_2 HCN NH_3 N CN HN NH_2 NCO NO N_2O NO_2

	Reaction with N-species		
1	$O+N_2=NO+N$	20	$CN+H_2=HCN+H$
2	$N+O_2=NO+O$	21	$HCN+O=CN+OH$
3	$N+OH=NO+H$	22	$HCN+OH=NCO+H_2$
4	$NH_3+OH=NH_2+H_2O$	23	$HCN+O=NCO+H$
5	$NH_3+H=NH_2+H_2$	24	$CN+CO_2=NCO+CO$
6	$NH_3+O=NH_2+OH$	25	$CN+O_2=NCO+O$
7	$NH_2+OH=NH+H_2O$	26	$CN+OH=NCO+H$
8	$NH_2+H=NH+H_2$	27	$NCO+H=NH+CO$
9	$NH_2+O=NH+OH$	28	$HCO+NH_2=HCN+H_2O$
10	$NH+OH=N+H_2O$	29	$NCO+NO=N_2O+CO$
11	$NH+H=N+H_2$	30	$NO_2+M=NO+O+M$
12	$NH+O=N+OH$	31	$NO_2+O=NO+O_2$
13	$NH_2+NH_2=NH_3+NH$	32	$2\,NO+O_2=NO_2+NO_2$
14	$NH+OH=NO+H_2$	33	$NO_2+H=NO+OH$
15	$NH+O=NO+H$	34	$NO+HO_2=NO_2+OH$
16	$NH+O_2=NO+OH$	35	$N_2O+H=N_2+OH$
17	$NH_2+NO=N_2+H_2O$	36	$N_2O+O=NO+NO$
18	$NH+NO=N_2+OH$	37	$N_2O+O=N_2+O_2$
19	$NH+NO=N_2O+H$	38	$N_2O+M=N_2+O+M$

Elementary reaction

NO formation from HCN

$CN+H_2 = HCN+H$ … (R1)

$HCN+O = CN+OH$ … (R2)

$HCN+OH = NCO+H_2$… (R3)

$HCN+O = NCO+H$ … (R4)

$CN+CO_2 = NCO+CO$ … (R5)

$CN+O_2 = NCO+O$ … (R6)

$CN+OH = NCO+H$ … (R7)

$NCO+H = NH+CO$ … (R8)

$HCO+NH_2 = HCN+H_2O$…(R9)

$NCO+NO = N_2O+CO$ … (R10)

NO formation from NH_3

$NH_3+OH = NH_2+H_2O$ … (R11)

$NH_3+H = NH_2+H_2$ … (R12)

$NH_3+O = NH_2+OH$ … (R13)

$NH_2+OH = NH+H_2O$ … (R14)

$NH_2+H = NH+H_2$ … (R15)

$NH_2+O = NH+OH$ … (R16)

$NH+OH = N+H_2O$ … (R17)

$NH+H = N+H_2$ … (R18)

$NH+OH = NO+H_2$ … (R21)

$NH+O = NO+H$ … (R22)

$NH+O_2 = NO+OH$ … (R23)

$NH_2+NO = N_2+H_2O$ … (R24)

$NH+NO = N_2+OH$ … (R25)

$NH+NO = N_2O+H$ … (R26)

Calculation condition:

- Gas temperature = Adiabatic temp. – 200K (heat loss)

[2

- Coal diameter: 200mesh-under [70 μm]

- Combustion space of a coal particle: determined by the flow rate and coal feeding rate etc.

$$d\max = \left(60 \cdot Ga \cdot d_p^{\ 3} \cdot \rho \Big/ \left(G \cdot \rho_a\right)\right)^{1/3}$$

- Coal property • Utah coal

Proximate Analysis (wt %)	
Volatile Matter	38.81%
Fixed Carbon	46.44%
Ash	11.72%
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Utah Coal		
	Ultimate Analysis (wt%)	Ultimate Analysis (wt%, daf)
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Pyrolysis products from fuel-N

We assume that component of nitrogen in raw coal (N: 1.44 wt%, daf) is combined as HCN and NH_3. The 31wt % of fuel-N is evolved as HCN, and the 6.0 wt% of fuel-N is evolved as NH_3 according to next equation, and the balance (i.e., others) of fuel-N is evolved as N_2. The volatile mass-loss history during devolatilization of coal will be modeled by following single reaction rate model:

$$\frac{dV}{dt} = \left(V_* - V\right) \; k_0 \exp\left(\frac{-E}{RT}\right)$$

V : mass of volatile matter kg   E : activation energy J/mol
R : gas constant J/mol K   T : temperature
k_o : constant of the single reaction-rate model 1/s , Abbriviation * : raw coal

Discussion point

The fuel NO_x formation behavior around a coal particle is theoretically analyzed.

discussion

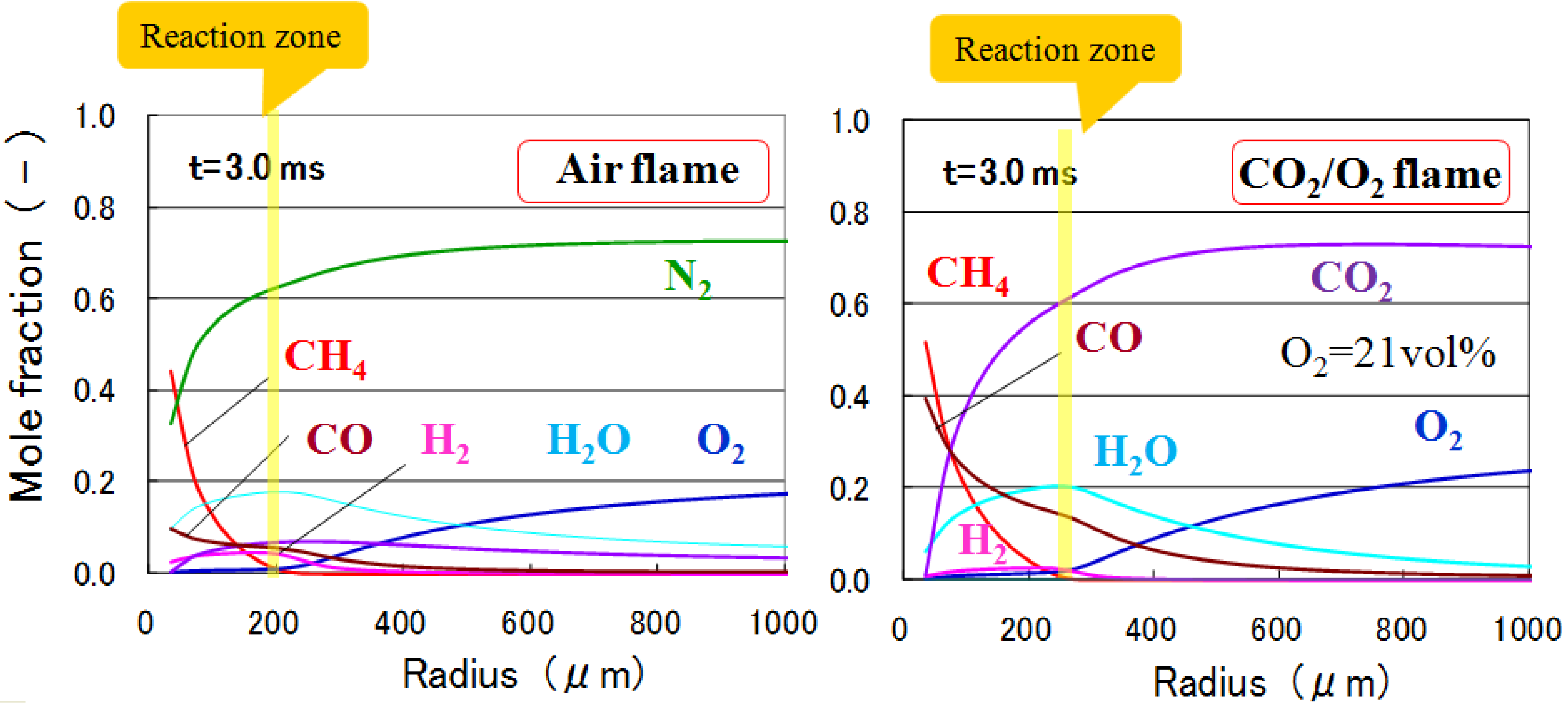
i. Extract the **solid–gas reaction**
ii. Effect of **flame temperature** on fuel-NOx level
iii. Effect of **O_2 concentration** on the fuel-NOx level

Separate

Calculation result

Comparison between air-flame and CO_2/O_2 flame

(ref) T=2000[K] Particle diameter = 70[μm]

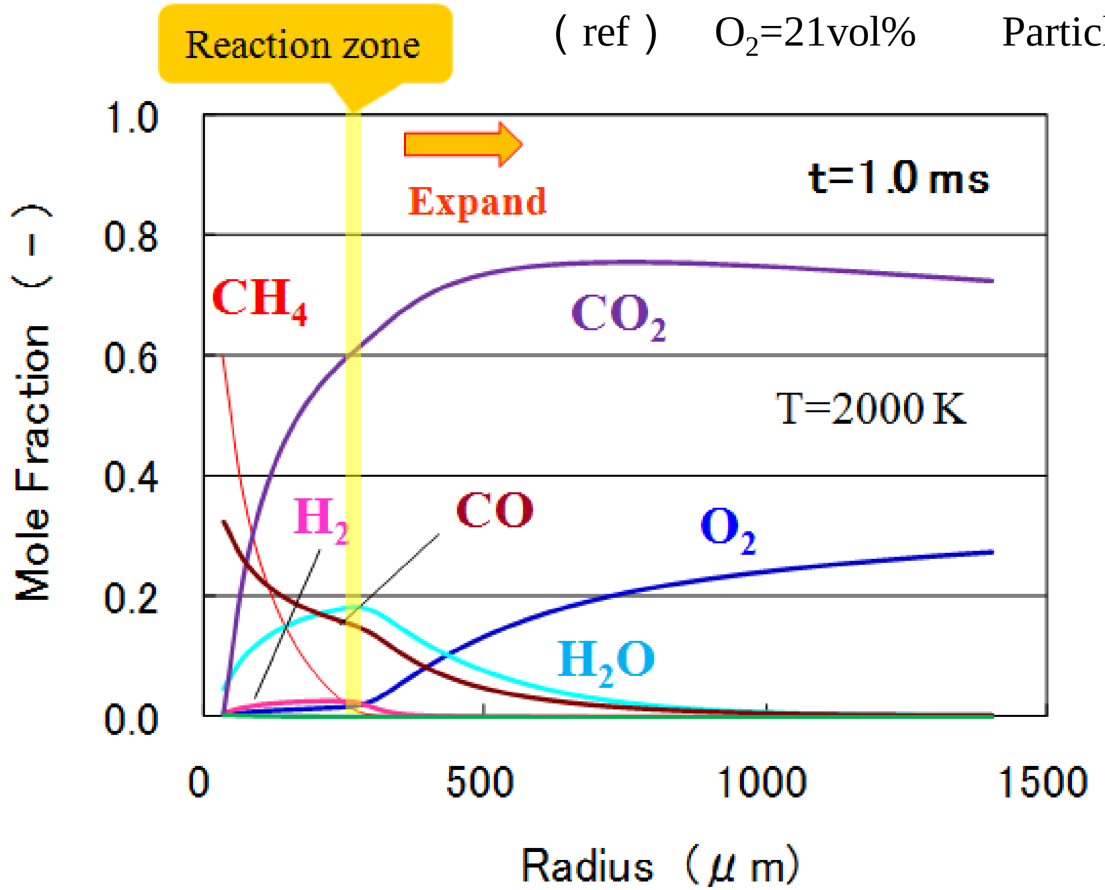


In the case of the CO_2/O_2 flame, <u>the gasification reaction between solid carbon and CO_2 is more vigorous</u> than in the case of the air flame.

Calculation result（CO_2/O_2 flame）

Concentration profiles around a coal particle

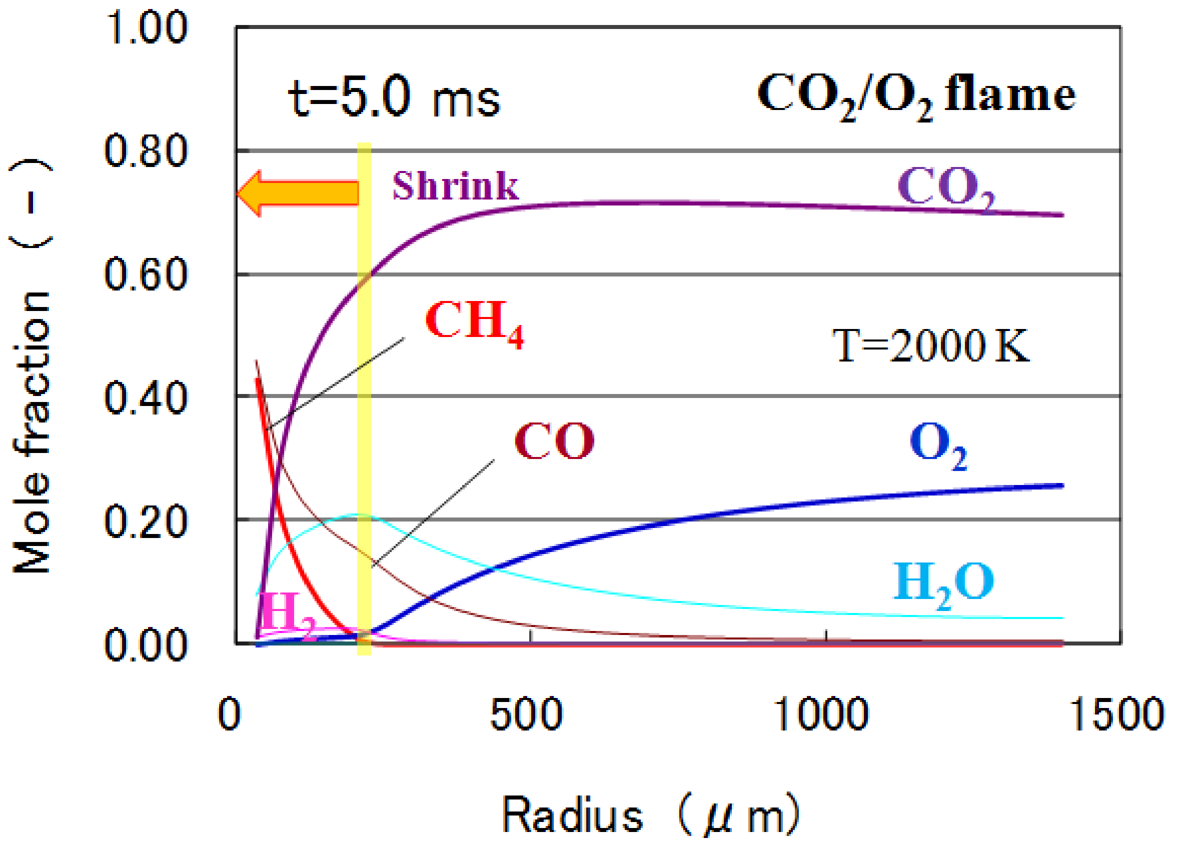
（ref） O_2=21vol%　Particle diameter = 70[μm]



The flame zone extends to 300 μm from a coal surface.

Concentration profiles around a coal particle

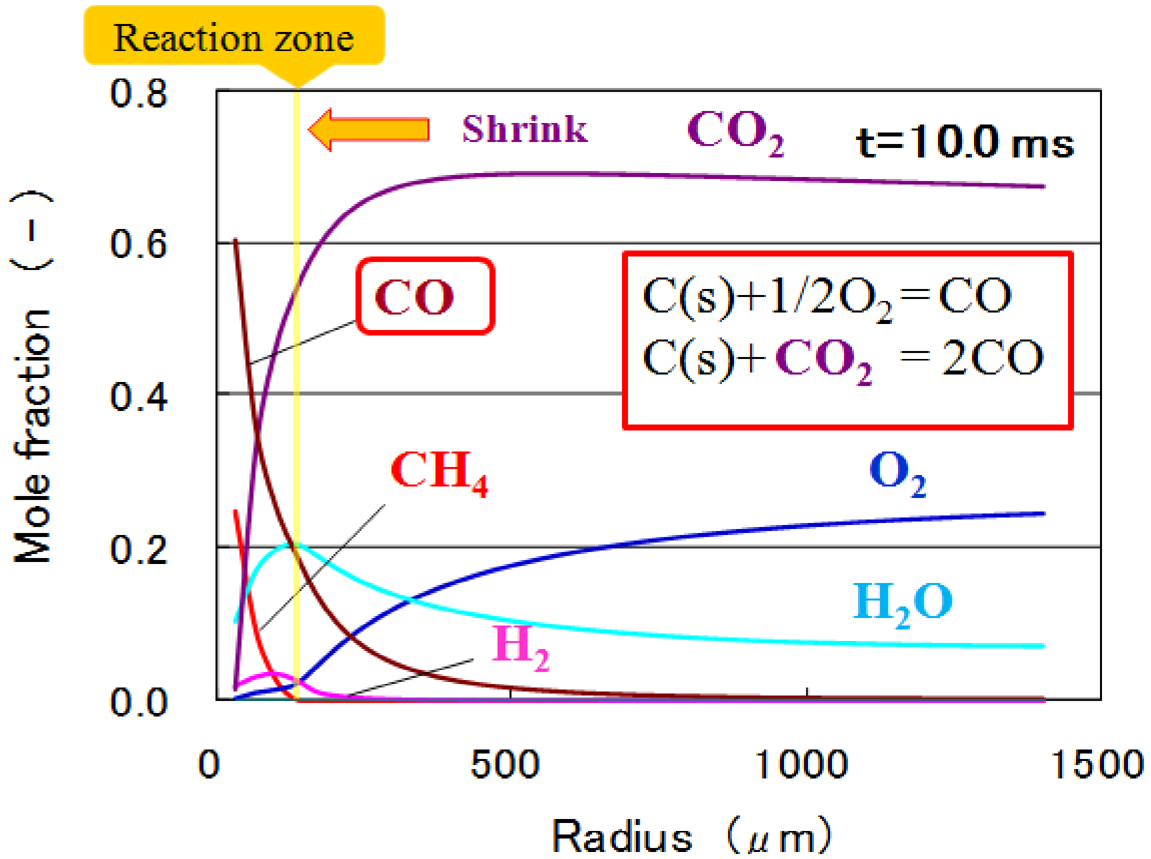
(ref)　O_2=21vol%　　Particle diameter = 70[μm]



At t =5.0ms, the flame zone shrinks to the particle surface.

Concentration profiles around a coal particle

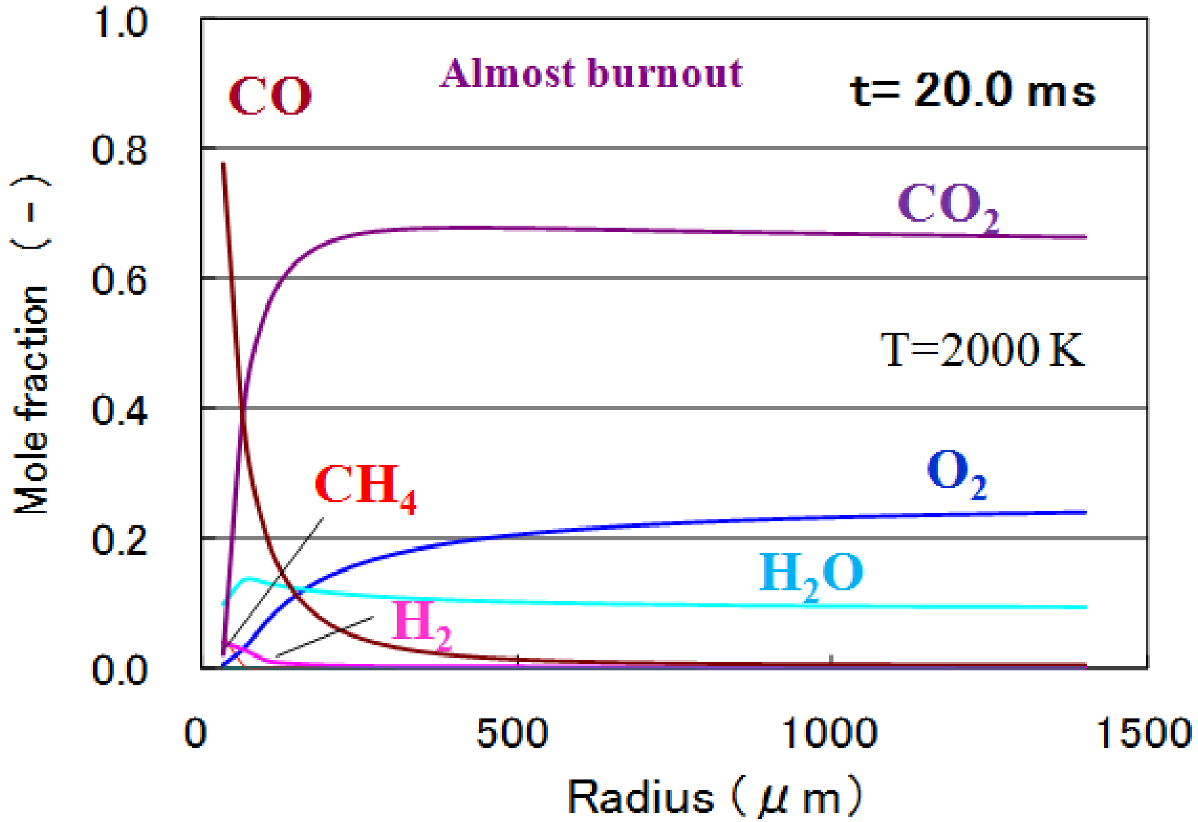
（ref） O_2=21vol% Particle diameter = 70[μm]



Volatile Comb. → Solid surface Comb.

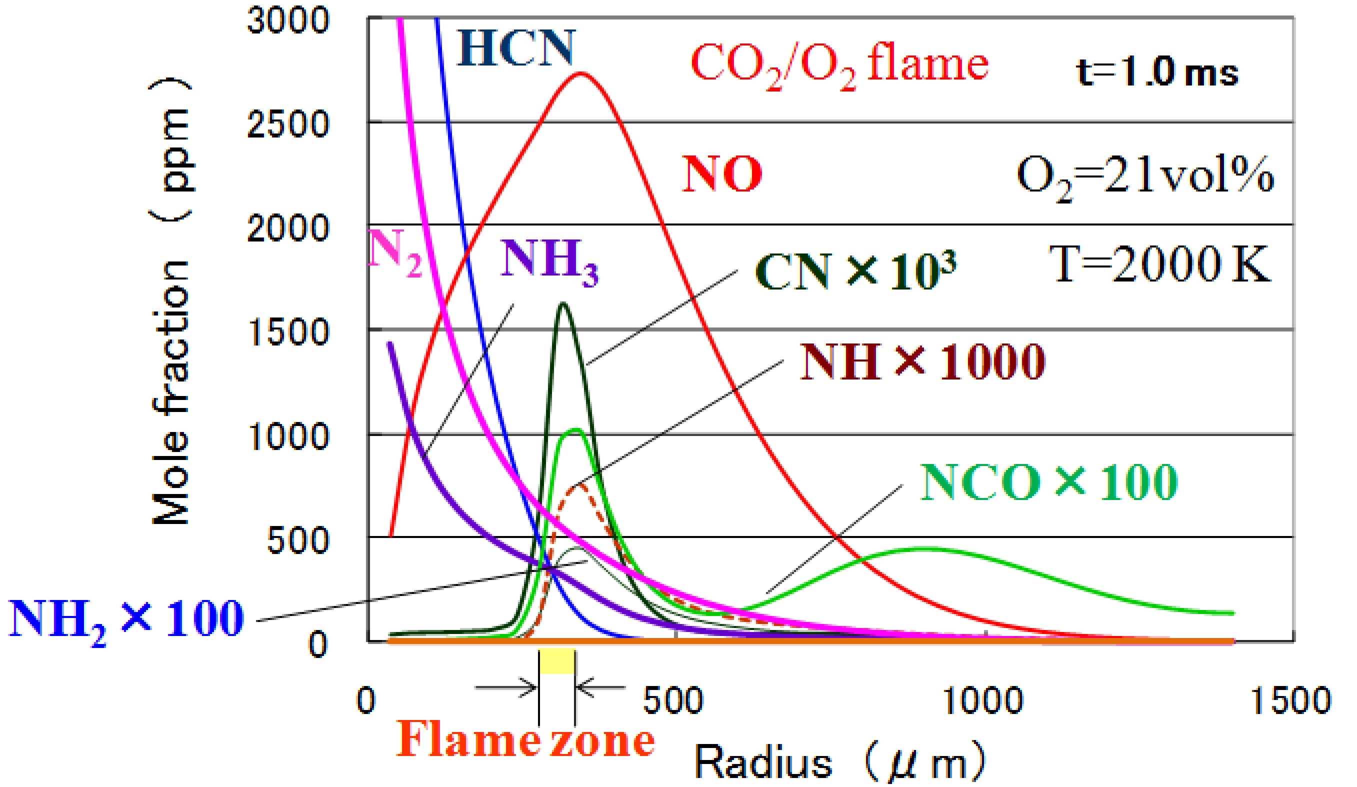
Concentration profiles around a coal particle

(ref) O_2=21vol% Particle diameter = 70[μm]



CO is formed and burned slowly by the surface reaction.

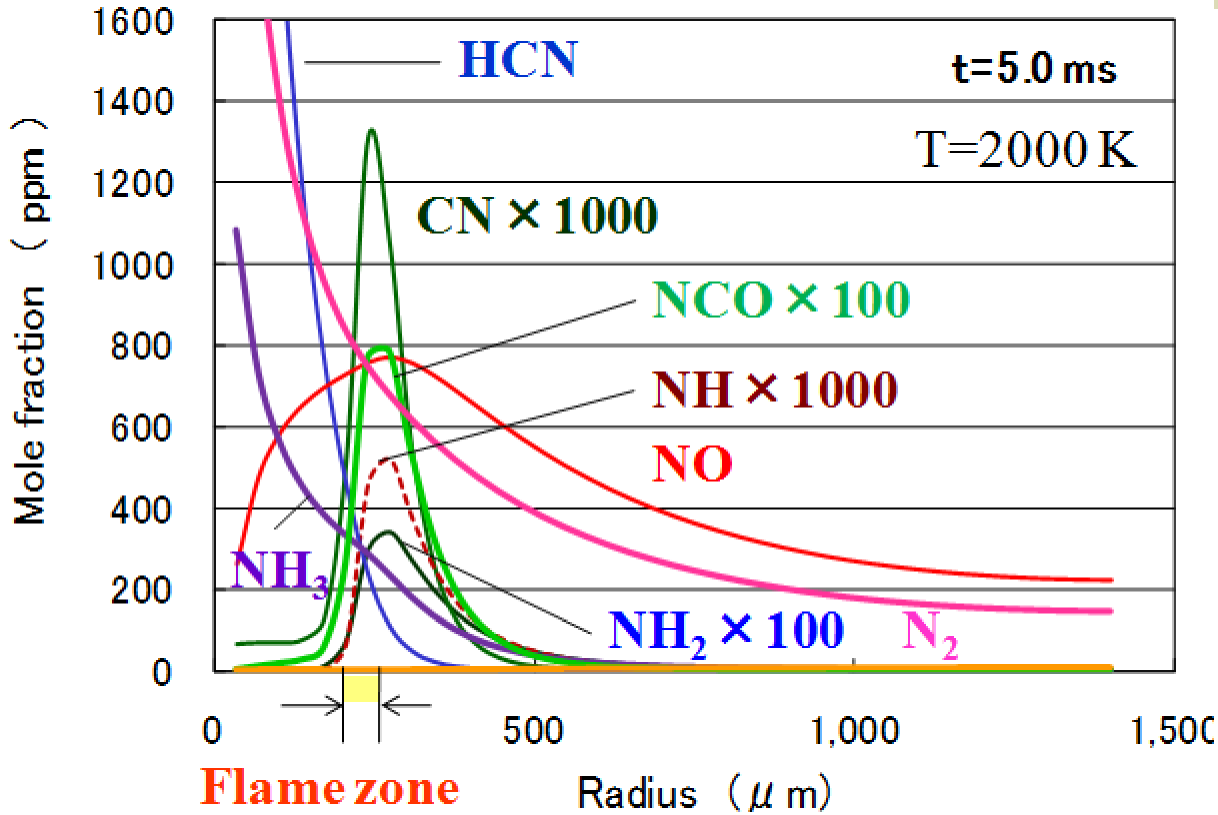
Behavior of fuel-NO formation around a coal particle (Thermal NOx= 0.0)



NH$_i$, NCO, and CN are formed in oxygen-rich region inside the flame zone and a large amount of fuel-NO is formed at the center of the flame zone.

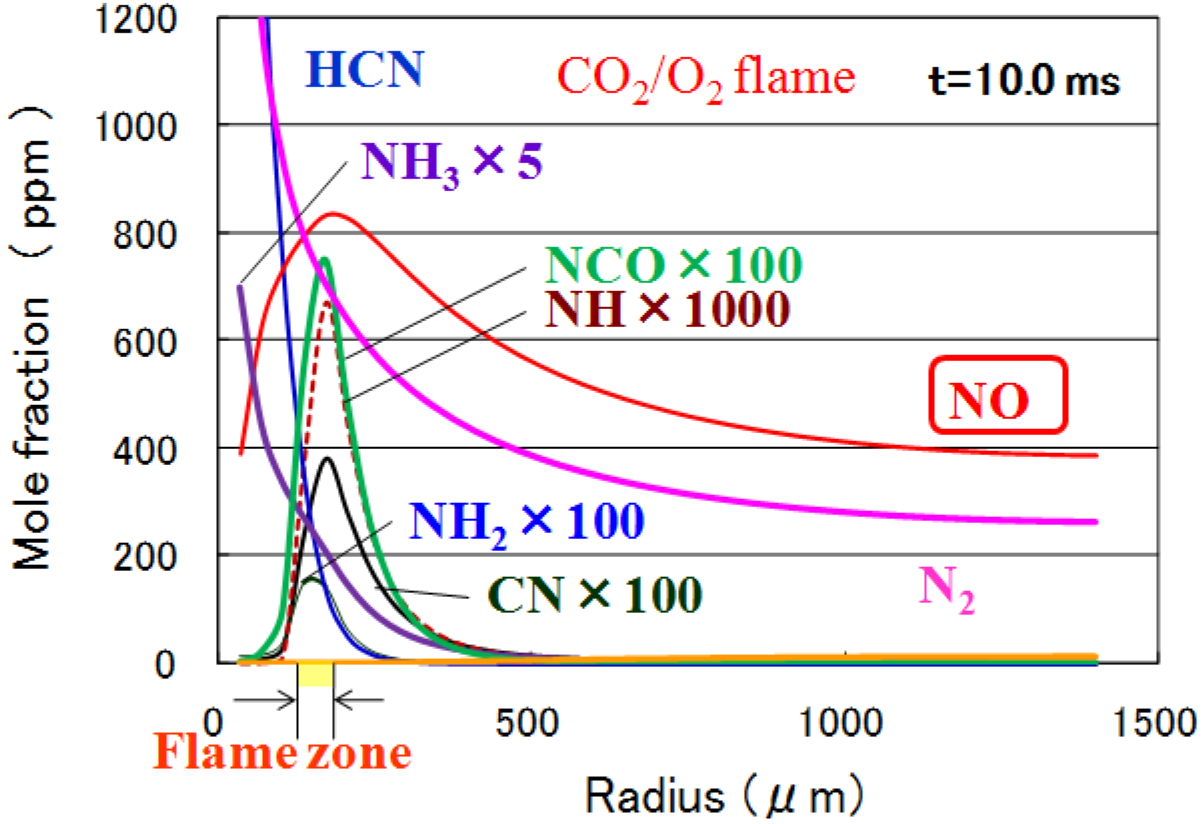
Behavior of fuel-NO formation around a coal particle (Thermal NOx= 0.0)

Nitrogen containing chemical species, **5.0[msec]**



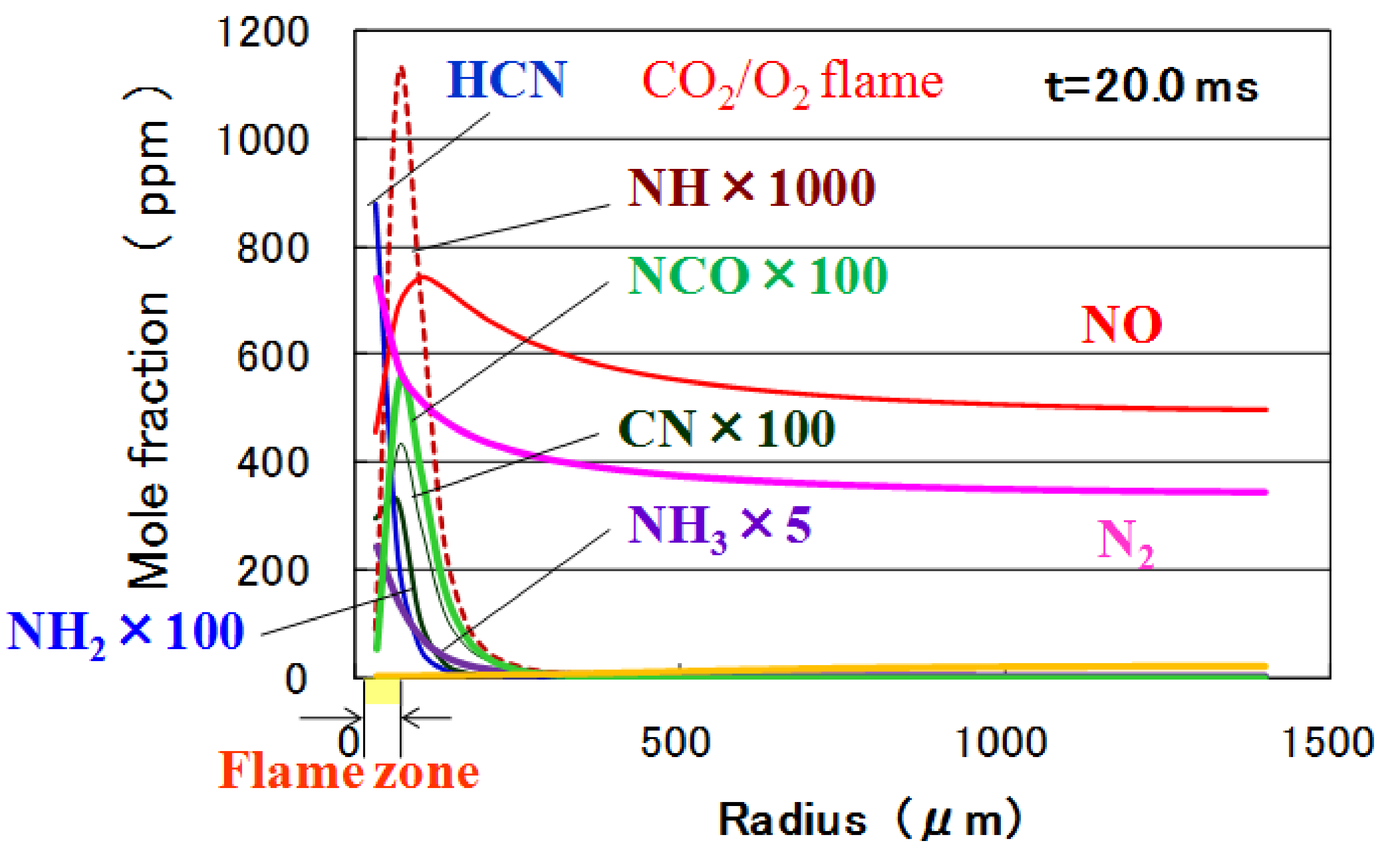
The fuel-N is converted into NO by rapid chemical reaction .

Behavior of fuel-NO formation around a coal particle (Thermal NOx= 0.0)



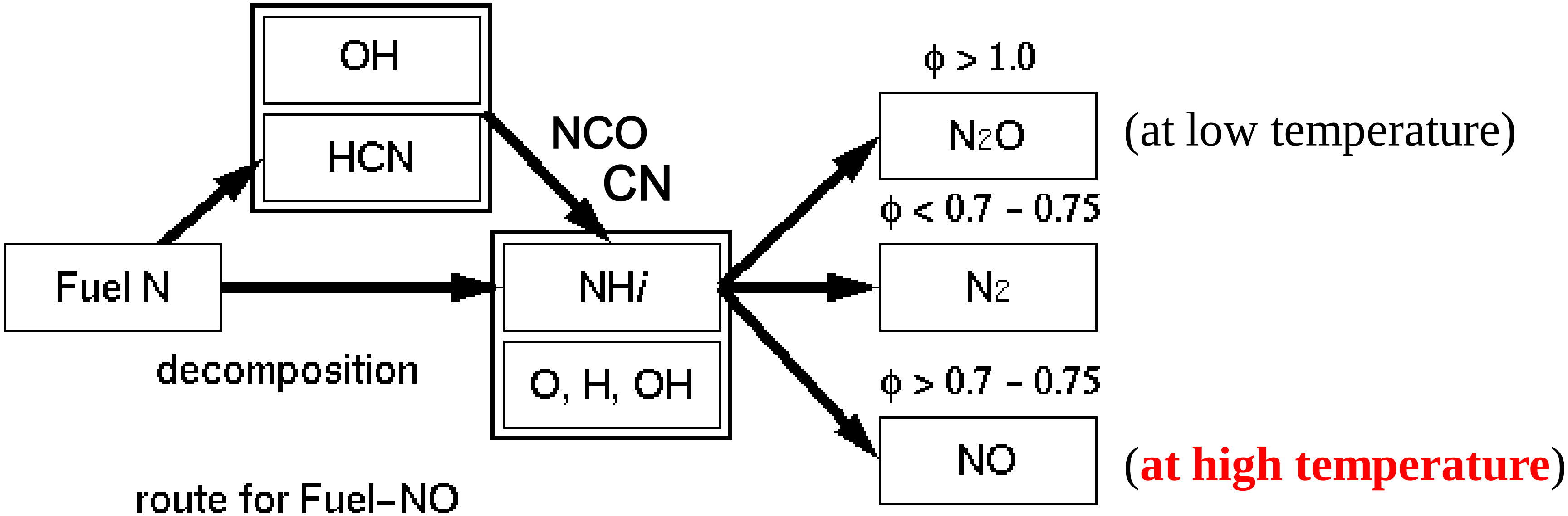
The NO concentration in outside of the flame zone increases because of diffusion effect.

Behavior of Fuel-NO formation around a coal particle (Thermal NOx= 0.0)



The NO formation have finished with the termination of evolving process.

Formation mechanism of Fuel NOx



Ref. Kishimoto M. et al., Transactions of the Japan Society of Mechanical Engineers. B Vol.68, (2002)

A large amount of HCN is evolved from coal, and nitrogen components are produced through the HCN • NCO, CN and NCO • NH_i reactions in flame zone.

Discussion point

The fuel NO_x formation behavior around a coal particle is theoretically analyzed.

discussion

i. Extract the **solid–gas reaction** **finished**

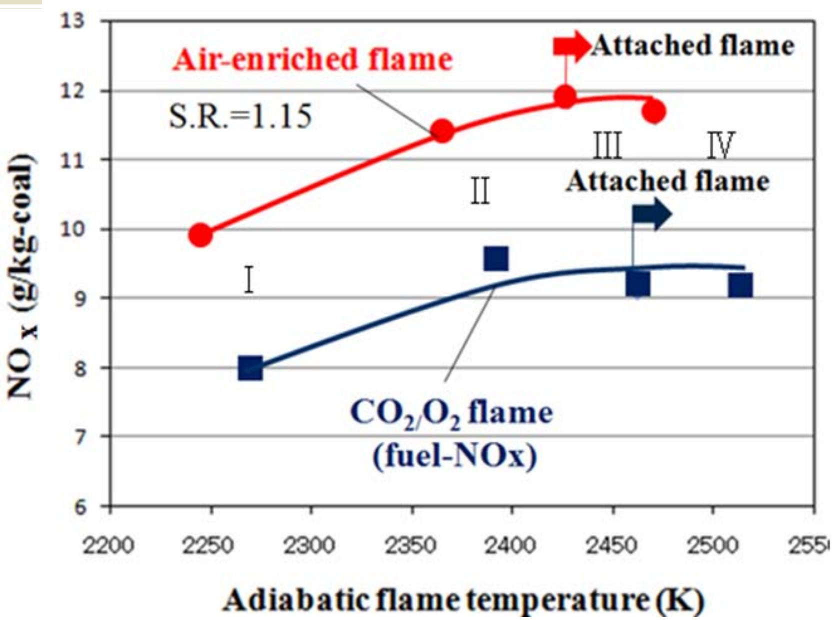
ii. Effect of **flame temperature** on fuel-NOx level

iii. Effect of **O_2 concentration** on the fuel-NOx level

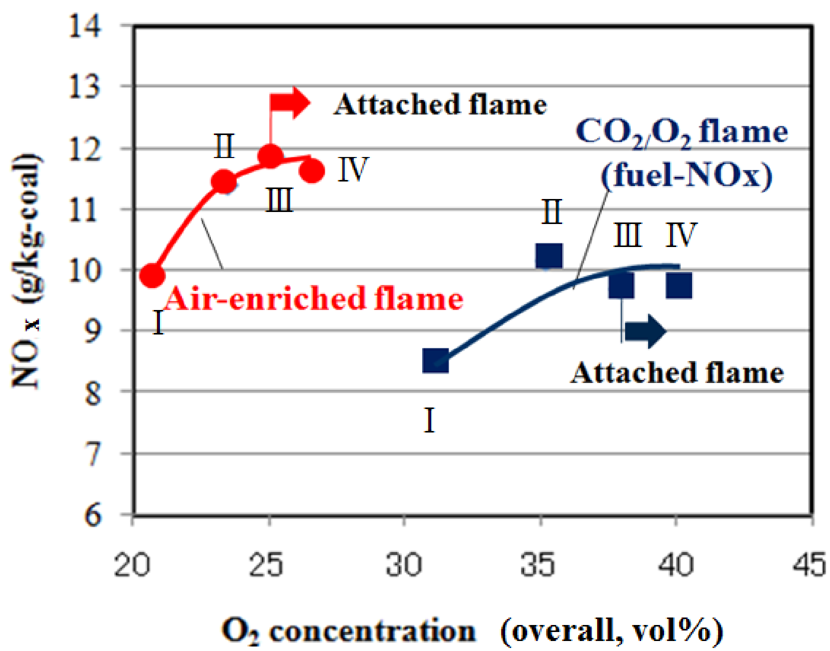
Separate

Which is dominant, the effect of flame temp. or the effect of O_2 conc. on NO_x formation in oxy-coal combustion?

Effect of flame temperature



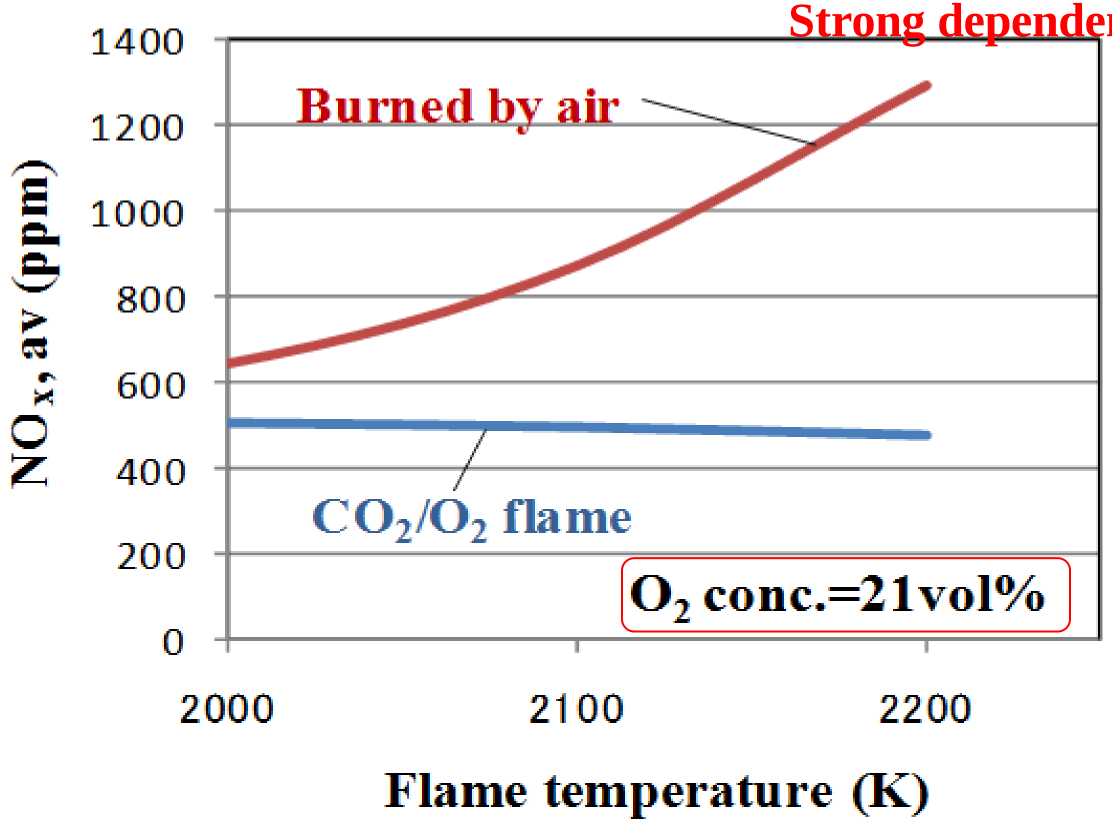
Effect of O_2 concentration



Effect of flame temperature

(ref)　O_2 conc.=21vol%　　Particle diameter = 70[μm]

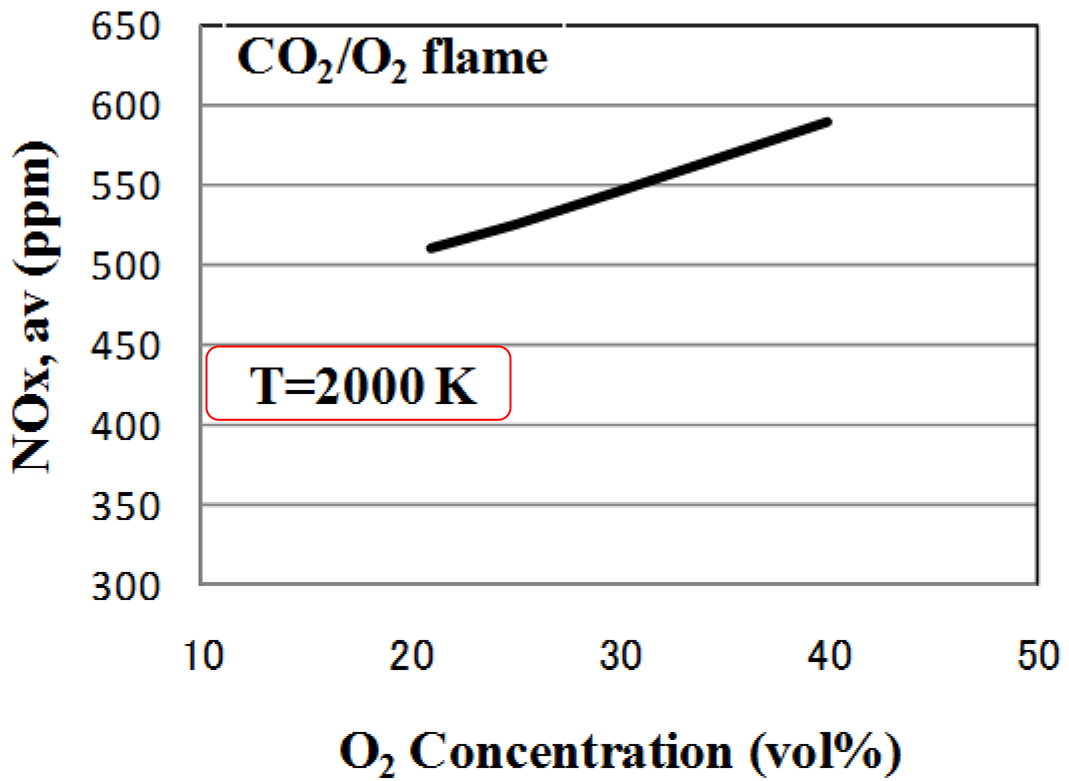
Strong dependence of temperature



The fuel-NO_x formation in oxycoal condition is less dependent on temperature than that in air case. (In air-case includes the thermal and prompt NO mechanism.)

Effect of oxygen concentration

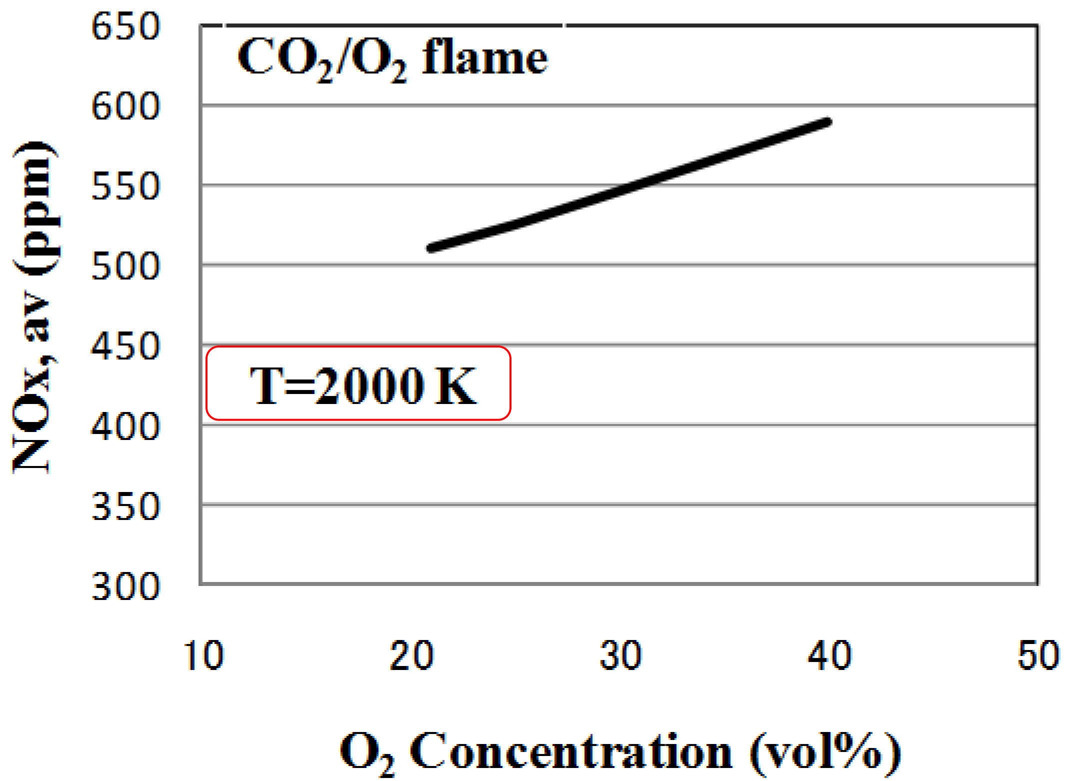
(ref) T=2000[K] Particle diameter = 70[μm]



This is due to the activation of reactions in which NO_x **precursors** are produced, such as HCN+**OH**• **NCO**+H_2 and HCN+**O**• **NCO**+H, NCO+H• **NH**+CO, etc. by **O and OH radical,** and subsequent to NH+OH• **NO**+H_2 at high oxygen concentrations.

Effect of oxygen concentration

(ref) T=2000[K] Particle diameter = 70[μm]

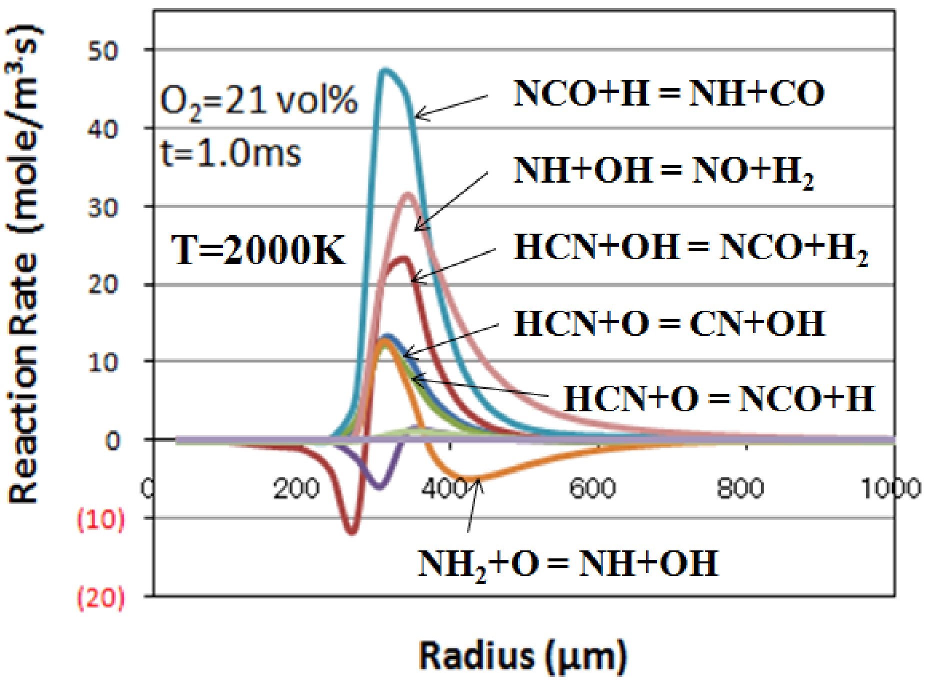


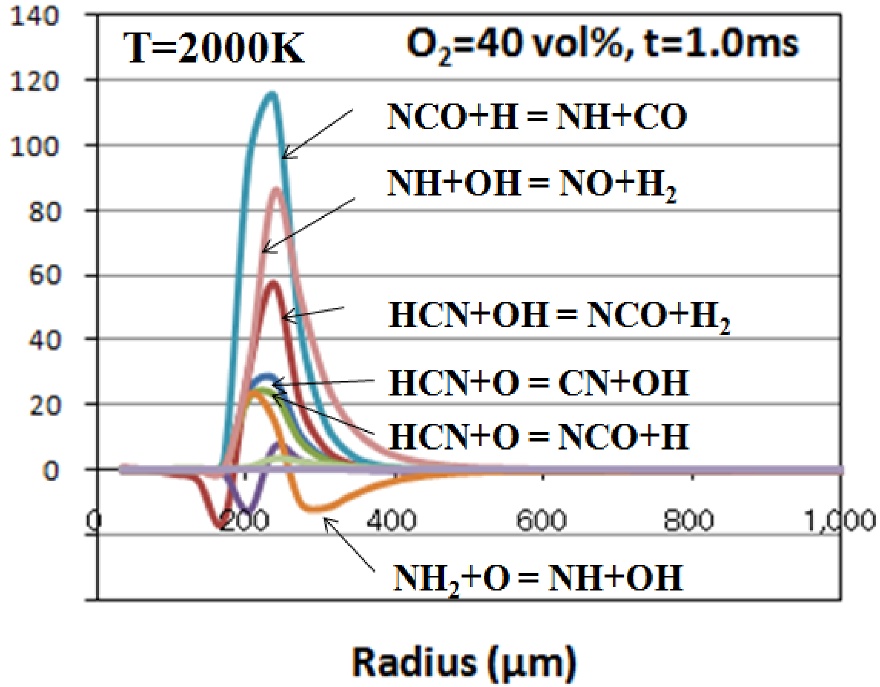
Experiment: The emission level of NO_x increases.

↓

The oxygen conc. is main factor of increasing NO_x in one-through oxy-coal condition.

Effect of oxygen concentration on reaction rate





CO_2/O_2combustion （ O_2=**21 vol%** ） CO_2/O_2combustion （ O_2=**40 vol%** ）

Conclusions

(1) **Mechanism of NO_x formation** : Fuel-NOx is formed from these radicals in the flame zone ; HCN and NH_3 evolve from coal, and NO_x is rapidly produced through the HCN • NCO, CN, NH in the case of HCN evolution and NH_3 • NH_i reactions in the case of NH_3 evolution.

(2) **Effect of O_2 /CO_2 ratio** : The emission level of fuel-NO_x increases with the O_2/CO_2 ratio. This is due to the activation of reactions in which NO_x **precursors** are produced, such as HCN+OH• **NCO**+H_2 and HCN+O• **NCO**+H, NCO+H• **NH**+CO, etc. by O and OH radical**,** and subsequent to NH+OH• NO+H_2 at high oxygen concentrations.

(3) **The solid–gas reaction** : Gasification reactions between CO_2 and carbon on the surface occur more vigorously during oxy-coal combustion than during combustion in air.

Thank you for your attention.

Slides for Question

✧ NO x formation

- NOx (Nitric oxides)

Thermal NOx
- Zeldovich NOx
- Prompt NOx [Hydrocarbon Fuel]

(O_2-enriched in Air)

Fuel NOx
- Volatile NOx
- ∨ Ref. (1)
- Char NOx

[Biomass]

(Oxy-coal)

Ref. (1) J. Wendt, D. Pershing et al., 7th Int. Combust. Inst., p.77, (1979)

Formation Mechanism of Fuel-NOx

by J.O.L. Wendt and E. Eddings (2002)

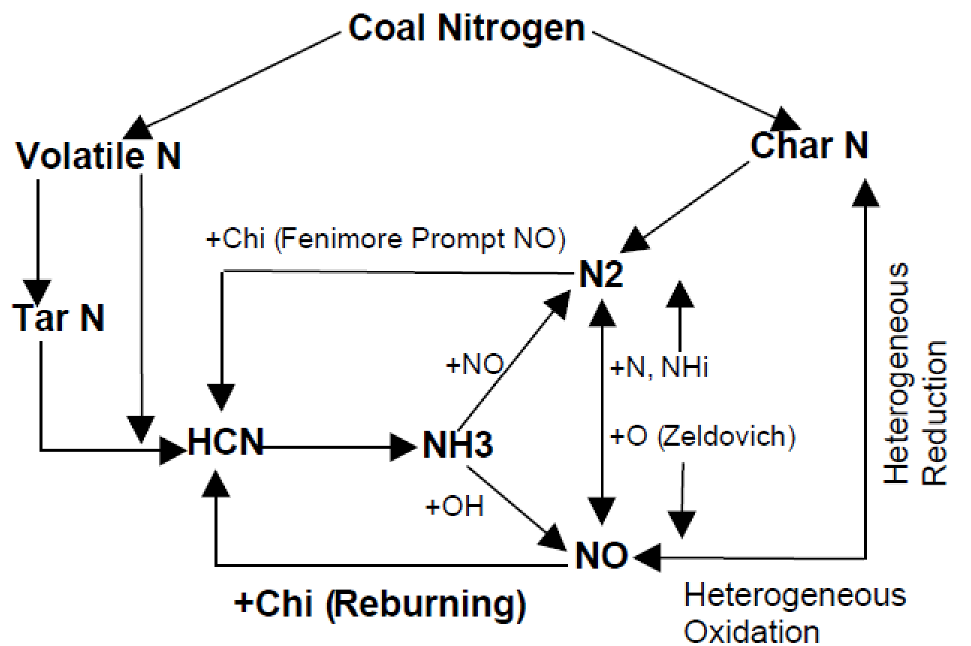


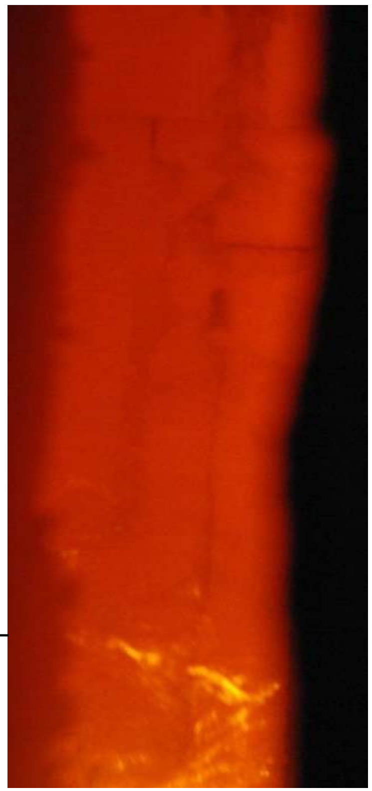
Figure 2. NOx production pathways in coal combustion[3]

PRESENTED AT:

The Nineteenth Annual International Pittsburgh Coal Conference Pittsburgh, PA

Detached flame :

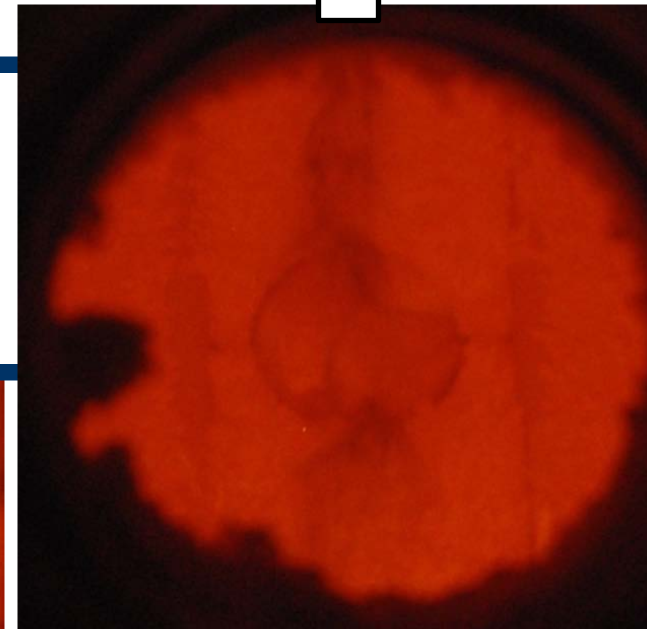
Mixing length



Ignition

Mixing length

Ignition



Near burner

1/4000 sec exposure

Pentax (Pentax K200D)

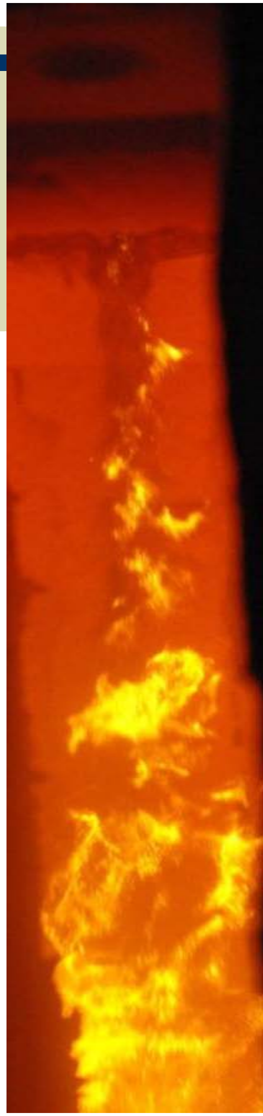
single lens reflection

•The smaller particle easily diffuses to oxidizer-side in mixing region (until ignition-point).

•The coal burns homogenously into the center of flame.

•Pulverized coal burns with a flame pattern **similar to partially premixed flame**.

Attached flame:



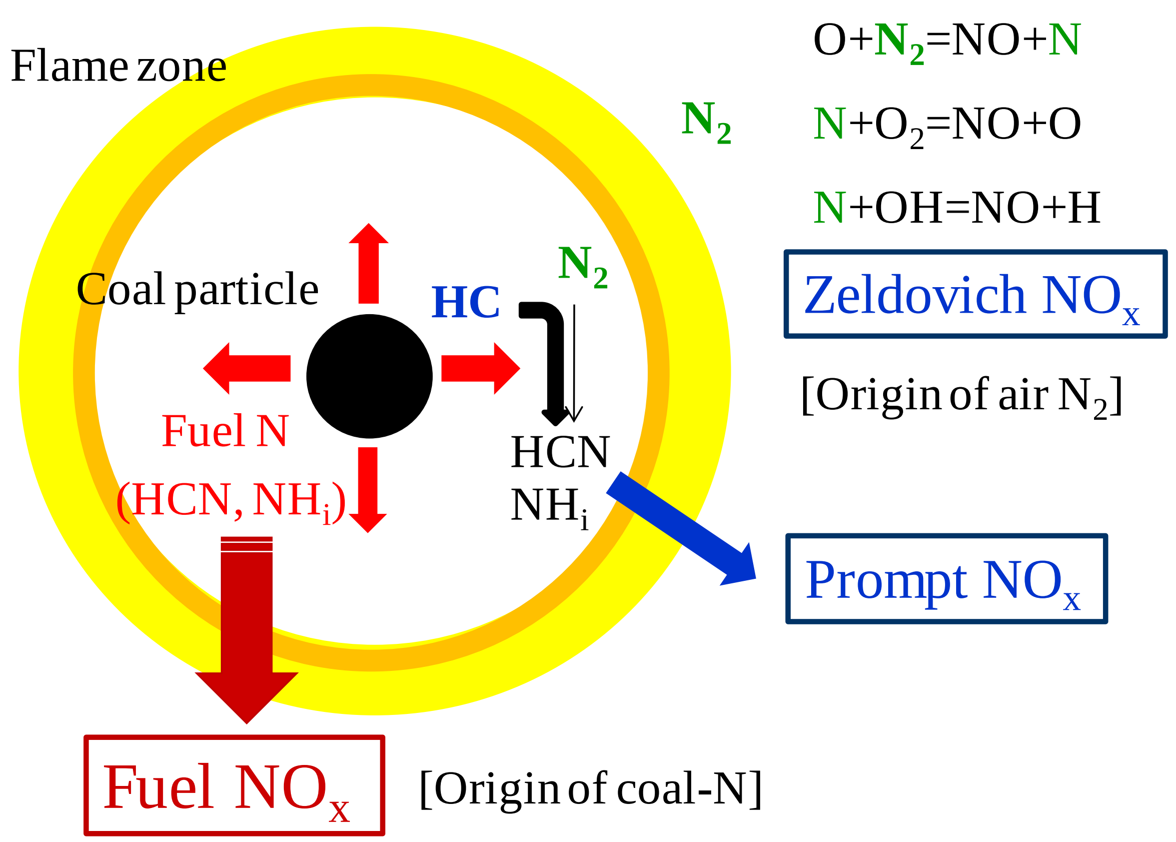
1/4000 sec exposure

Pentax (Pentax K200D)

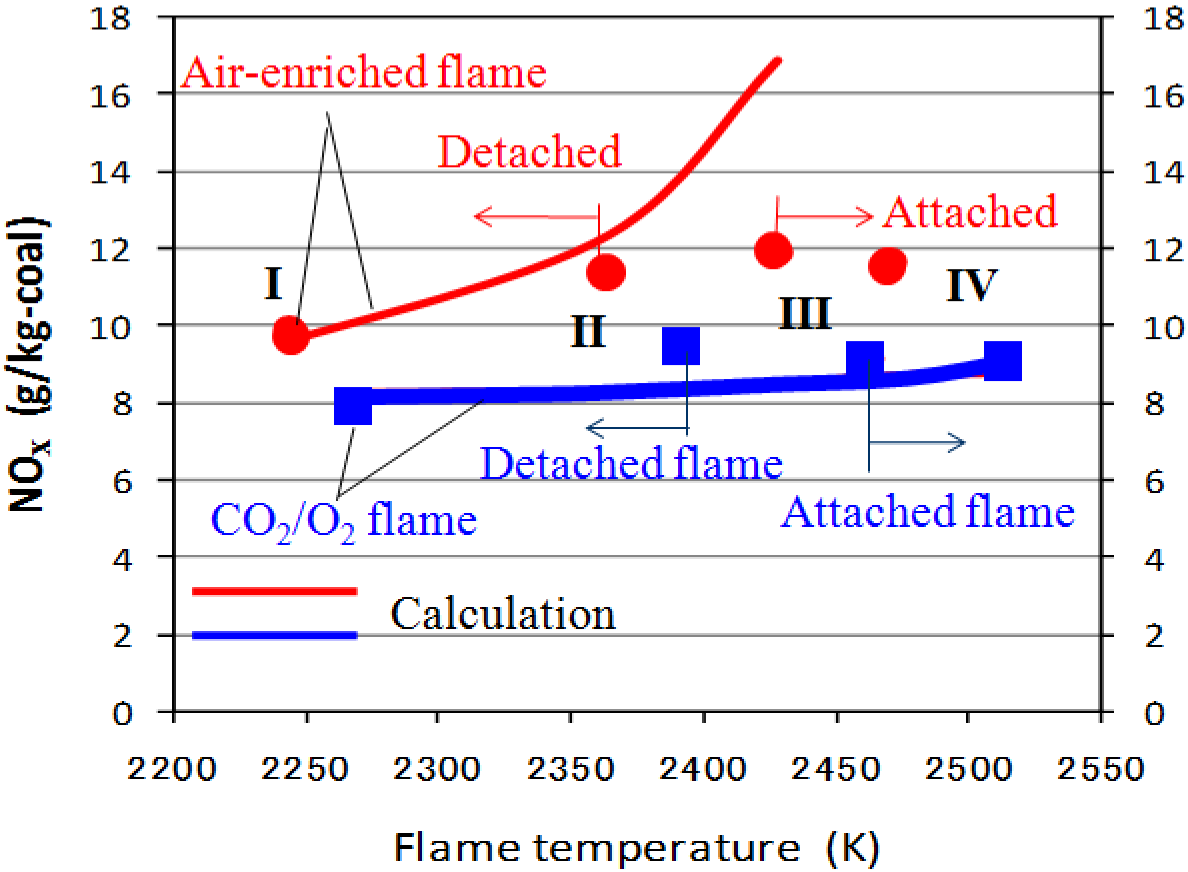
single lens reflection

- The combustion does not progress into inner zone of flame.
- Pulverized coal burns with a flame pattern similar to diffusion flame.
- The reduction zone in near burner will be existed by insufficient mixing.

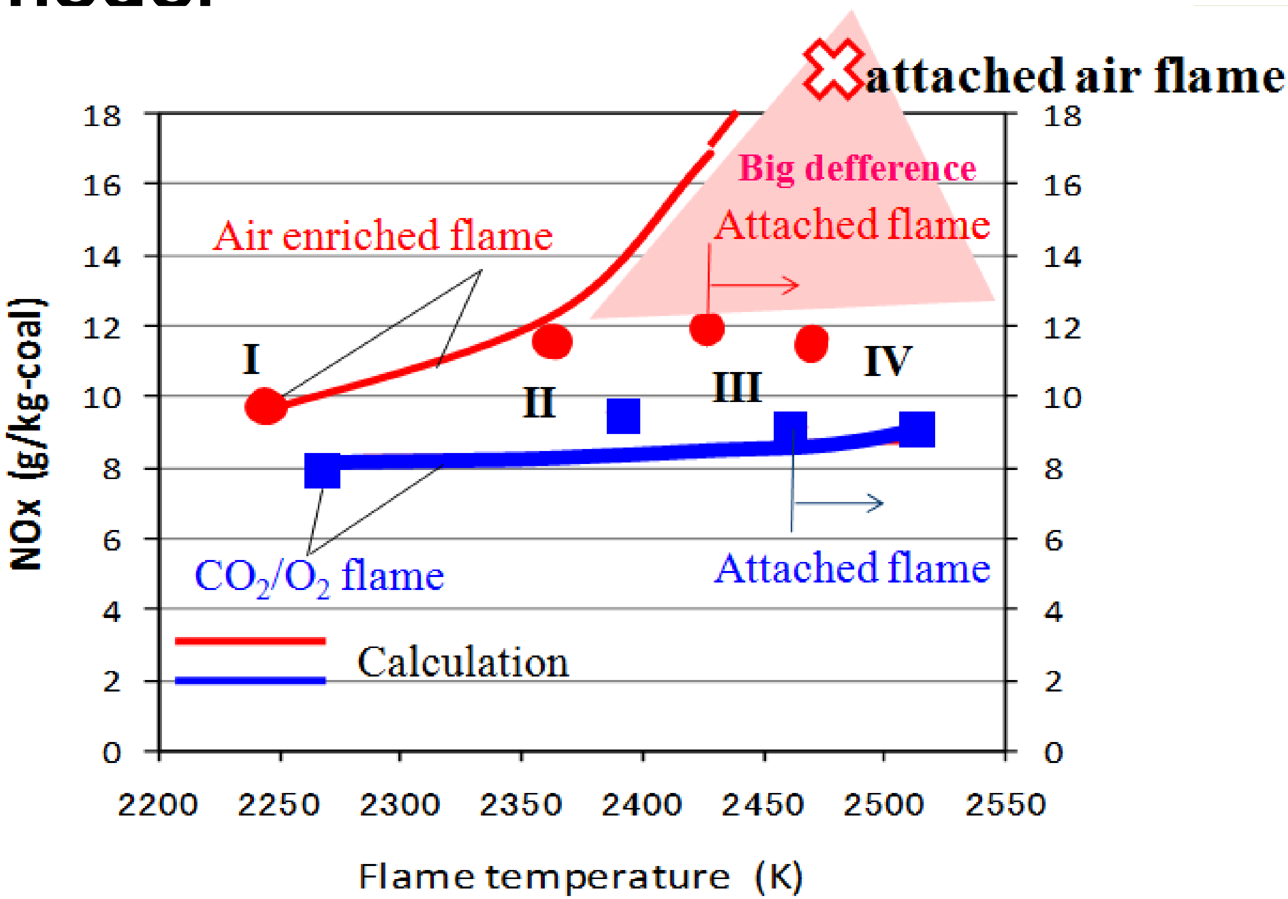
Outline of formation of NOx in air



Type of flame		Experimental case			
		I	II	III	IV
CO_2/O_2 flame	Oveall O_2 (vol%)	31.2	35.2	37.9	40.1
	Adiabatic temp. (K)	2270	2390	2460	2510
Air enriched flame	Oveall O_2 (vol%)	20.8	23.5	25.2	26.6
	Adiabatic temp. (K)	2240	2360	2430	2470



Application range of single particle model



This model can not be applicable for the attached flame. In attached flame, the pulverized coal burns with a flame pattern similar to diffusion flame.

What are initial/boundary conditions of volatile matters?

$$\frac{dV}{dt} = \left(V^{*} - V\right)\ k_0 \exp\left(\frac{-E}{RT}\right) \quad [\text{kg/s}] \cdots\cdots \quad (4)$$

Initial condition: $t = 0$; $V = 0$

Boundary condition: $r = r_0$; $V=V$

(It is assumed that V kg of volatile matter (CH_4, HCN, NH_3, and N_2) is evolved from the particle surface, according to eq. (4))

Boundary condition: $r = r_{\bullet}$; $dY_k/dr = 0$

(The concentration gradient of the evolved volatile matter (CH_4, HCN, NH_3, and N_2 or Y_k of the reaction product) is assumed to be 0)

r represents the radius; V, the mass of volatile matter;

0, the index of the radius of the coal particle;

• , the index of the oxidant-space occupancy radius for a coal particles;

k, the chemical species;

Y, the mass fraction.

Completion of combustion

Completion of combustion was confirmed on the basis of the O_2, CO and CO_2 level, carbon mass balance before and after the reaction, and ash analysis. In detail, we confirm the complete-combustion by next three ways:

1) CO is 0 or very low at the far-burner region. (globally)

2) Analyze ash LOI (Loss-On-Ignition). Low LOI means complete combustion.

3) O_2 and CO_2 level: measured = calculated. Mass balance enclosed.

Generally, the value of LOI is low. (for example, LOI = 2-3% at overall O_2 = 31.2 %)

LOI linearly decreases in area of SR = 1.0-1.1, above which it does not change. It is considered that above fact relates to the nonlinear-decrease profile of carbonized matter.

The adiabatic temperature

The adiabatic temperature has been calculated on the basis of the quantities of coal, oxidant, CO_2, and N_2 supplied and by assuming complete combustion. In detail,

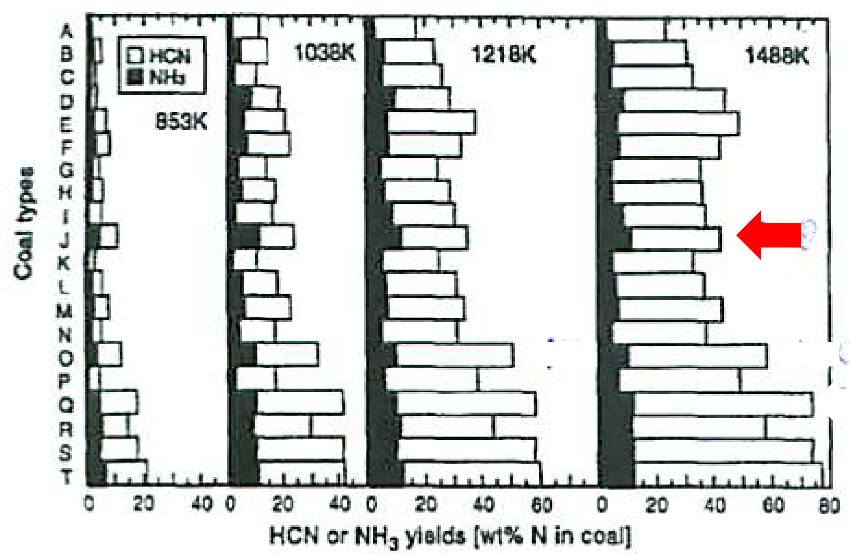
1) Assume complete combustion (no dissociation), the products are O_2, CO_2, H_2O, N_2, and SO_2(from the S compound in coal and can be actually neglected)
2) C_p's are calculated by using thermodynamics data in CHEMKIN database.
3) No heat loss.
4) reactants' enthalpy + heat release from coal (higher heat value) = products' enthalpy

(Ref) S. Kambara, T. Takarada, M. Toyoshima, K. Kato, Relation between functional forms of coal nitrogen and NOx emissions from pulverized coal combustion, Fuel, Vol. 74, Issue 9, (1995), pp. 1247-1253.

Table 1 Fuel analysis

Coal name	Key	Source	Proximate analysis (wt%, db)			Ultimate analysis (wt%, daf)				
			Ash	VM	FC	C	H	N	O[a]	S
Eagle Mountine	A	Canada	10.0	20.8	69.2	88.1	4.5	1.2	5.8	0.37
Oakdale	B	Australia	12.4	26.3	61.4	85.1	4.8	1.7	8.0	0.40
Lithgow	C	Australia	16.2	29.6	54.2	84.9	5.0	1.9	7.6	0.61
Core sample A	D	Australia	8.0	30.3	61.7	84.6	5.1	2.3	7.1	0.94
Newlands	E	Australia	12.6	26.6	60.8	83.9	4.7	1.7	9.3	0.36
Aberdare	F	Australia	12.4	31.9	55.7	82.6	5.2	1.4	10.5	0.32
Core sample B	G	Australia	7.4	29.0	63.7	82.5	4.6	1.9	10.5	0.51
Bayswater	H	Australia	8.3	31.8	60.0	81.9	5.2	1.8	10.3	0.74
Datong	I	China	5.8	31.4	62.9	81.9	4.8	1.0	11.8	0.50
Muswellbrook	J	Australia	8.8	39.1	52.1	81.8	5.6	1.8	10.0	0.78
Warkworth	K	Australia	13.2	32.8	54.0	81.5	5.4	1.9	10.7	0.51
Hunter Valley	L	Australia	9.7	33.8	56.5	81.1	5.3	1.8	11.3	0.49
Wattle Glen	M	Australia	11.1	30.7	58.1	80.8	5.1	1.4	12.3	0.39
Blair Athol	N	Australia	7.3	30.6	62.1	80.8	4.5	1.8	12.7	0.25
Ebenezer	O	Australia	9.6	41.8	48.6	80.1	5.9	1.4	12.0	0.55
Quinsam	P	Canada	7.7	38.3	54.0	78.0	5.3	1.0	15.6	0.14
Taiheiyo	Q	Japan	11.8	44.8	43.4	76.2	6.1	1.2	16.5	0.07
Roshell	R	USA	5.1	43.5	51.4	72.8	4.6	1.1	21.3	0.16
Usibelli	S	USA	8.1	48.8	43.0	69.2	4.9	0.9	25.0	0.04
Yallourn	T	Australia	1.5	47.1	51.4	65.4	4.4	0.6	29.4	0.28

[a] O = 100 − (C + I



Combustion space of a coal particle

Mass of a coal particle is:

$$M_p = \pi \cdot d_p{}^3 \cdot \rho / 6 \qquad \text{[kg/particle]}$$

d_p is diameter of coal particle. • is density of coal particle: • [kg/m^3].

Number of coal particle feeding per unit time is:

$$N = G \Big/ \left(10^4 \cdot \pi \cdot d_p{}^3 \cdot \rho\right) \qquad \text{[particle/s]}$$

G[g/min] is feeding rate. As defined as air flow rate Va [g/s],

the flow rate of air volume is:

$$Va = Ga \times 10^{-3} \Big/ \rho_a \qquad \text{[m}^3\text{/s]}$$

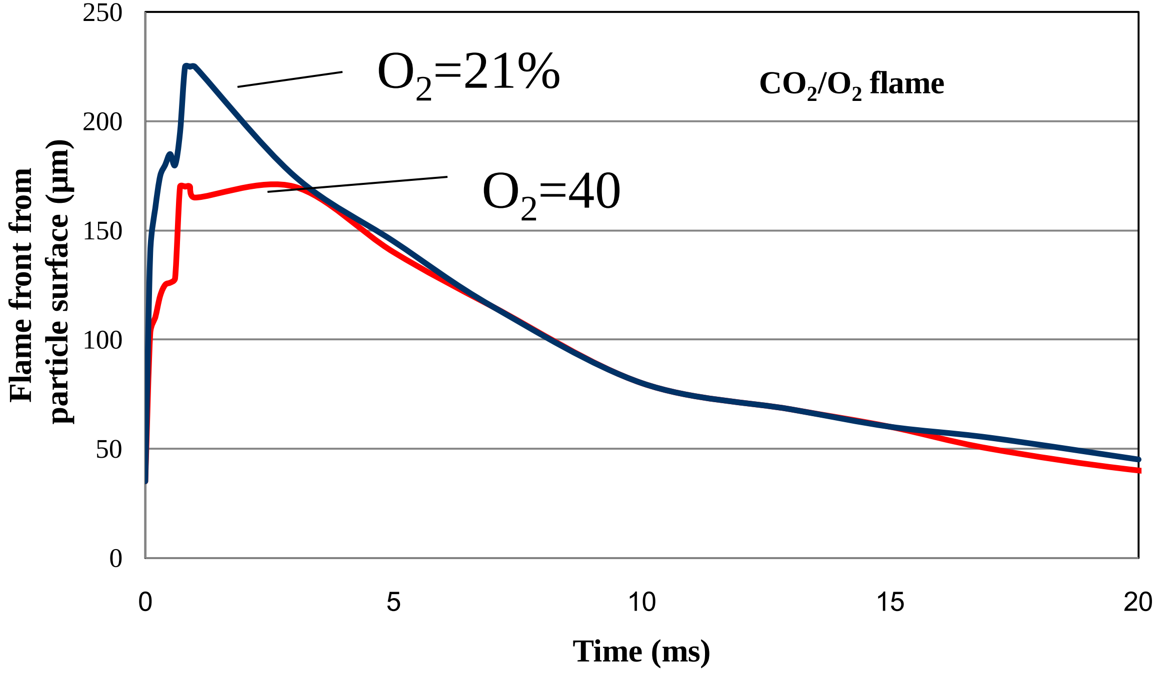
$\bullet_a$ Here, • is density of air [kg/m^3]. Then the volume of space occupied by a coal particle is:

$$\Delta V = 10 \cdot Ga \cdot \pi \cdot d_p{}^3 \cdot \rho \Big/ \left(G \cdot \rho_a\right) \qquad \text{[m}^3\text{/particle]}$$

Then Combustion space of a coal particle is defined as below:

$$d\max = \left(60 \cdot Ga \cdot d_p{}^3 \cdot \rho \Big/ \left(G \cdot \rho_a\right)\right)^{1/3} \qquad \text{[m]}$$

➢ Effect of O_2 conc on burn out time



（備考） T=1700[K]　　粒子直径＝70[μm]

Result of calculation

The actual combustion of pulverized coal is not as simple as that shown in this model, since coal particles make a complicated flight and a rotational motion caused by recoil forces exerted by volatile components evolved through cracks generated on the particle surface. However, HCN released from coal particles in the flame zone definitely plays an important role in the formation of NO_x through HCN • NCO, CN and NCO • NH_i reactions.