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Syngas Reburning and Co-firing Characteristics of Biomass in a Coal firing Combustion System

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Backgrounds

- The main energy source of humanity is the fossil fuel of hydrocarbon-based
  - Environmental pollution is a serious problem due to combustion product
  - Atmospheric pollutants: NOx, CO_2, CO, soot, ash etc.
- NOx: The major sources of anthropogenic NOx emissions caused by human activities is fossil fuel (more then 90%)
- Co-firing of renewable fuel in a thermoelectric power plant has become an important issue
  - In the case of Korea RPS (Renewable portfolio standard) was applied to power production since 2012, and Korean government is planning to conduct RHO (Renewable heat obligation) policy for a legal obligation of renewable energy application in the near future
- NOx regulations of South Korea's power plant (Ministry of Environment)

Fuel	Power	Date of establish power plant	Environmental regulation(NOx)
Gaseous fuel	~ 28.78 MW	~2014. 12. 31	≤ 150 (4)
		2015. 1. 1 ~	≤ 60 (4)
	28.78 MW ~	~2014. 12. 31	≤ 150 (4)
		2015. 1. 1 ~	**≤ 40 (4)**
Liquid fuel	~ 28.78 MW	~2007. 1. 31	≤ 180 (4)
		2007. 2. 1 ~ 2014. 12. 31	≤ 100 (4)
		2015. 1. 1 ~	≤ 70 (4)
	28.78 MW ~	~ 2001. 6. 30	≤ 130 (4)
		2001. 7. 1 ~ 2014. 12. 31	≤ 70 (4)
		2015. 1. 1 ~	**≤ 50 (4)**
Solid fuel	All	~ 2007. 1. 31	≤ 120 (6)
		2007. 2. 1 ~	**≤ 70 (6)**

( ): O_2 concentration of standard in the combustion gas

Formation of NOx mechanism in combustion system

- Thermal NOx: Fixation of atmospheric (molecular) N by O_2 at high temperature(>1300℃) in oxidizing atmospheres

  $N_2 + O \leftrightarrow NO + N$

  $O_2 + N \leftrightarrow NO + O$

  $OH + N \leftrightarrow NO + H$ [Zeldovich mechanism]

- Prompt NOx: Fixation of atmospheric (molecular) nitrogen by hydrocarbon fragments in reducing atmospheres

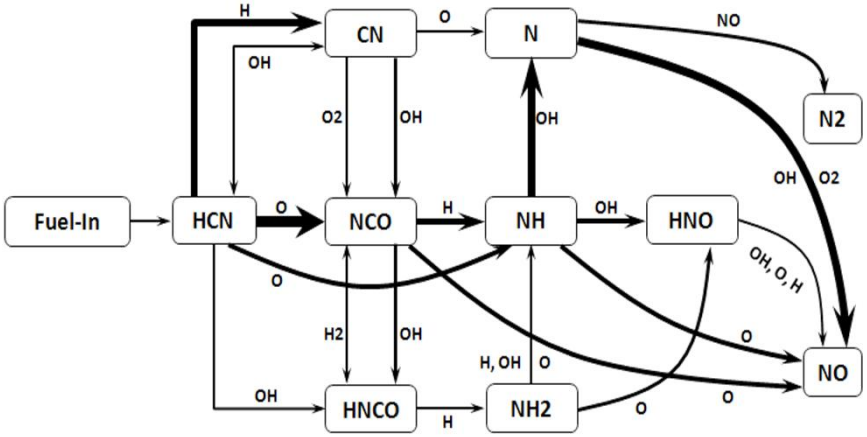
  $N_2 + CH \leftrightarrow HCN + N$

  $N_2 + 2C \leftrightarrow 2CN$

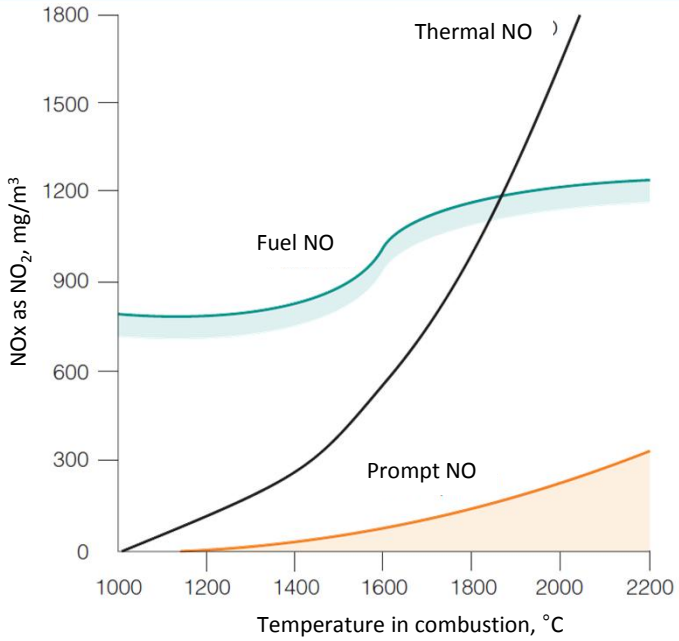
  $HCN + O \leftrightarrow NO + CH$

  $2CN + O \leftrightarrow NO + 2C$

- Fuel NOx: oxidation of nitrogen compounds organically bound in the coal at temperatures greater than 750 ℃



[John Zink combustion hand book]

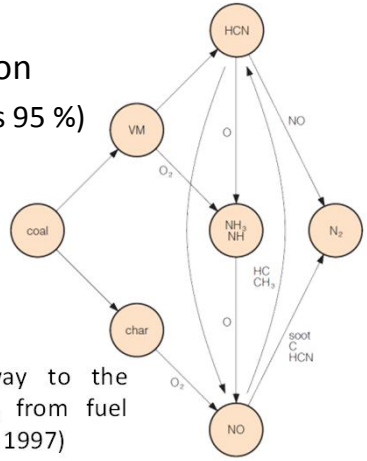


Temperature influence on the amount of NOx produced from the three NOx formation mechanisms in coal combustion. (Soud and Fukasawa, 1996)

- Overall contribution to NOx formation
  - Fuel NOx: ~ 75 %(sometimes as high as 95 %)
  - Thermal NOx: 2 ~ 25 %
  - Prompt NOx: < 5 %

  [Stuart C Mitchell, 1998]

[NO, N_2 reaction of coal combustion]



Simplified reaction pathway to the formation of NO and N_2 from fuel nitrogen(Visona and others, 1997)

Purpose of this study

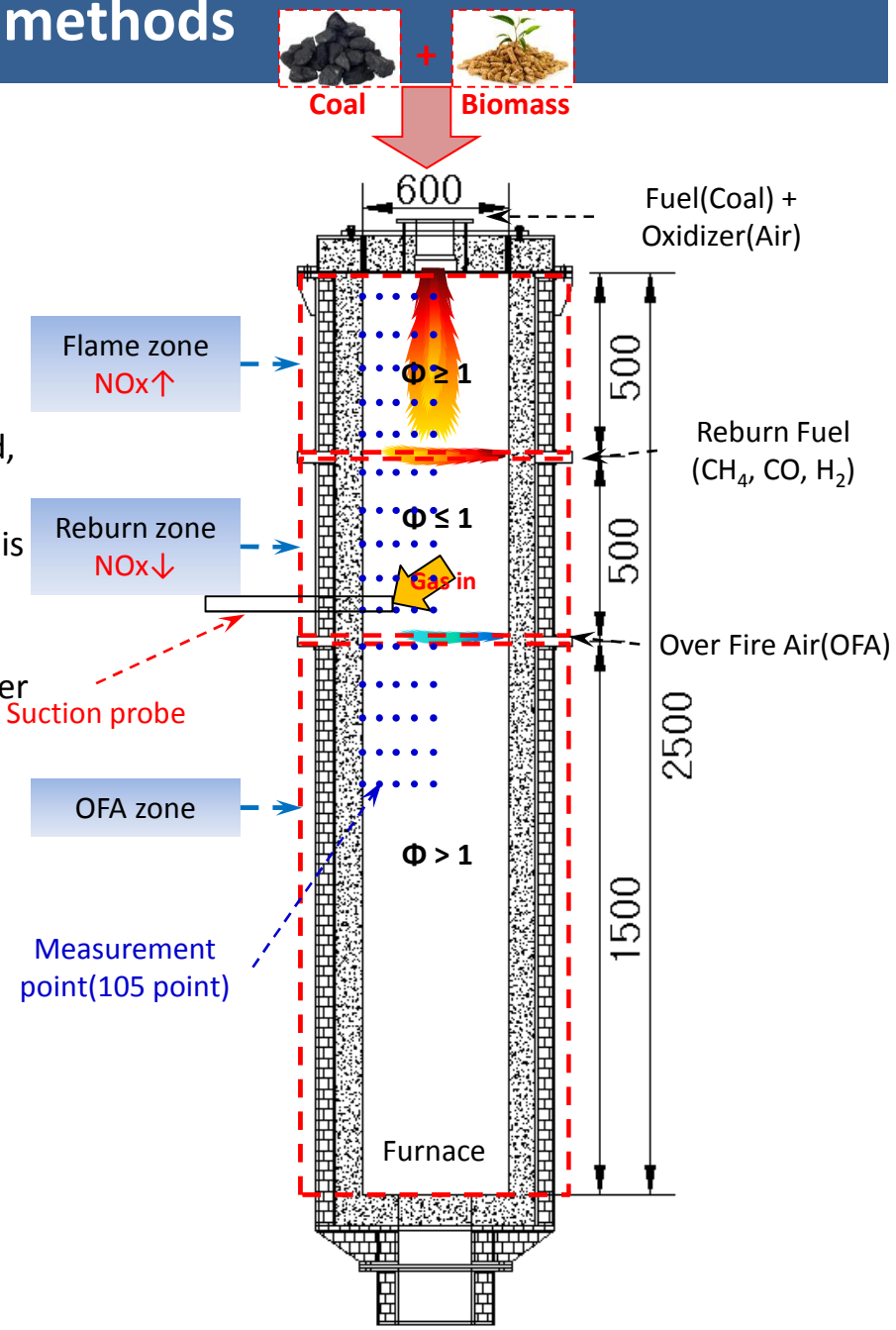
- An experimental study was performed in a bench-scale furnace to investigate characteristics of syngas reburn in combustion system and biomass co-firing in combustion system
  - Equipment: 80 kW_{th} down firing furnace
  - Main fuel: Coal
  - Reburn fuel: CH_4, CO, H_2
  - Co-fired fuel: Wood pellet, Palm kernel shell, Empty fruit bunch, Walnut shell
- Distributions of O_2, CO, CO_2, and NOx concentrations as well as, gas temperatures have been measured in the furnace for various of the reburn fuels and co-firing ratio
- Investigation NOx reduction behavior using syngas reburn method in coal combustion
- **Syngas reburn in the coal combustion system** is aimed to investigate effects of each combustible gas species in the syngas to NOx reduction, and finally to suggest favorable conditions of the syngas from the gasifier
- **Coal and biomass co-firing in the combustion system** presents an evaluation of the combustion characteristics of the coal blended with biomass in a bench scale combustion system

Experimental methods

- **Reburning**: combustion of CH based fuels such as CH_4 (most efficient NO reduction), oil, or coal in the upper flame region
  - Formation of three zones in a furnace
    - **Flame zone**: In the first stage (main combustion zone) a greater part of fuel (about 85%) is burned, in little air excess: combustion is almost completed, with few unburnt hydrocarbons.
    - **Reburn zone**: In the second stage only reburn fuel is injected, fuel rich area, reburn fuel is injected by 10~20% of the total fuel(heat base)
    - **OFA zone**: In the third stage only air is injected (over fire air), to reach the stated air excess

∵ NOx is reduced

- **Co-firing** is the combustion of two different types of materials at the same time
  - One of the advantages of co-firing is that an existing plant can be used to burn a new fuel, which may be cheaper or more environmentally friendly
- Measurement
  - Vertical distance at intervals of 100 mm
  - Horizontal distance at intervals of 50 mm



Reburn method used in this study

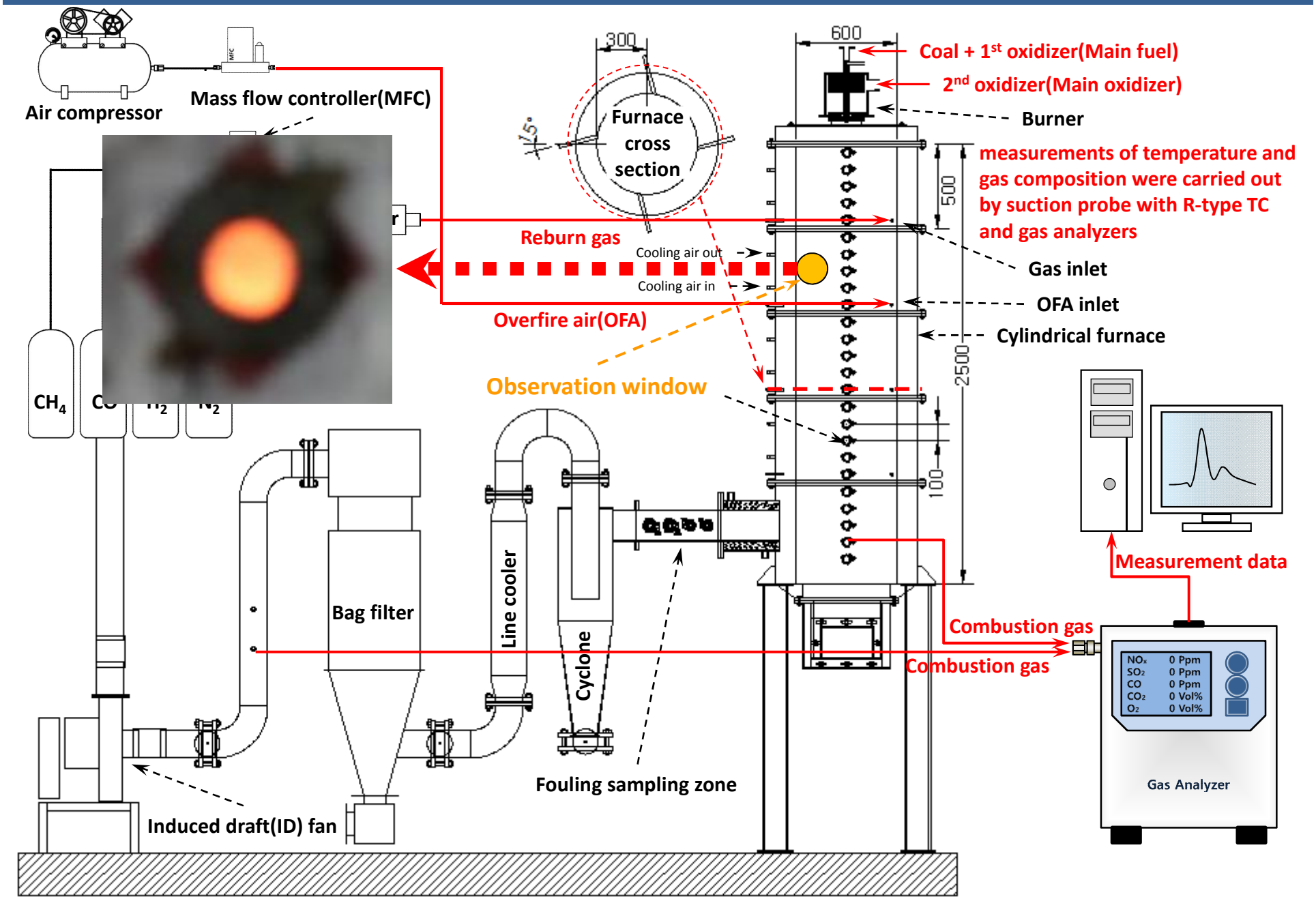
Chemistry of the reburning process

- The following equations are not intended to be exact but only approximate representations of the complex, free-radical reactions that occur during reburning

- **Primary combustion zone:** The major reactions occurring in the primary combustion zone are fuel combustion and NOx formation
  - Main Fuel + O_2 → CO_2 + CO + H_2O + Other Species
  - N(fuel) + O_2 → NOx
  - N_2 (air) + O_2 → NOx
- **Reburn zone:** The chemistry in the reburn zone is very complex. NOx reacts with hydrocarbon free radicals to form reduced nitrogen species which, in turn, react with additional NOx to form nitrogen gas
  - Reburn Fuel → CHx + Other Species
  - CHx + NOx → •CN + •NH_2 + H_2O
  - NOx + •NH_2 → N_2 + H_2O
  - NOx + •CN → N_2 + CO
  - NOx + CO → N_2 + CO_2
- **Burnout zone:** The main function of the burnout zone is to complete combustion of the fuel. However, any unreacted reduced nitrogen compounds may be reoxidized to NOx. This latter effect is normally small, and the overall result of reburning is a reduction in NOx emissions
  - Air + CHx + CO → CO_2 + H_2O
  - •CN + •NH_2 + O_2 → NOx + CO_2 + H_2O

[Reburning Technologies for the Control of Nitrogen Oxides Emissions from Coal-Fired Boilers(May 1999)]

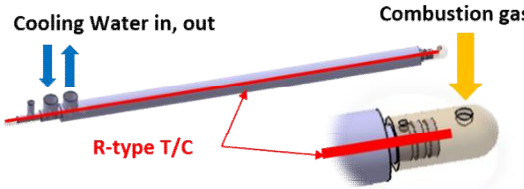
Experimental set-up



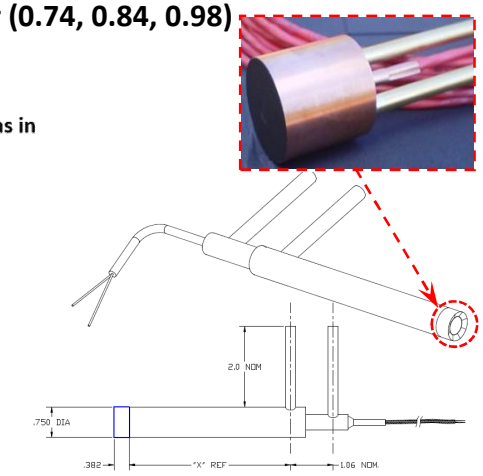
Picture of experimental equipment

- Gas burner: Commercial gas burner (Max: 80 kW_{th})
- Coal burner: Tangential vane swirl type burner
  - Swirl number 0.84

Swirl test of Coal burner (0.74, 0.84, 0.98)



Suction probe



Total heat flux meter(Vatell Corp.)

Coal burner

Gas burner

Cyclone, Line cooler

Bag filter

Furnace

Experimental conditions(Reburning)

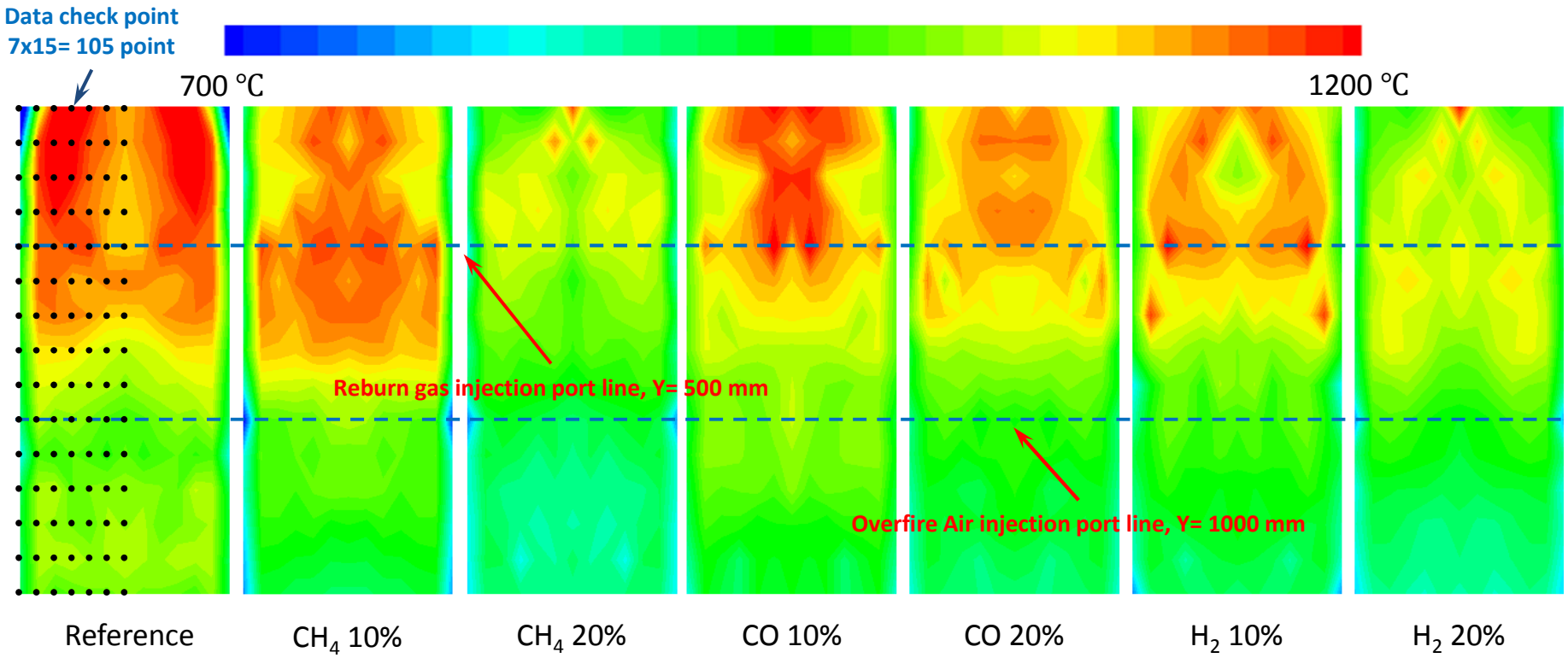
- Main fuel: Bituminous coal(Trafigura), LHV: 28.8 MJ/kg-wet
- Reburn fuel: CH_4, CO, H_2
- Thermal input: 74 kW
- Stoichiometric ratio: 1.2

Proximate analysis(%wet)				Ultimate analysis(%wet)				
Moisture	VM	FC	Ash	C	H	O	N	S
3.08	31.23	52.95	12.73	66.1	4.6	10.1	0.36	0.56

Fuel	Case	Reference	CH_4 10%	CH_4 20%	CO 10%	CO 20%	H_2 10%	H_2 20%
Main fuel	Heat ratio (%)	100	90	80	90	80	90	80
	Fuel rate (kg/hr)	10	9	8	9	8	9	8
Reburn fuel	Heat ratio (%)	0	10	20	10	20	10	20
	Stoichiometric ratio of the reburn zone	1.2	1.08	0.96	1.08	0.96	1.08	0.96
	Residence time of the reburn zone (s)	0	1.07	1.20	1.07	1.20	1.07	1.20
	Combustible gas flow rate (Nm^3/hr)	0	0.8	1.61	2.28	4.56	2.67	5.33
	N_2 flow rate (Nm^3/hr)	0	4.6	3.79	3.12	0.84	2.73	0.07
	OFA flow rate (Nm^3/hr)	0	9.18	18.37	6.51	13.02	7.62	15.23

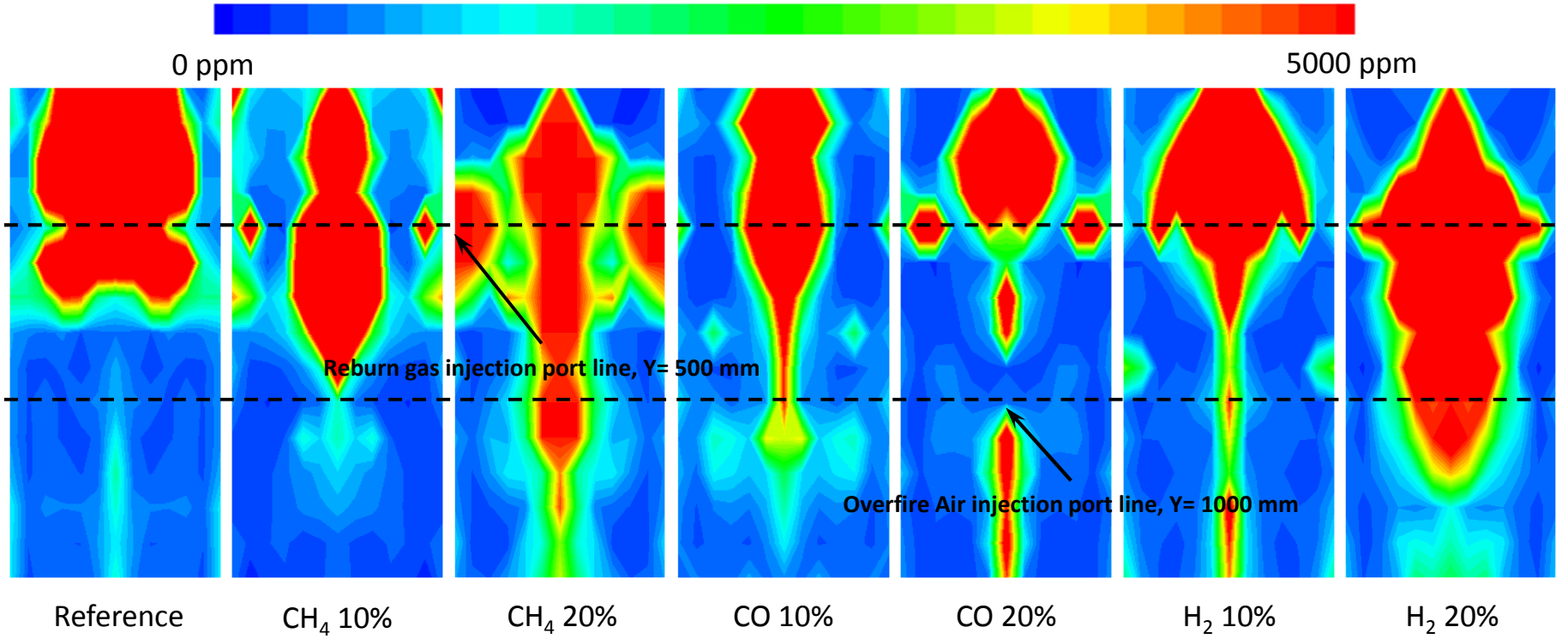
Temperature distribution in the upper section of the furnace(Reburn)

- Temperature of the reference case is higher than reburn cases
  - Main fuel ratio is larger than other cases
- Reburning ratio increases, the temperature in the primary zone decreases because the volumetric heat release by the main fuel is reduced corresponding to the reburn ratio
  - Burnout zone temperature in the reburn cases is lower than that in the reference case due to the cooling effect of the OFA and the nitrogen included in the reburn fuel
- As reburn ratio increased, the temperature is reduced for all cases
  - Due to reduction of the main fuel in all reburn cases, initial temperature was decreased



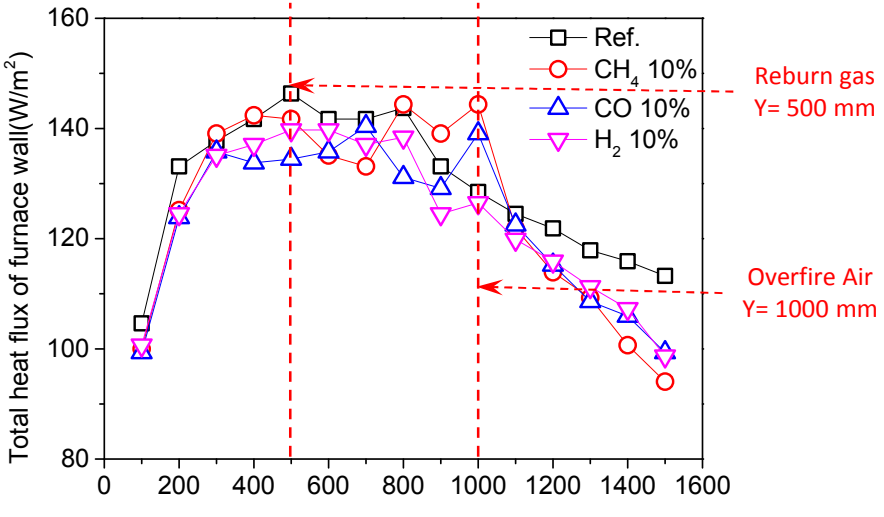
Distribution of CO concentration(Reburning)

- Distribution of CO concentration shows the active combustion zone
- Reburn case, the CO concentration is increased around the centerline in the furnace, where combustion of the main and reburn fuels are active
- In all reburn cases, the CO concentration in the reburn zone is higher than the reference case ➔ partial oxidization, NOx reduction
- Initial burn out zone, CO concentration of the reburn cases is higher than reference case ➔ burn out of the unburned carbon
- CO concentrations in the reburn zone increase as the reburn ratio increases

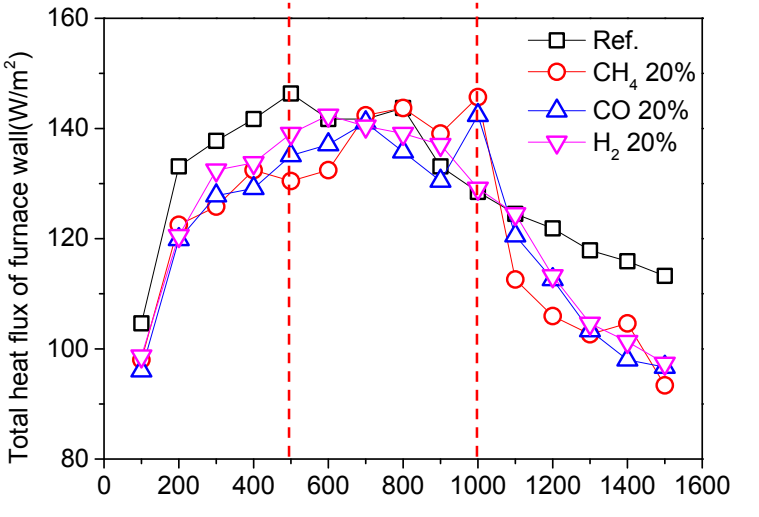


Total heat flux of furnace wall(Reburning)

- Total heat flux measured by heat fluxmeter along the furnace wall
- The total heat flux of the reference case is slightly higher than reburn cases
  - In general, there is no significant change in heat transfer for reburn cases compared with the reference case
- Total heat flux of the reference case in after the OFA zone(x > 1000 mm) is higher than reburn cases, which is caused by nitrogen cooling effect
- Total heat flux of OFA input port area in the reburn cases is quite high
  - Due to burn out of the unburned carbon
- Increasing the reburn ratio
  - Reduces total heat flux for upper part the input port of the reburn fuel(0 < x < 500mm)
  - Increases total heat flux for below part the input port of the reburn fuel(500 < x < 1000 mm)



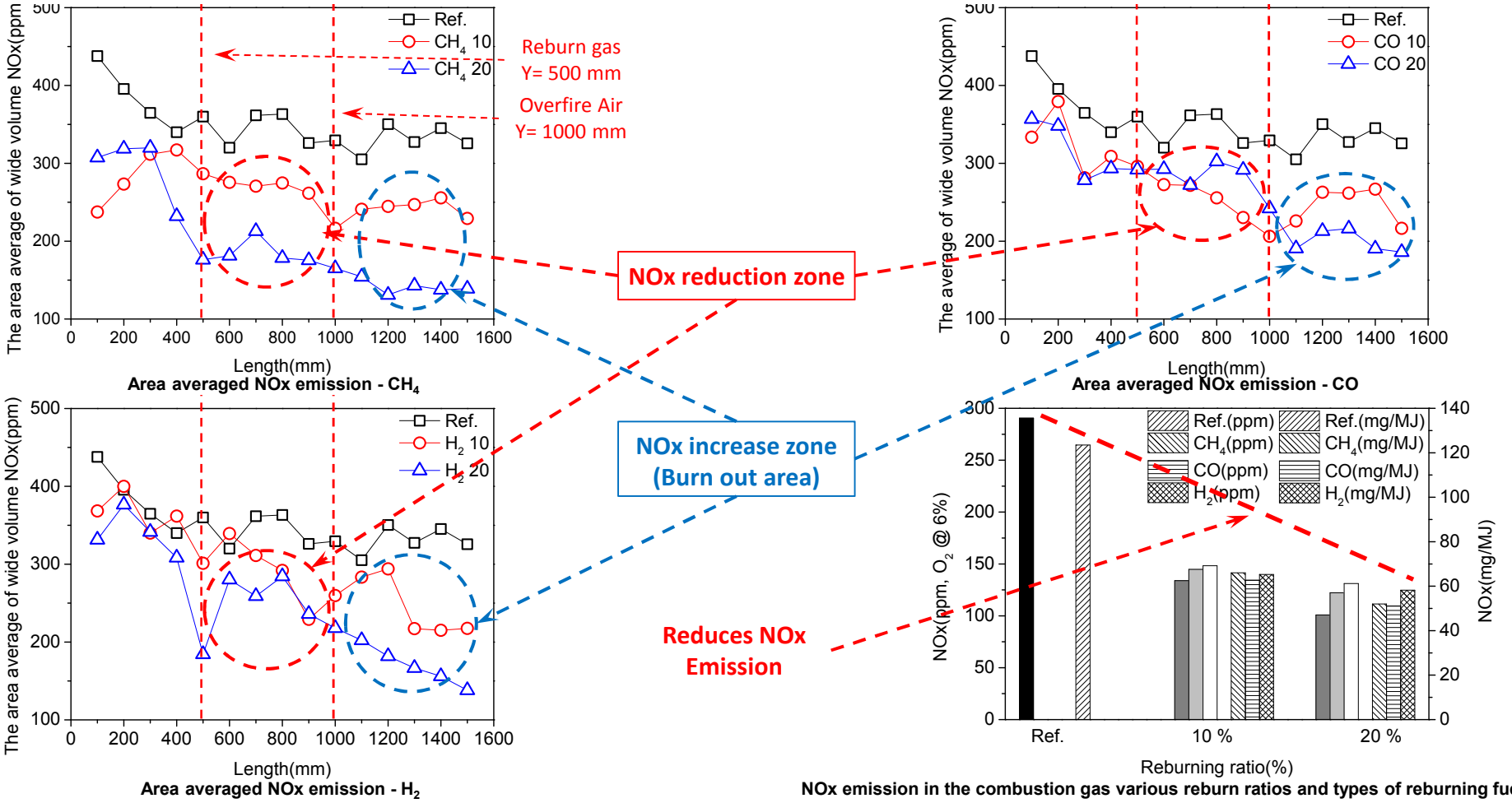
Total heat flux of furnace wall – reburn ratio 10%



Total heat flux of furnace wall – reburn ratio 20%

Distribution of NOx emission(Reburning)

- All concentrations are normalized for an O_2 concentration of 6% in the combustion gas, but the unit, 'mg/MJ', is utilized as well, for removing the dilution effects caused by N_2 in the reburn gas
- NOx reduction ratio differ from reburn fuel, however the reduction of NOx emission as increasing of reburn ratio is similar regardless of reburn fuel



Experimental conditions (Co-firing)

- Fuel: Coal(Bituminous coal, Trafigura), Biomass(Wood pellet, PKS, EFB, Walnut shell)
- Thermal input: 74 kW
- Stoichiometric ratio: 1.2

Fuel	Proximate analysis(%wet)				Ultimate analysis(%wet)				
Component	Moisture	VM	FC	Ash	C	H	O	N	S
Trafigura (Coal)	3.1	31.2	53.0	12.7	67.2	4.7	10.3	1.4	0.6
Wood pellet (BM)	8.3	82.0	8.6	1.1	45.5	5.5	39.6	0.1	0
Palm kernel shell (BM)	9.8	59.6	15.9	14.8	38.8	4.6	31.3	0.8	0
Empty fruit bunch (BM)	7.7	73.5	17.8	1.0	43.2	5.2	42.6	0.3	0
Walnut shell (BM)	9.3	70.5	19.2	1.1	41.1	6.0	31.6	1.1	0

Fuel	Parameter	Cases								
	Name	Ref.	WP 10%	WP 20%	PKS 10%	PKS 20%	EFB 10%	EFB 20%	WS 10%	WS 20%
Coal	Heat ratio (%)	100	90	80	90	80	90	80	90	80
	Fuel rate (kg/hr)	10	9	8	9	8	9	8	9	8
BM	Heat ratio (%)	0	10	20	10	20	10	20	10	20
	Fuel rate (kg/hr)	0	1.6	3.2	1.9	3.8	1.7	3.4	1.6	3.2
Oxi.	1st (Nm3/hr)	9.2	9.1	8.2	8.4	8.2	8.3	8.1	8.3	8.1
	2nd (Nm3/hr)	85.5	84.4	83.5	84.7	83.5	83.7	83.4	83.8	82.8

Internal of the furnace

- Internal of the furnace
  - Reference case is indicate low slagging and fouling tendency
  - Ash deposition of co-firing case is higher than reference case
    - Coal ash: 12.7%, Biomass ash: 1.0 ~ 14.8%
    - Due to coal and biomass co-firing in combustion

Fuel particle size (㎛)					
size(um)	Coal(%)	Wood pellet(%)	PKS(%)	EFB(%)	Walnut shell(%)
600 ↑	0	0	0.7	0	28.2
500 ↑	0	10.5	3.5	1.5	8.5
300 ↑	0.7	25.6	21.1	39.9	15.3
100 ↑	0.4	43.6	43.8	43.6	14.5
75 ↑	35.8	7.3	8.8	5.9	15.8
75 ↓	63.0	13.0	22.1	9.0	17.7
Total	100	100	100	100	100

Reference case

PKS 20%

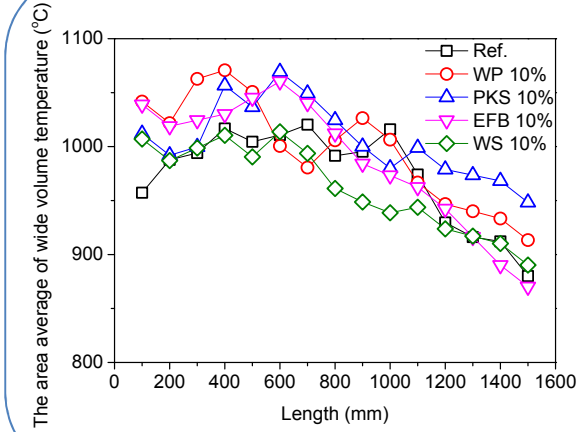
EFB 20%

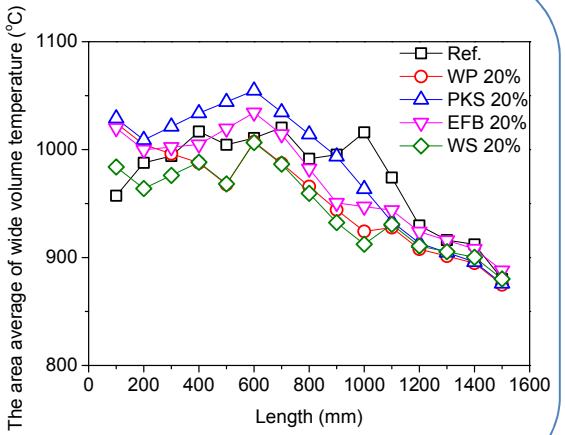
WP 20%

WS 20%

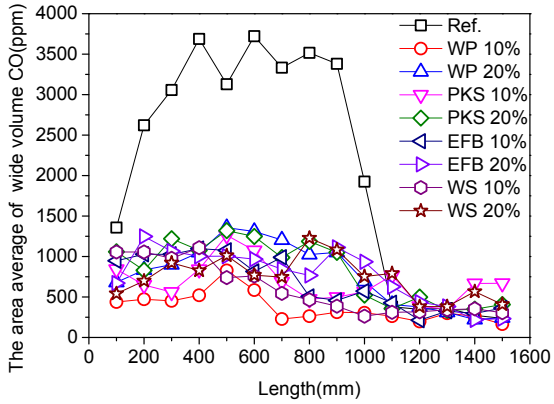
Distributions in the furnace(Co-firing)

- Temperature distribution for the all co-firing cases are quite similar to reference case
- Increasing the co-firing ratio slightly reduces temperature due to biomass contain more moisture and low fixed carbon contents
- Temperature of the co-firing cases increases near the burner outlet in the furnace
- In case of biomass co-firing, the average particle size is larger than reference cases which means it has difficulty in combustion and this leads to low CO concentration in flame zone and unstable combustion state
- The initial experimental phase
  - The fuel Injection rate is slight error due to the fuel input is determined by volume base
    - Currently, the load cells were installed at the under of the coal and biomass feeder





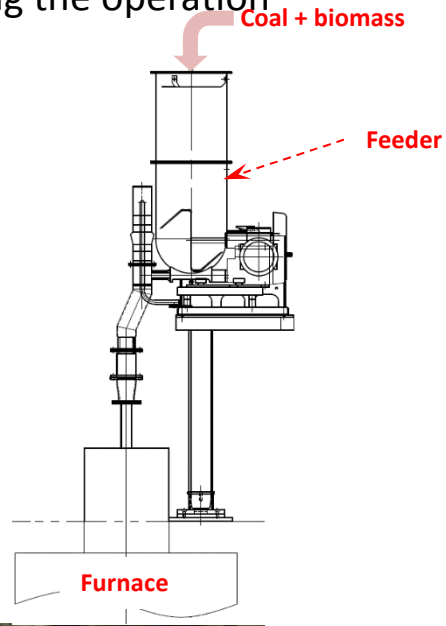
The area average of wide temperature distribution in the furnace(°C)



The area average of wide volume CO(ppm)

Equipment retrofit (coal, biomass feeder)

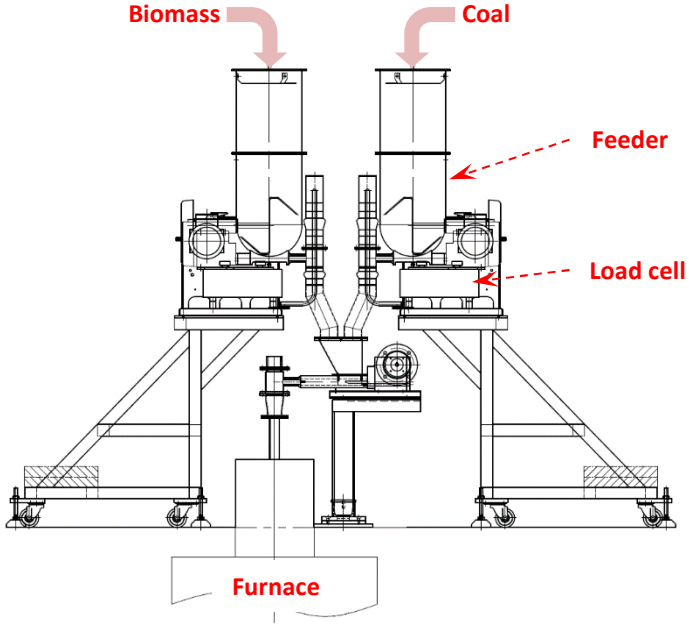
- Initial experimental equipment(1 set)
  - Needs mixer(cylinder type mixer used)
  - Change of co-firing ratio is impossible during the operation



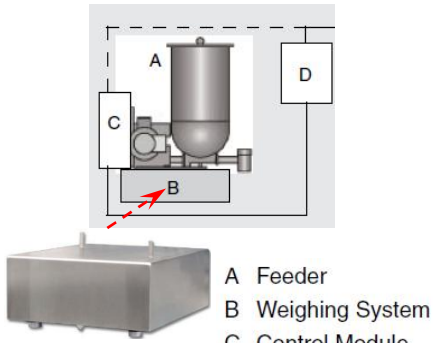
1 set feeder

Cylinder type mixer

- Retrofit experimental equipment(2 set)
  - Mass can be measured
  - Change of co-firing ratio is easy



2 set feeder



Load cell was installed

A Feeder
B Weighing System
C Control Module
D Operator Interface

Conclusion

- Syngas reburn in coal combustion system
  - We found the importance of the reburn gas ratio (10, 20%) as well as of the reburn fuels
  - NOx reduction ratio of coal combustion(ppm)
    - Reburn fuel CH_4: in case of reburn ratio 20%, NOx has been reduced by 65.3%
    - Reburn fuel CO: in case of reburn ratio 20%, NOx has been reduced by 57.9%
    - Reburn fuel H_2: in case of reburn ratio 20%, NOx has been reduced by 54.9%
  - Main conclusions obtained from this study can be summarized as follows
    - Temperature of the reference case is higher than reburn cases
    - As reburn ratio increased, the temperature is reduced for all cases
    - Burnout zone temperature in the reburn cases is lower than that in the reference case due to OFA
    - NOx emission of the reference case is higher than reburn cases
    - As reburn ratio increased, the NOx emission is reduced for all cases
    - Total heat flux of the reference case was slightly higher than other reburn cases
- Coal and biomass co-firing in combustion system
  - Reference case is indicate low slagging and fouling tendency
  - Temperature distribution for the all co-firing cases are quite similar to reference case
  - Increasing the co-firing ratio slightly reduces temperature due to biomass contain more moisture and low fixed carbon contents
  - The initial experimental phase
    - The fuel Injection rate is slight error due to the fuel input is determined by volume base
    - Currently, the load cells were installed at the under of the coal and biomass feeder

Thank you for your attention