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Biomass Co-firing Studies for Commercial-Scale Applications in Korea

Won YANG[1,2]

Principal researcher/Professor

[1]Thermochemical Energy System Group
Korea Institute of Industrial Technology

[2]University of Science and Technology, Korea

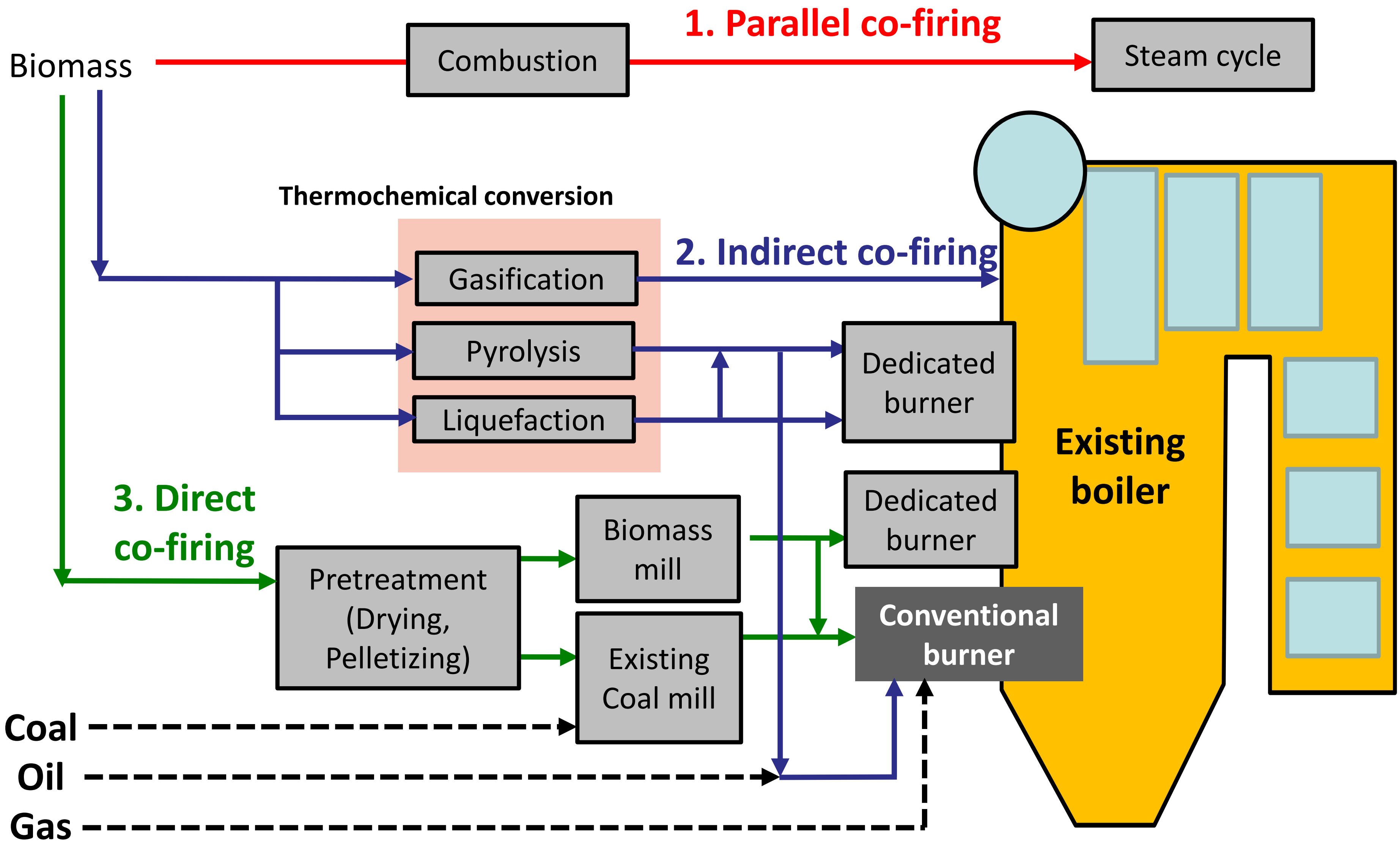
Current issues in coal power generation

- Fuel diversity: Low-rank coals, Bio-SRFs
  - Energy security
  - *RPS (Renewable portfolio standard)*

- CO_2 abatement: 37% reduction on BAU bases by 2030 (25.7% domestic and 11.3% with purchasing carbon credit)
  - CCUS
  - ***Biomass co-firing***
    - The easiest way to reduce CO_2 and secure REC(Renewable energy certificate)
    - > 90% should be imported from other countries
  - Efficiency enhancement: Retrofit & USC/A-USC

- Emission of particulate matters: PM10 and PM2.5
  - Effects to current PM concentration in Korea have not clearly found yet
  - But causes reduction in portion of coal power generation (currently ~ 40% of total electricity generation in Korea) by new government (10/05/2017~)

Co-firing of renewable fuels to conventional boilers



Biomass-dedicated PowerGen

- Donghae CFBC biomass power plant(EWP): 30 MW – New plant

- Several plants are under construction
  - KOSEP: Yeongdong Unit #1 (125 MW): Retrofit
  - GS EPS: Samcheok biomass-dedicated powergen (105 MW): New plant
  - …

Donghae CFBC Biomass-dedicated Power Plant (30 MW, EWP) - Currently in operation

Yeongdong Unit #1 (125 MW, Pulverized coal, KOSEP) - being retrofitted to biomass-dedicated power generation system

Project overview: biomass co-firing to a PC power plant

- Background: Obligation to produce electricity partially by renewable energy (RPS)
- Purpose
  - Maximize co-firing ratio (up to > 10%)
    - Securing REC(Renewable energy certificate) for power companies in KOREA
  - Flexibility in co-fired fuels: Wood pellet ➔ PKS, EFB, and BioSRF
  - Reduce NOx in the furnace: using reburning
- Applied to Samchunpo Power Plant in Korea
  - 500 MWe, Pulverized coal power plant (Owned and operated by KOEN)

Wood pellet (WP)

Empty fruit bunch pellet (EFBP)

Palm kernel shell (PKS)

Walnut shell(WS)

Torrefied biomass(TB)

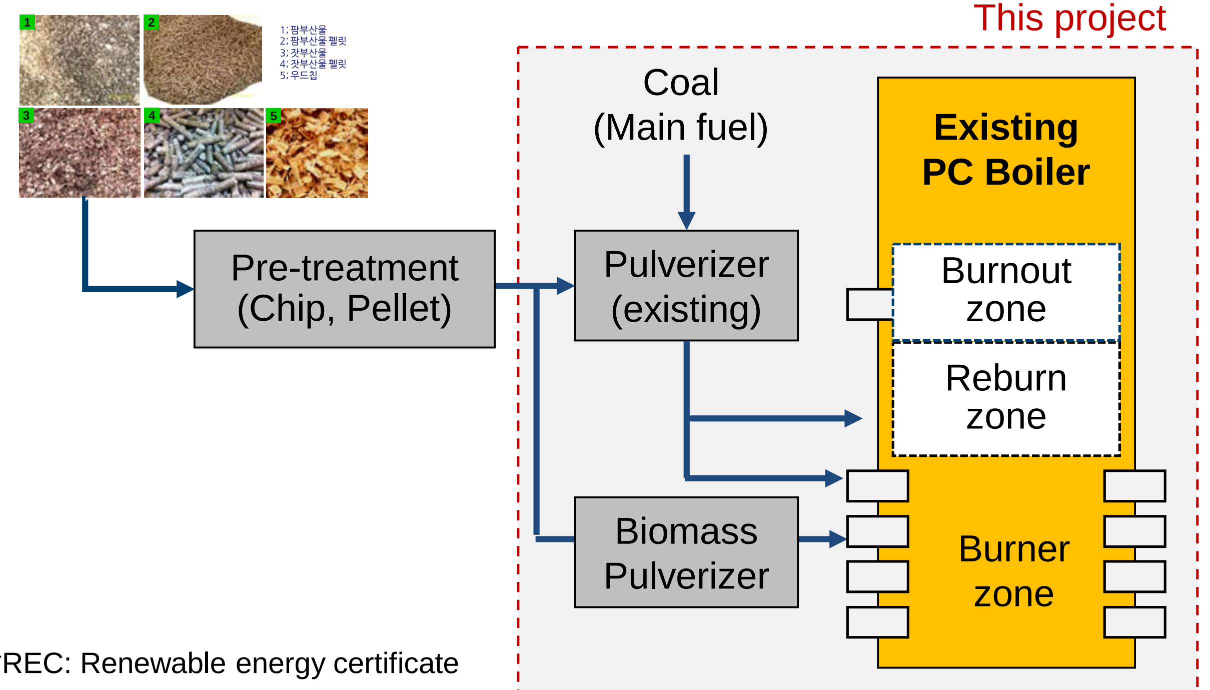
Samcheonpo Thermal Power Plant

Basic concept

- Tested in
  - 80 kWt test furnace in KITECH (combustion, slagging/fouling..)
  - 1 MWt multi-burner furnace in KITECH (Co-firing methods)
  - Commercial power plant (500 MWe) in Samcheonpo TPP, KOREA)

Various renewable fuels

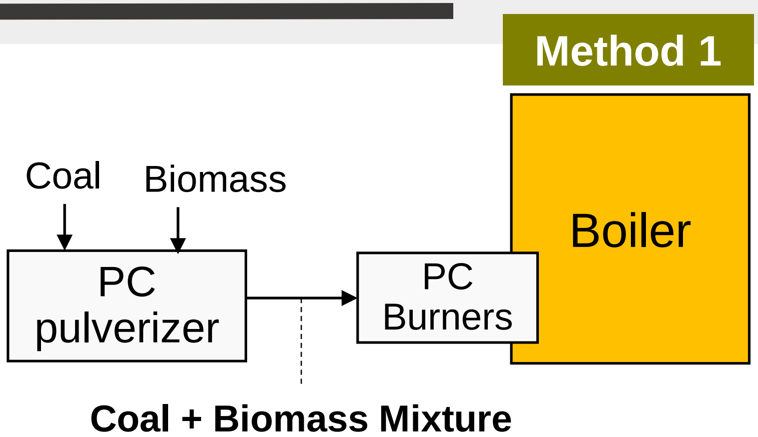
Co-firing + Reburning
- Maximizing co-firing ratio
- Fuel flexibility + NOx reduction



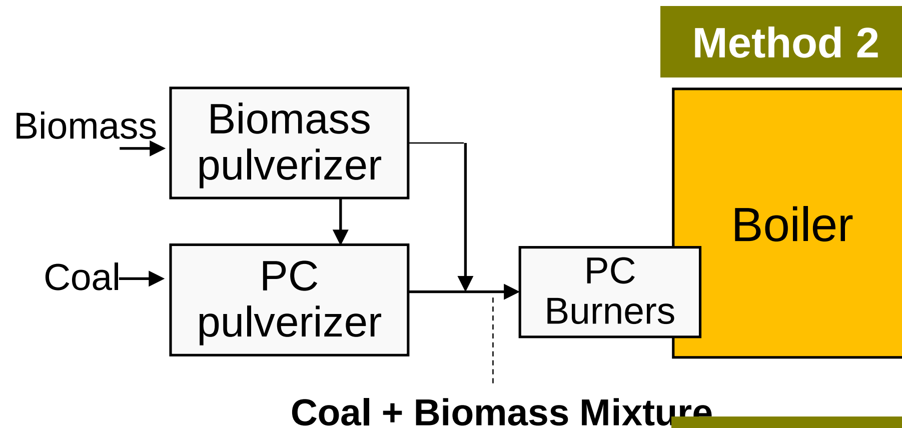
*REC: Renewable energy certificate

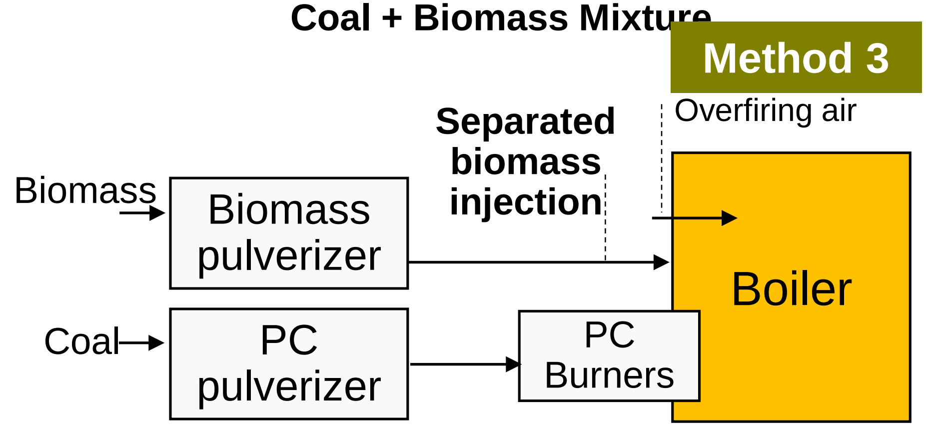
Direct co-firing study

- Process simulation for various biomasses
- Bench-scale experiments
  - Co-firing: blending
  - Reburning: syngas reburning (for observation of NOx reduction)
- Numerical Simulation



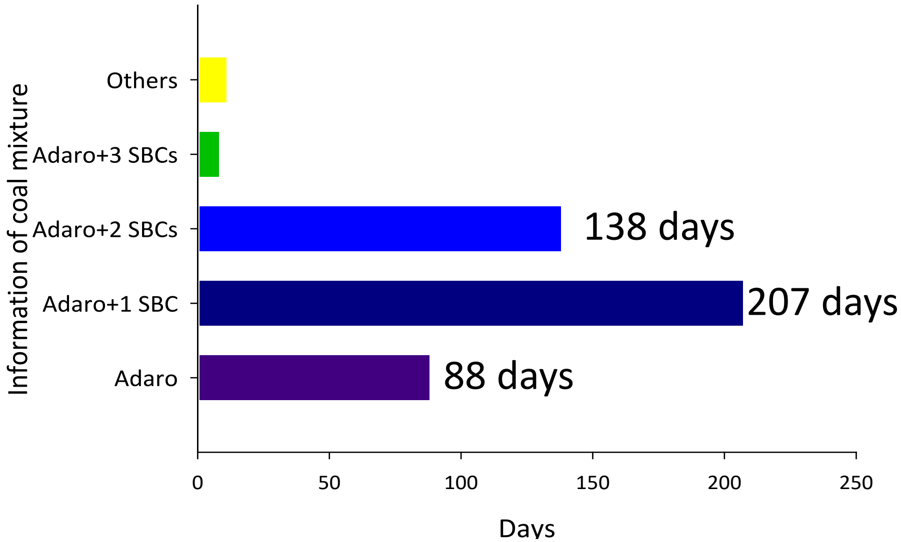
- For 3 Co-firing Methods
  - Method 1
    - No facility addition (Except biomass handling system)
    - Limited co-firing ratio due to the low grindability for biomass fuels
  - Method 2
    - Biomass dedicated pulverizer
    - No boiler modification
  - Method 3
    - Traditional reburning system

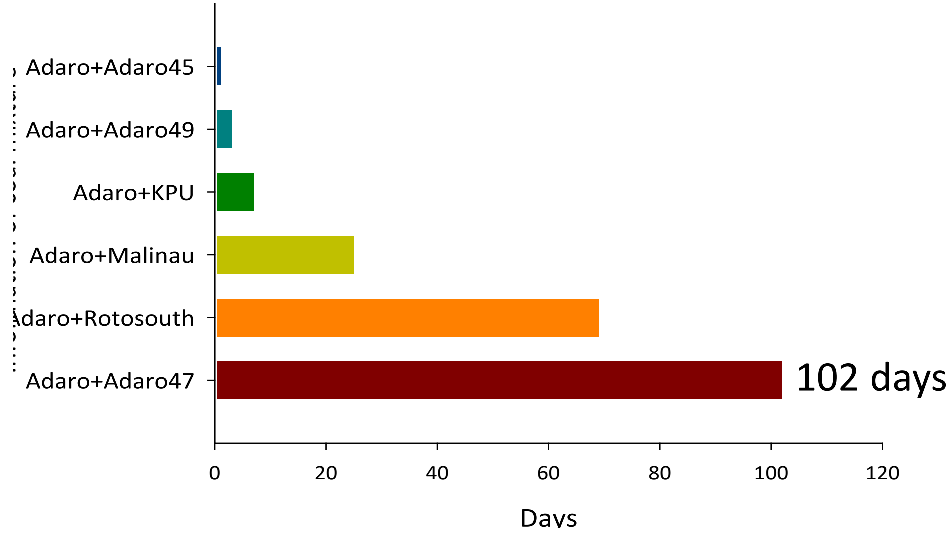




Process Simulation: Case selection

- Main coals (sub-bituminous coals) confirmed from the target plant (500MW)



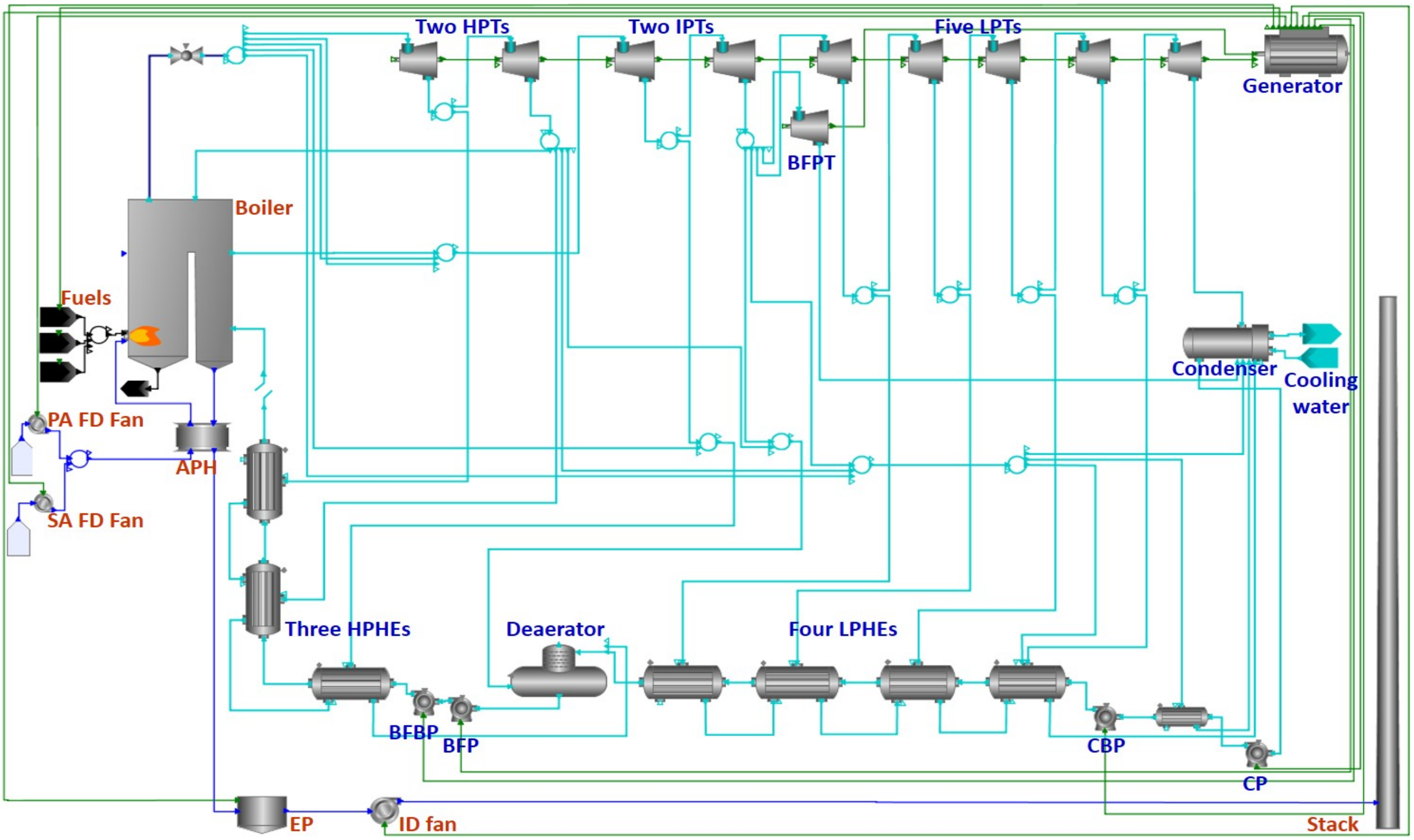


		Proximate analysis (wt.%)[a]				Ultimate analysis (wt.%)[a,b]						HHV[c] (Kcal/kg)
Fuel		M	VM	FC	A	C	H	N	S	O	Cl	
Coal	Design	10.3	42.0	46.2	1.5	64.4	4.7	0.89	0.098	18.1	-	6249.0
	Adaro	17.2	39.2	40.8	2.9	57.7	4.0	0.98	0.083	17.2	-	5489.5
	Adaro47	19.5	39.9	37.2	3.4	55.7	3.9	0.91	0.089	16.5	-	5310.0
	TL	32.0	28.0	25.0	15.0	37.7	3.0	0.71	0.900	10.7	-	3666.7
Biomass	WP	8.3	82.0	8.6	1.1	46.8	5.6	0.10	0.010	40.7	0.003	4471.8
	EFBP	7.7	73.5	17.8	1.0	47.0	5.7	0.28	0.004	46.3	0.015	4375.2
	PKS	9.8	59.6	14.8	15.9	48.4	5.7	1.04	0.014	39.1	0.018	4605.2
	WS	9.3	70.5	19.2	1.1	48.5	7.1	1.33	0.029	37.2	-	5110.2
	TB	3.1	62.5	33.3	1.1	71.2	4.6	0.01	0.010	22.3	-	6666.3

a: Wet basis, b: Elemental analyzer, c: Channiwala and parnikh equation, TL: Texas lignite, WP: Wood pellet, EFBP: Empty fruit bunch pellet, PKS: Palm kernel shell, WS: Walnut shell, TB: Torrefied biomass (from torrefaction under 325 ^{o}C, 30 min)

Process flow diagram on the target PCPP (gCCS)

- Coupled analysis of gas side and water/steam side



Simulation procedure

- Basic input parameters for process simulation
  - Physical property method: Peng-Robinson equations for gas side and IAPWS-25 for turbine island
  - Steady-state flow
  - Same parameters on turbine island in all case: Mass flowrate of feed-water and pressure
  - Oxygen concentration at the exit of the furnace: 3 % in case studies
  - Air leakage at the air pre-heater: 6.79 wt.%

$$\frac{\textbf{Mass flowrate of air in leakage}}{\textbf{Mass flowrate of flue gas}} \times 100$$

- Main simulation conditions

Parameters	M.V.	Combustion of low rank coals				Biomass co-firing				
		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9
Coal (Thermal share %)	D (100)	TL (100)	A (100)	A47 (100)	A+A47 (60+40)	A+A47 (60+30)	A+A47 (60+30)	A+A47 (60+30)	A+A47 (60+30)	A+A47 (60+30)
Biomass (Thermal share %)						WP (10)	EFBP (10)	PKS (10)	WS (10)	TB (10)

D: Design coal, TL: Texas lignite, A: Adaro coal, A47: Adaro47 coal, WP: Wood pellet, EFBP: Empty fruit bunch pellet, PKS: Palm kernel shell, WS: Walnut shell, TB: Torrefied biomass

Power consumption in the pulverizer

- Power consumption of pulverizers obtained from HGI* test
  - HGI of the fuel is directed related to the power consumption of mills
  - Coal-biomass blends have lower HGI and higher fuel feedrate
    - ➔ More milling power is required
  - However, AC+TB(Torrefied biomass) has similar milling power requirement due to high HGI and lower fuel feedrate than other biomass co-firing cases

*Hardgrove grindability index
**Bond work index

Fuel (Thermal base %)	TL (100%)	AC (100%)	A47C (100%)	AC (60%) +A47C (40%)	AC (90%) +WP (10%)	AC (90%) +EFB (10%)	AC (90%) +PKS (10%)	AC (90%) +WS (10%)	AC (90%) +TB (10%)
More than 75 μm (g)	-	-	-	-	45.56	45.45	45.24	46.14	**45.11**
HGI	60	51	51	51	43.8	44.5	46.0	39.8	**46.9**
BWI (kJ/kg)	30.82	34.06	34.06	34.06	36.65	36.60	35.86	38.09	**35.53**
Fuel amount (kg/s)	86.76	56.54	58.52	57.34	58.86	59.52	58.49	58.14	**56.21**
Milling power requirement (MWe)	**2.673**	**1.926**	**1.993**	**1.952**	**2.157**	**2.166**	**2.097**	**2.215**	**1.997**

Minimum power consumption among biomass co-firing cases

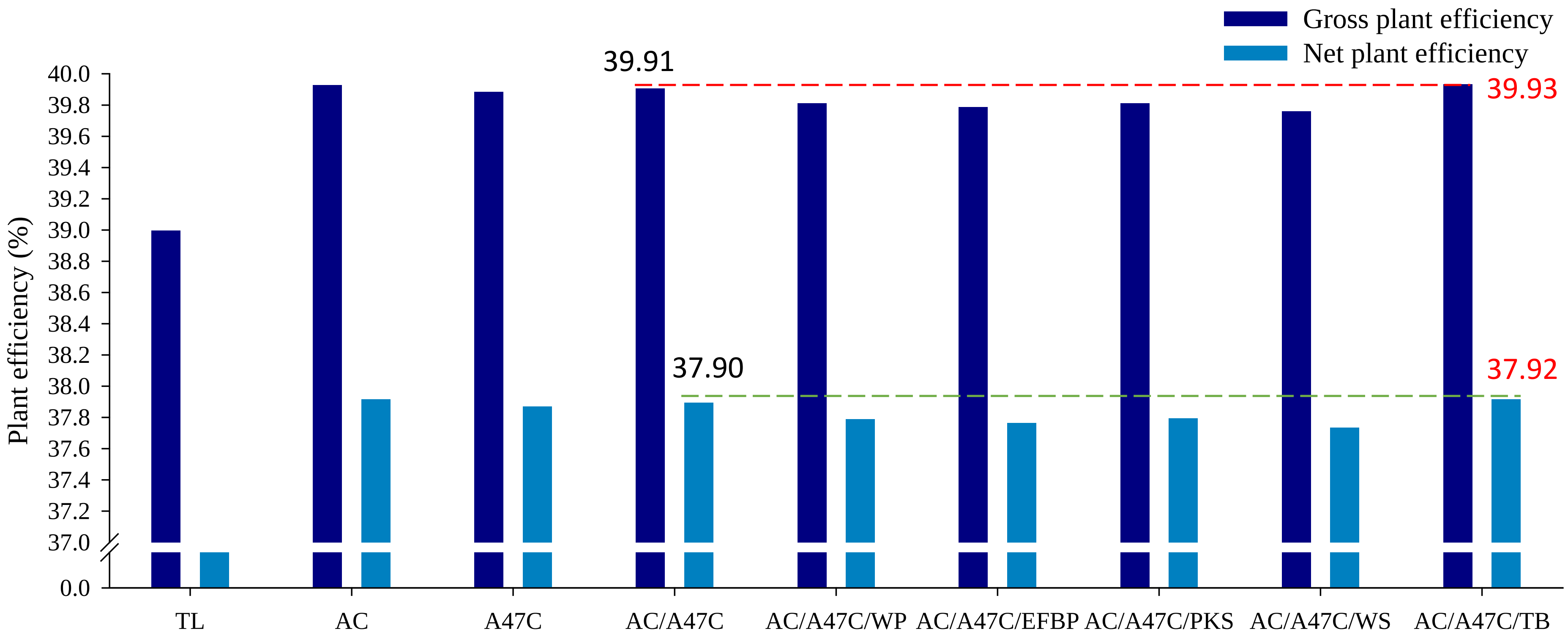
Plant efficiency

- Gross plant efficiency
- Net plant efficiency

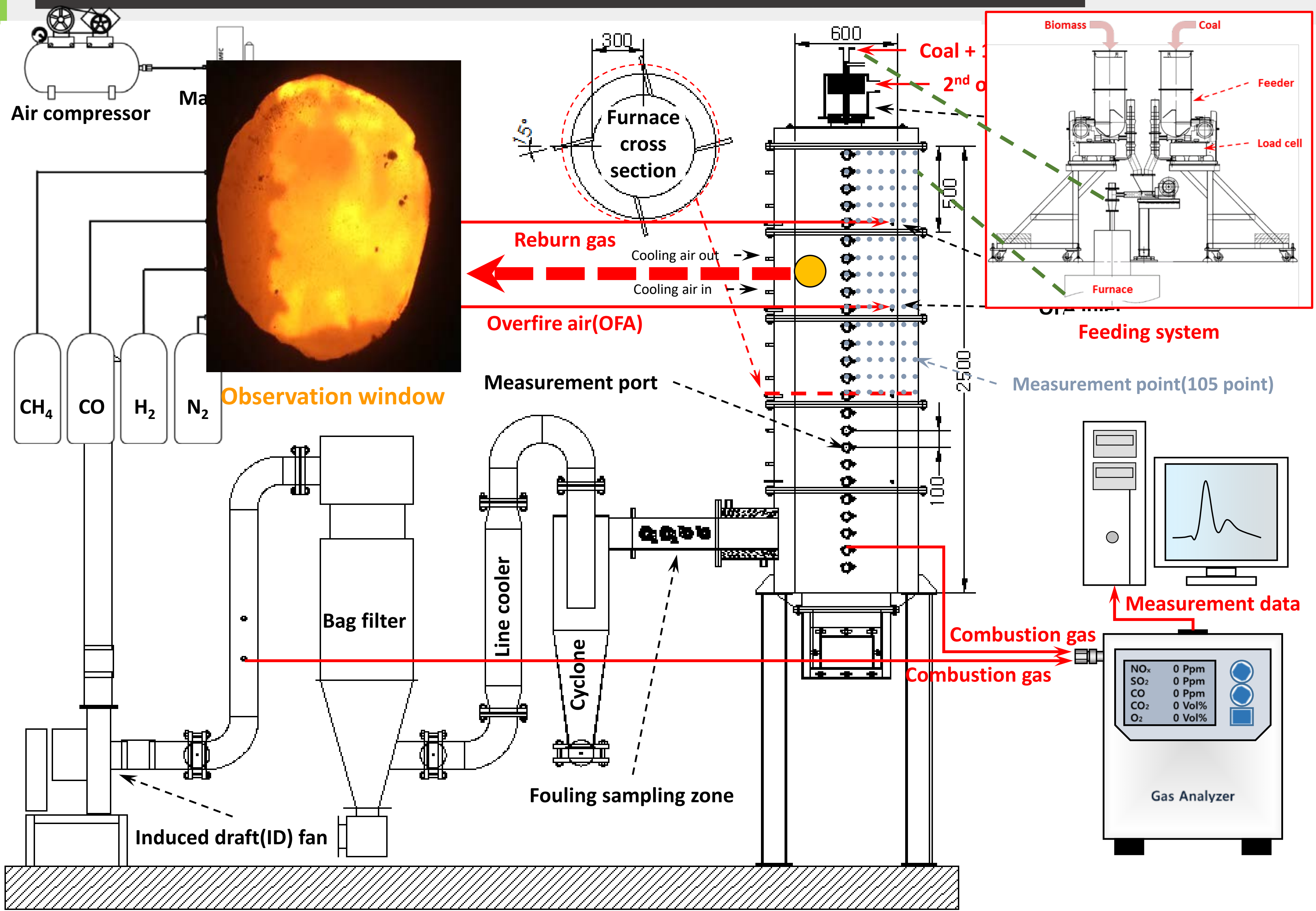
$$\eta = \frac{Gross\ power\ generation\ \times 100}{Mass\ flowrate\ of\ fuel \times HHV\ of\ fuel}$$

$$\eta = \frac{(Gross\ power\ generation - Total\ power\ consumption)\ \times 100}{Mass\ flowrate\ of\ fuel \times HHV\ of\ fuel}$$

- Less efficiency for biomass co-firing case, but
- TB co-firing case shows the larger efficiency than the AC/AC47 case



Experimental works – 80 kW_{th} furnace



Test condition for direct co-combustion

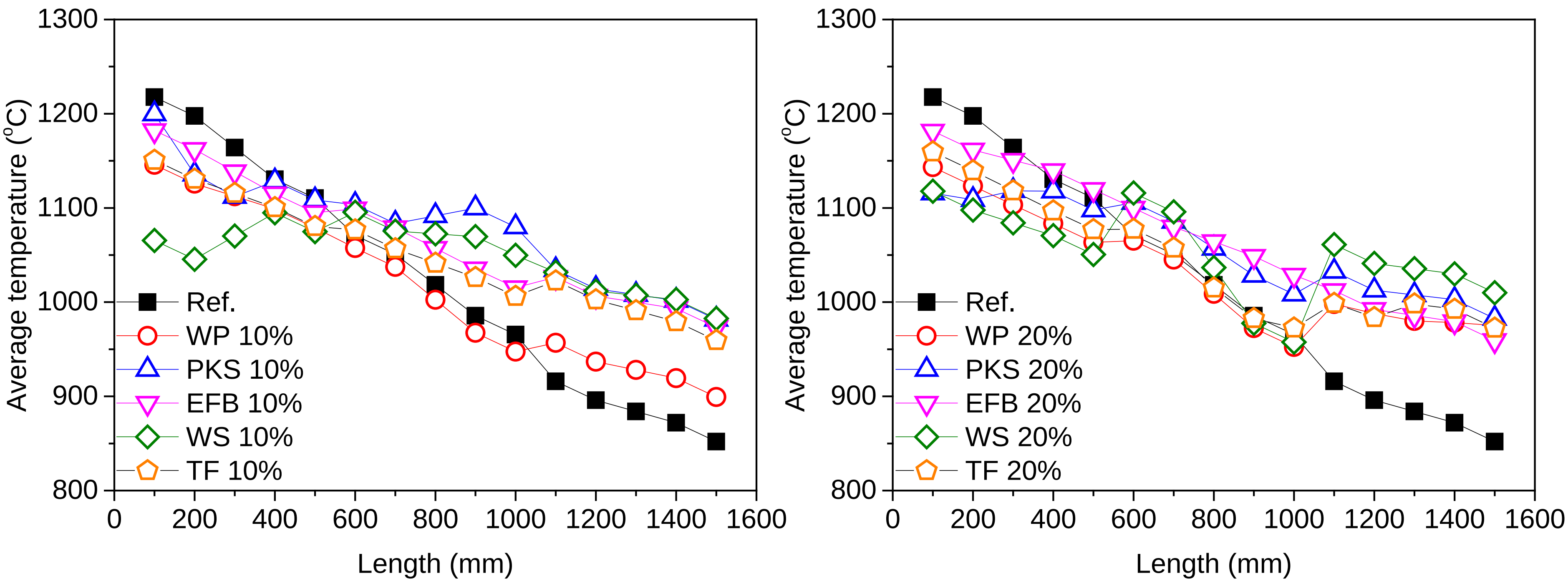
- Fuel: Trafigura (Bituminous coal)
- Co-fired biomass: Wood pellet, Palm kernel shell, Empty fruit bunch, Walnut shell
  - Average particle size: 400 μm
  - Directly mixed with coal and introduced to the burner
- Thermal input: 80 kW
- Stoichiometric ratio: 1.2

Fuel	Conditions	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
Biomass	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
Flowrate of Oxidizers	*PA (Nm^3/hr)	9.2	8.4	8.2	8.4	8.2	8.4	8.1	8.4	8.1
	**SA (Nm^3/hr)	85.5	84.4	83.5	84.7	83.5	83.7	83.4	83.8	82.8

*PA: Primary air
**SA: Secondary air

Temperature distribution

- In co-firing cases,
  - Upper part of the furnace temperature was lower than reference case
    - Because biomass contains more moisture and less fixed carbon ➔ Low heating value
  - Higher temperatures in the downstream due to the fact that
    - Particle size of the biomasses was larger than coal
    - Char reaction became slow, caused increase in burn-out time



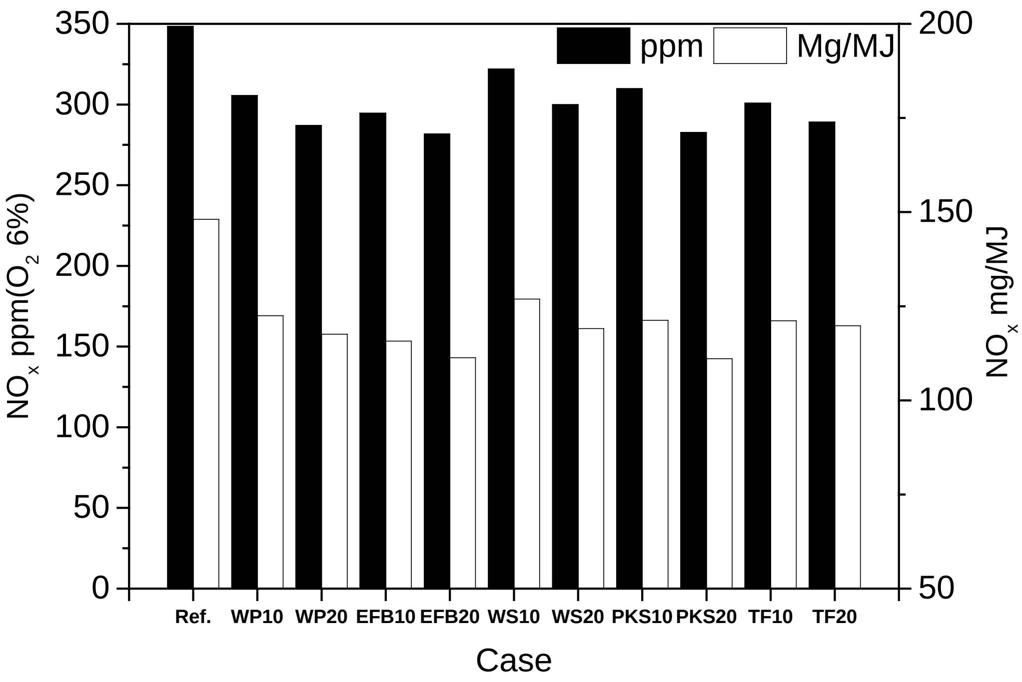
(a) 10% co-firing (b) 20% co-firing

Area-averaged temperature distribution along axial distance

Gas concentration at the exit

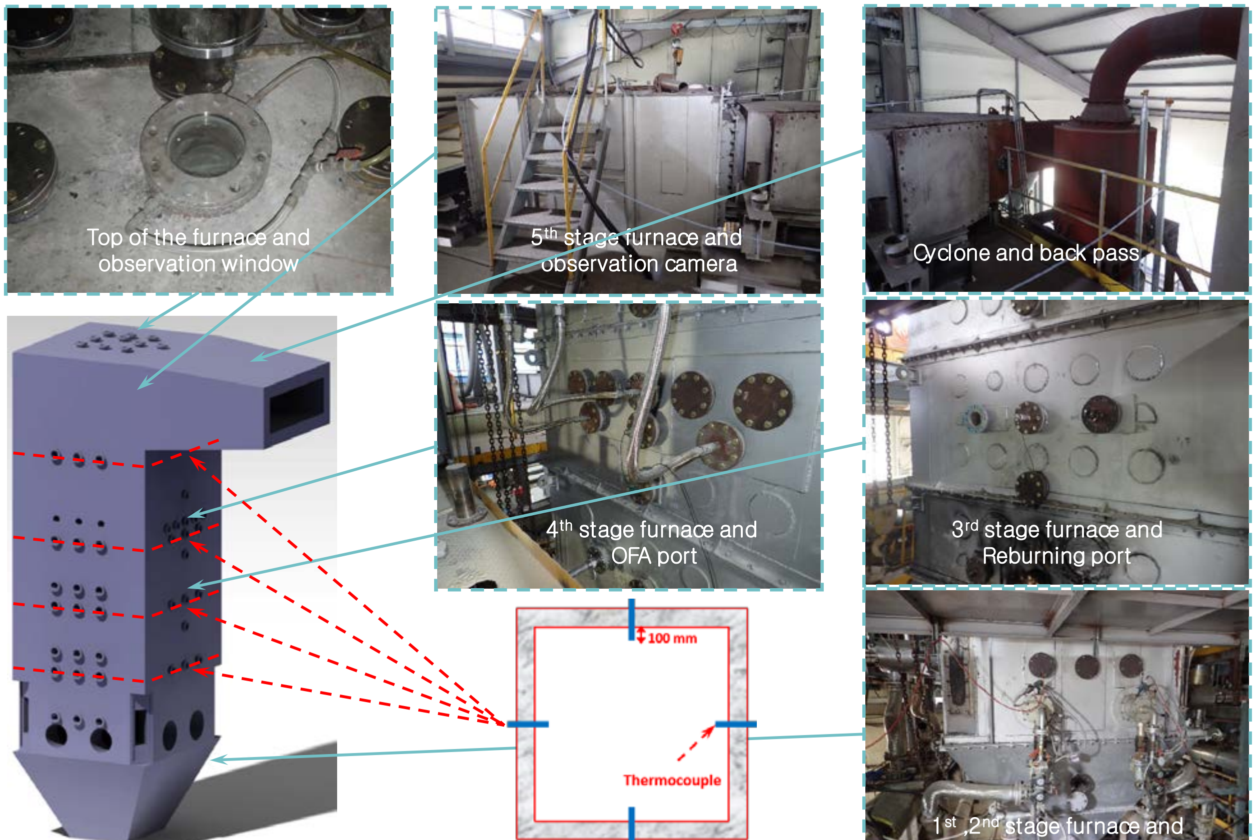
- CO concentration at the exit increases by biomass co-firing
  - Due to slow reaction of biomass char oxidation ($C + ½O_2 \rightarrow CO$)
- NO_x concentration
  - NO_x emission decreases by biomass co firing
  - Reference case: 348.5 ppm, **EFB 20%** case: 282 ppm ➔ **Max 19.1 % reduced**
    - Other combustion conditions (e.g. local stoichiometric ratio) can affect the NOx emission regardless of the fuel nitrogen

Component	Ultimate analysis(%wet)				
	C	H	O	N	S
Trafigura	67.2	4.7	10.3	**1.4**	0.6
Adaro	55.8	5.3	17.1	**0.7**	0
Wood pellet	45.5	5.5	39.6	**0.1**	0
Palm kernel shell	38.8	4.6	31.3	**0.8**	0
Empty fruit bunch	43.2	5.2	42.6	**0.3**	0
Walnut shell	41.1	6.0	31.6	**1.1**	0
Torrefied biomass	61.9	5.8	28.1	**0.7**	0

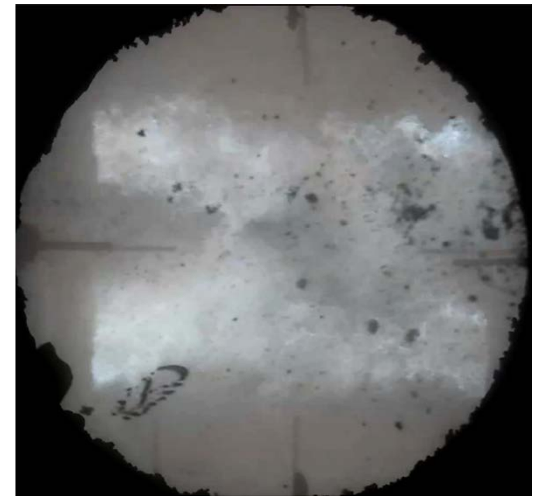


During co-firing experiment -1 MW_{th} furnace

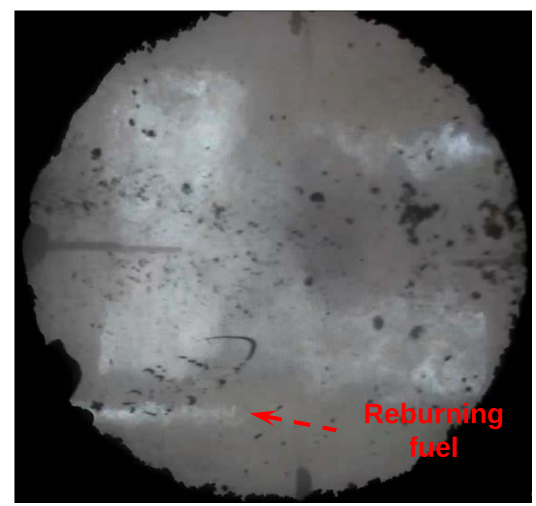
- Stable combustion can be observed for 20% biomass co-firing



Temperature measurement locations



Co-firing

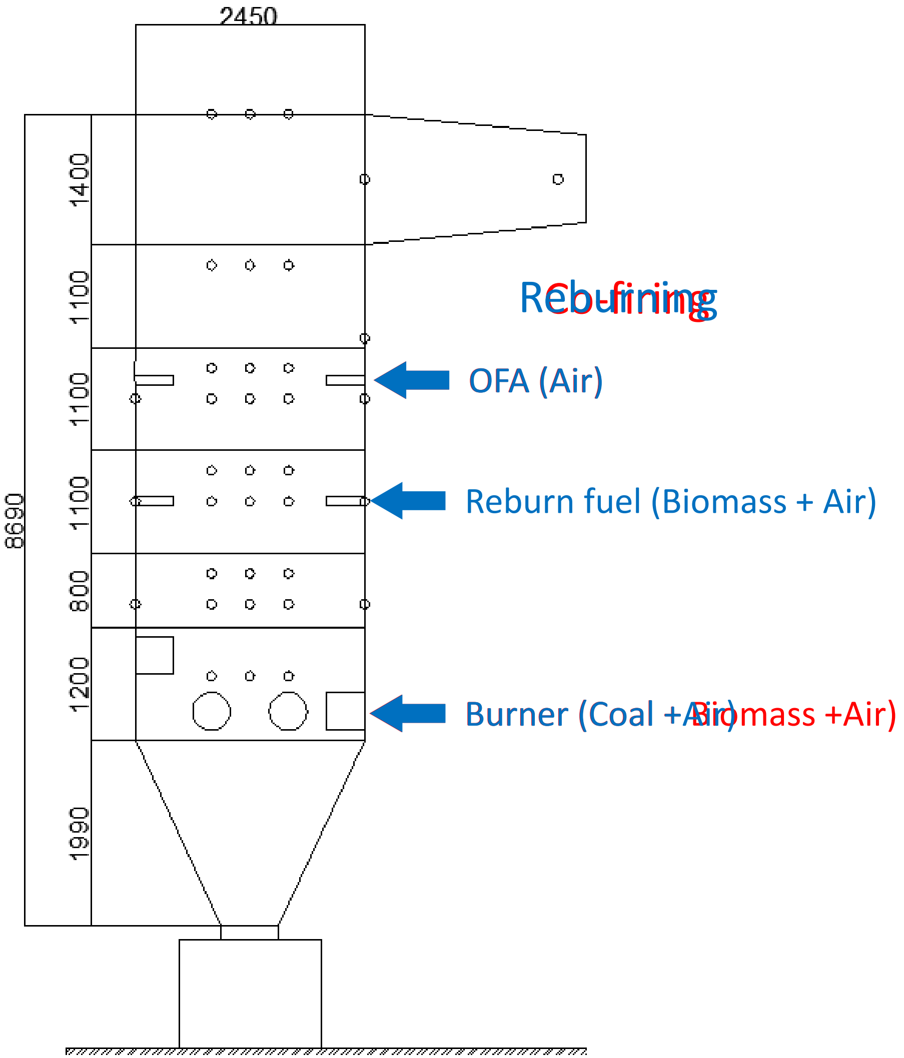


Reburning

Test conditions

- Main fuel: Adaro (Subbituminous coal)
- Co-firing fuel: Wood pellet, Empty fruit bunch, Torrefied biomass
- Thermal input: 1 MW
- Stoichiometric ratio: 1.2

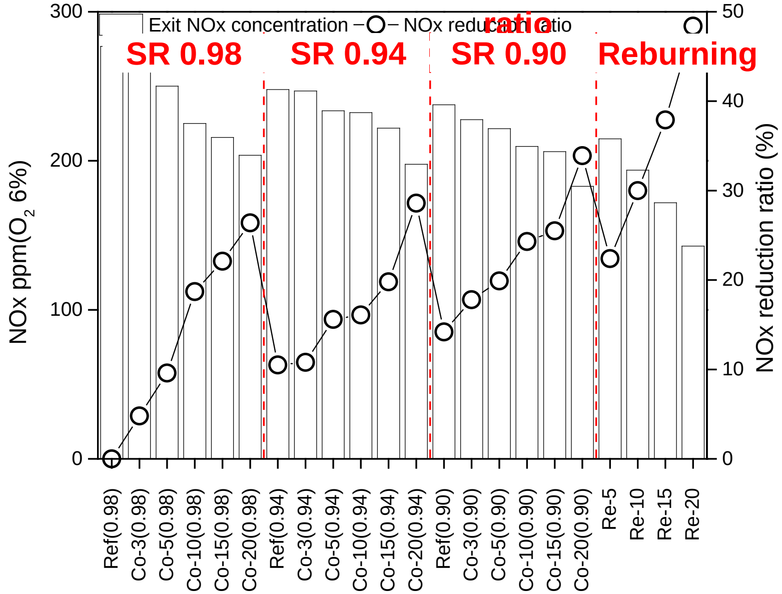
Combustion type		Coal 100%	Co-fir		
Fuel	Name	Ref.	Co-3	Co-5	Co-1
Coal	Heat ratio (%)	100	97	95	90
Coal	Fuel rate (kg/hr)	161	156	153	145
BM	Heat ratio (%)	0	3	5	10
WP	Fuel rate (kg/hr)	0	5.6	9.4	18.
TB	Fuel rate (kg/hr)	0	4.5	7.5	15.
EFB	Fuel rate (kg/hr)	0	-	11.8	23.

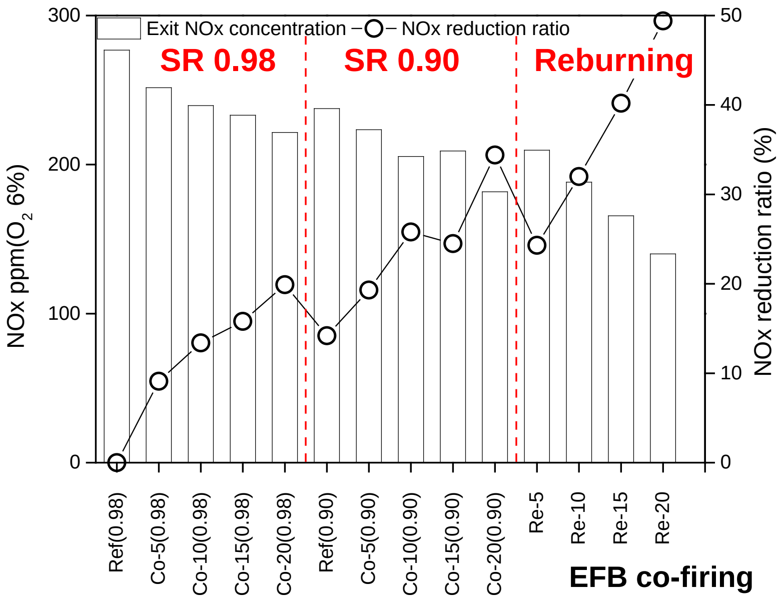


Result of direct co-firing condition – 1MW$_{th}$ furnace

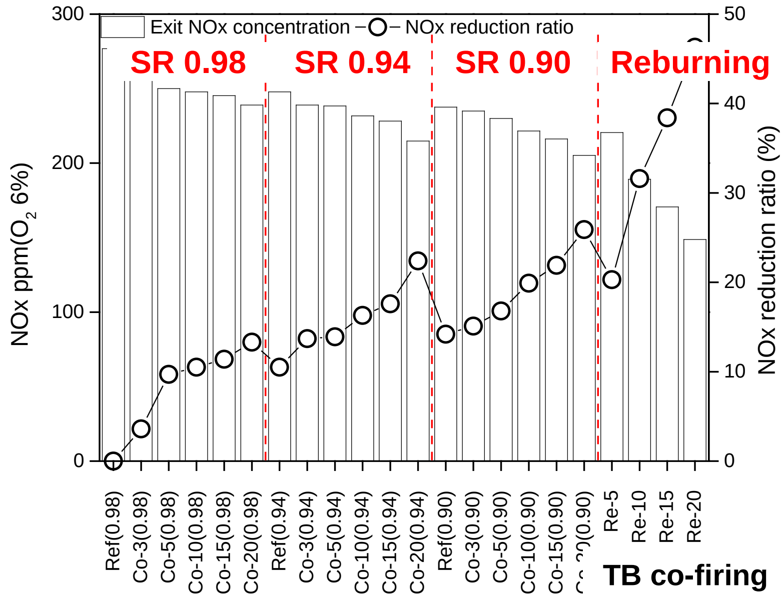
- NOx concentration decreases as SR(stoichiometric ratio) decreases
  - Air staging is effective for NOx reduction
- NOx reduction
  - Co-firing < Co-firing + Air staging < Reburning
- Torrefied biomass shows slightly higher NOx concentration than other biomass
  - Contain less moisture compared to biomass

SR: Burner zone stoichiometric ratio



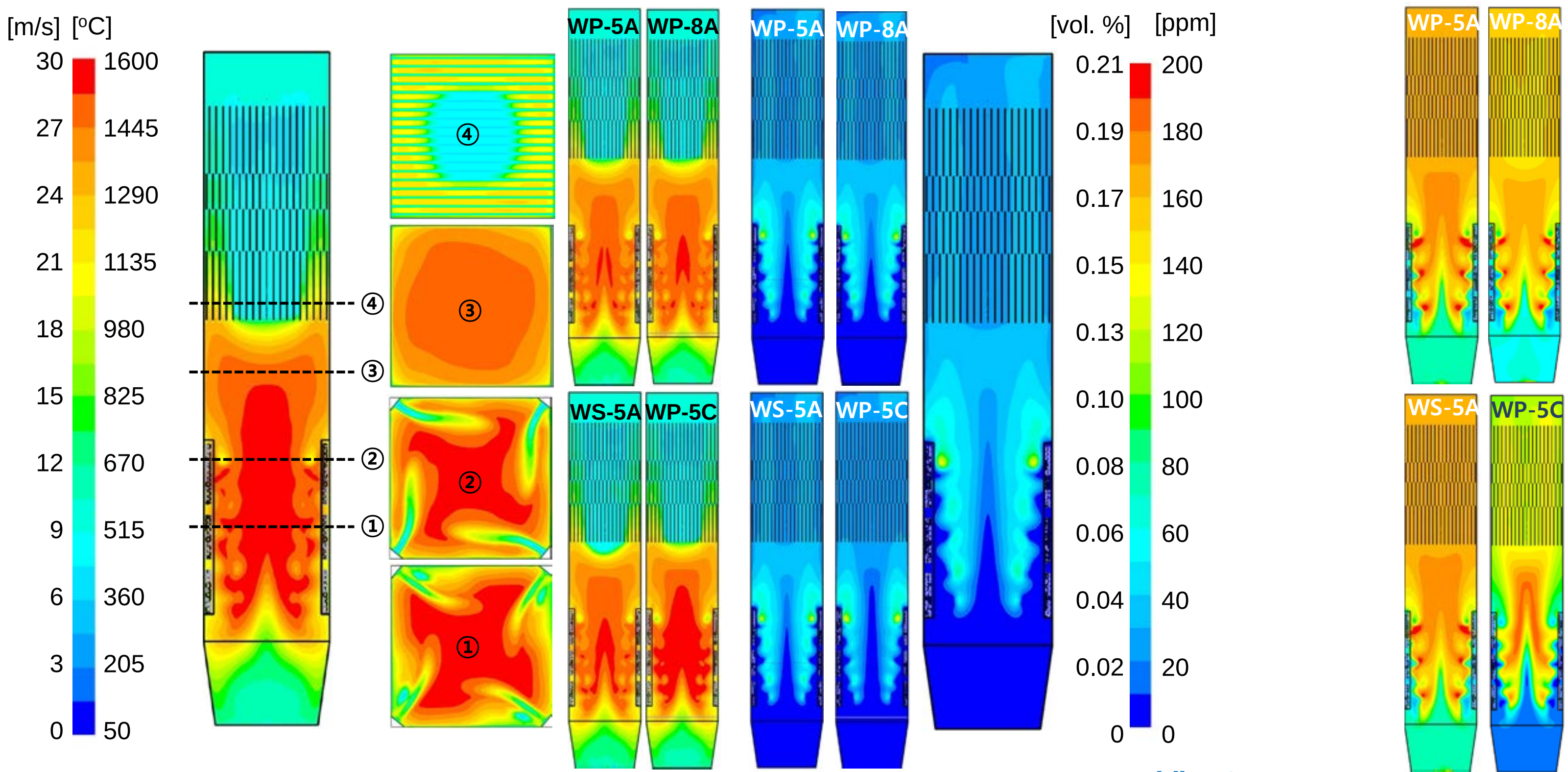


EFB co-firing



TB co-firing

CFD simulation results (500 MW) 1



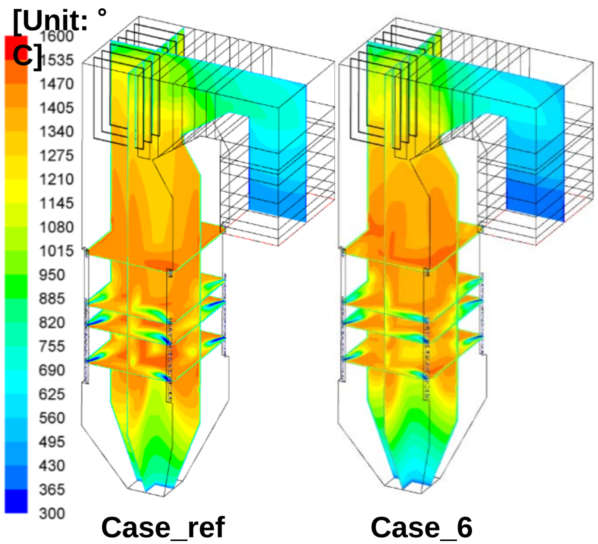
(a) Pathline (b) Temperature (c) O_2 concentration (d) NOx concentration

Case Name	Furnace exit temperature	Furnace heat recovery	NOx (reduction)
Reference	1295 ºC	1043 MW_{th}	184 ppm
WP-8A	1236 ºC	1001 MW_{th}	156 ppm (-15%)
WP-5A	1239 ºC	1010 MW_{th}	163 ppm (-11%)
WP-5B	1199 ºC	1030 MW_{th}	155 ppm (-16%)
WP-5C	1249 ºC	1011 MW_{th}	**119 ppm (-35%)**
PKS-5A	1188 ºC	1016 MW_{th}	175 ppm (-5%)

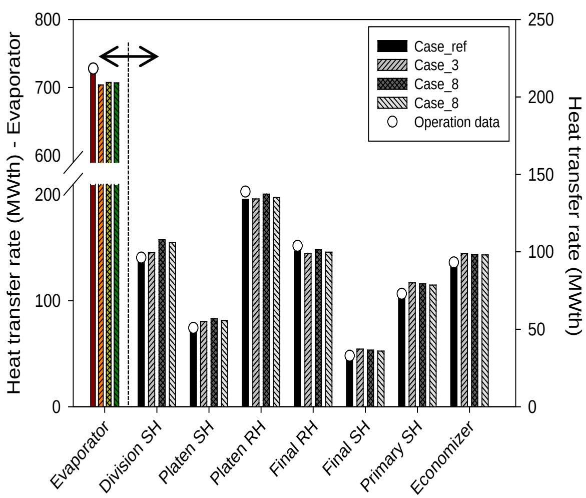
- Various biomasses, Co-firing ratios & Co-firing methods
- Co-firing method is most important for NOx reduction

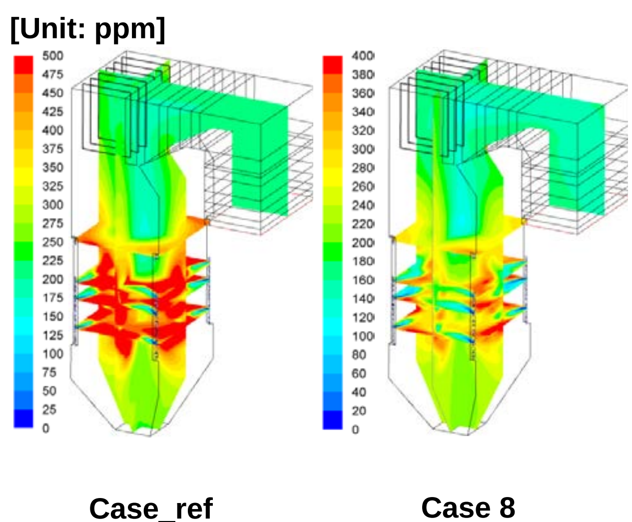
CFD simulation results (500 MW) 2

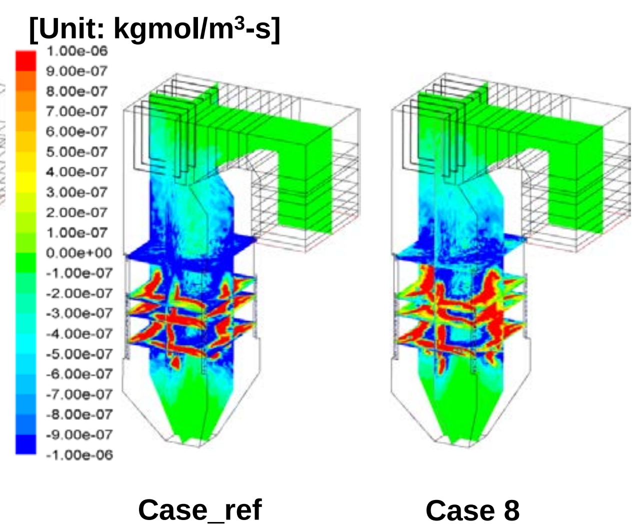
- Target: In-furnace NOx reduction
- Main operating parameter: Equivalence ratio in the burner zone



	Eqv. ratio		Biomass	Co-firing ratio(heat basis, %)	Exit O2 (vol %)	NOx (ppmv)	NOx Reduc. ratio(%)
	BNR	OFA					
Ref	0.995	0.125	-	-	2.4	214	-
1	0.90	0.22	Wood pellet	3	2.9	166	22.4
2				5	2.9	160	25.2
3	0.98	0.14		3	2.3	171	20.0
4				5	2.4	169	21.0
5	0.90	0.22	Torrefied biomass	3	2.9	165	22.9
6				5	2.9	158	26.2
7	0.98	0.14		3	2.9	166	22.4
8				5	2.9	160	25.2

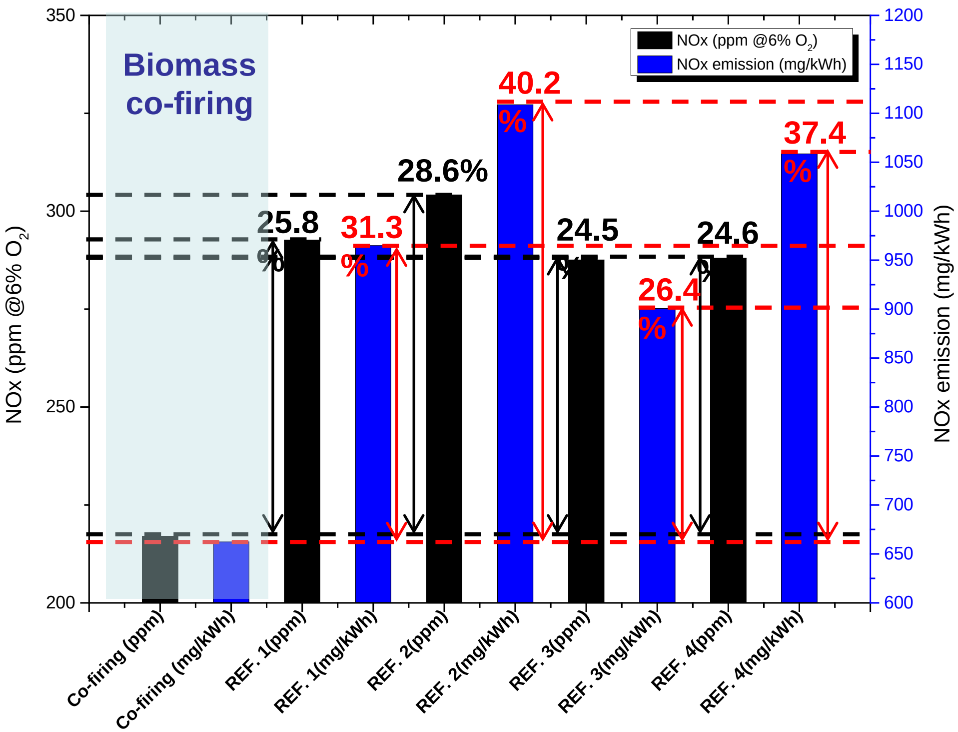






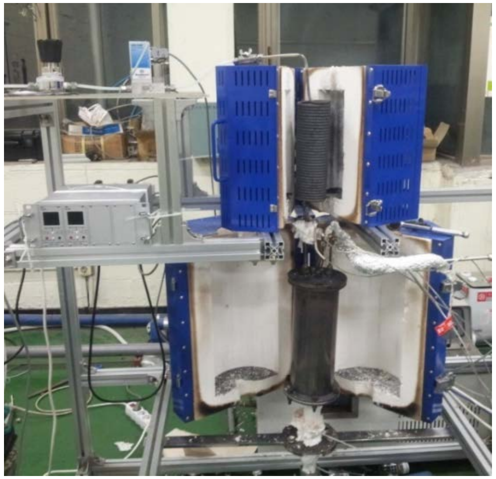
Commercial operation

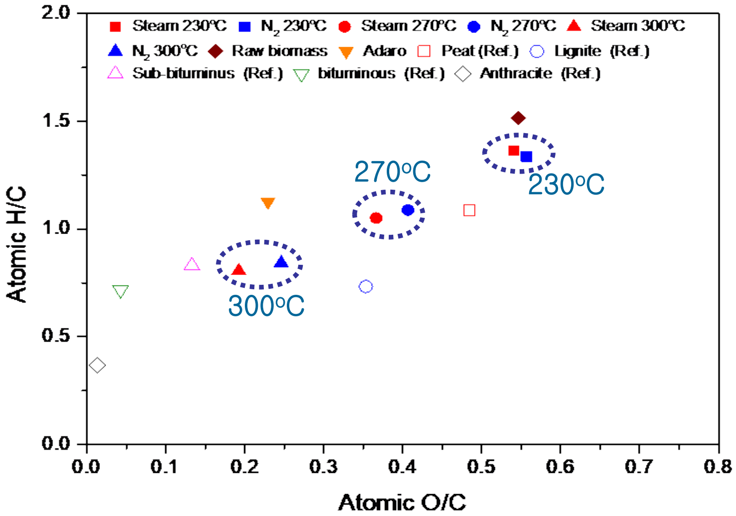
- Commercial power plant(500MW$_e$) in Samcheonpo, Korea
  - NOx reduction characteristics for biomass co-firing and coal firing
  - Operating condition
    - fuel : Coal - Bituminous coal+ subbituminous coal , Biomass - Woodpellet
    - Experiment Period for biomass co-firing : 57 hr
    - Biomass co-firing ratio : mass basis 6%, heating value basis 4.9%
  - NOx reduction ratio by co-firing : Max 28.6%, Min 24.5%
- Reburning of biomass was not applied – Risks in adding new facility(Biomass dedicated mill)
- Torrefaction can be a good option for enhancing co-firing ratio



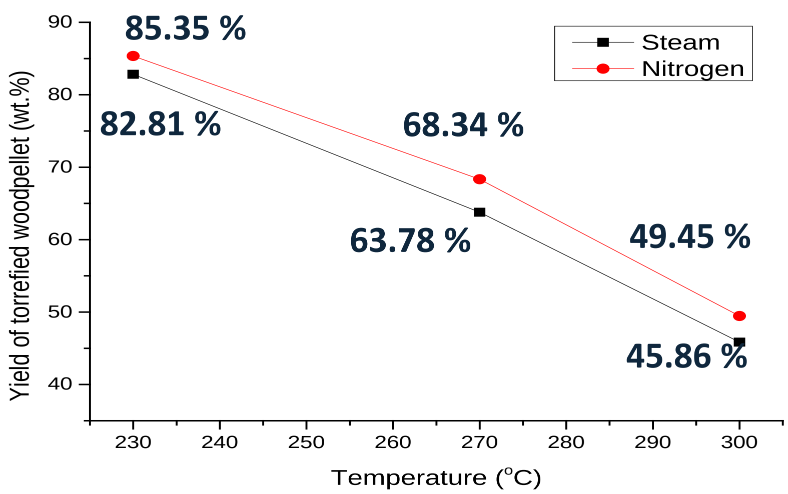
Lab-scale torrefaction experiment (1)

- Lab-scale fixed-bed type
- Major parameters
  - Nitrogen vs Steam
  - Temperature

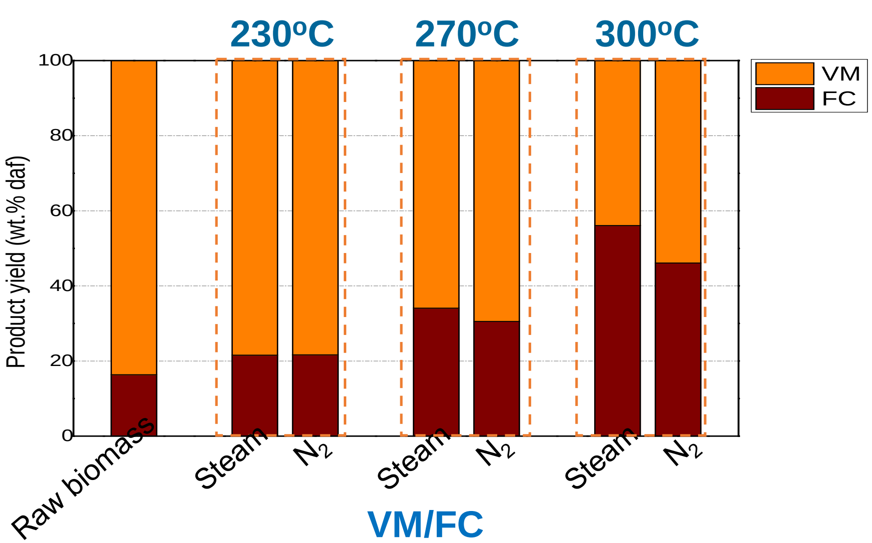




<Van Krevelen diagram of various samples>



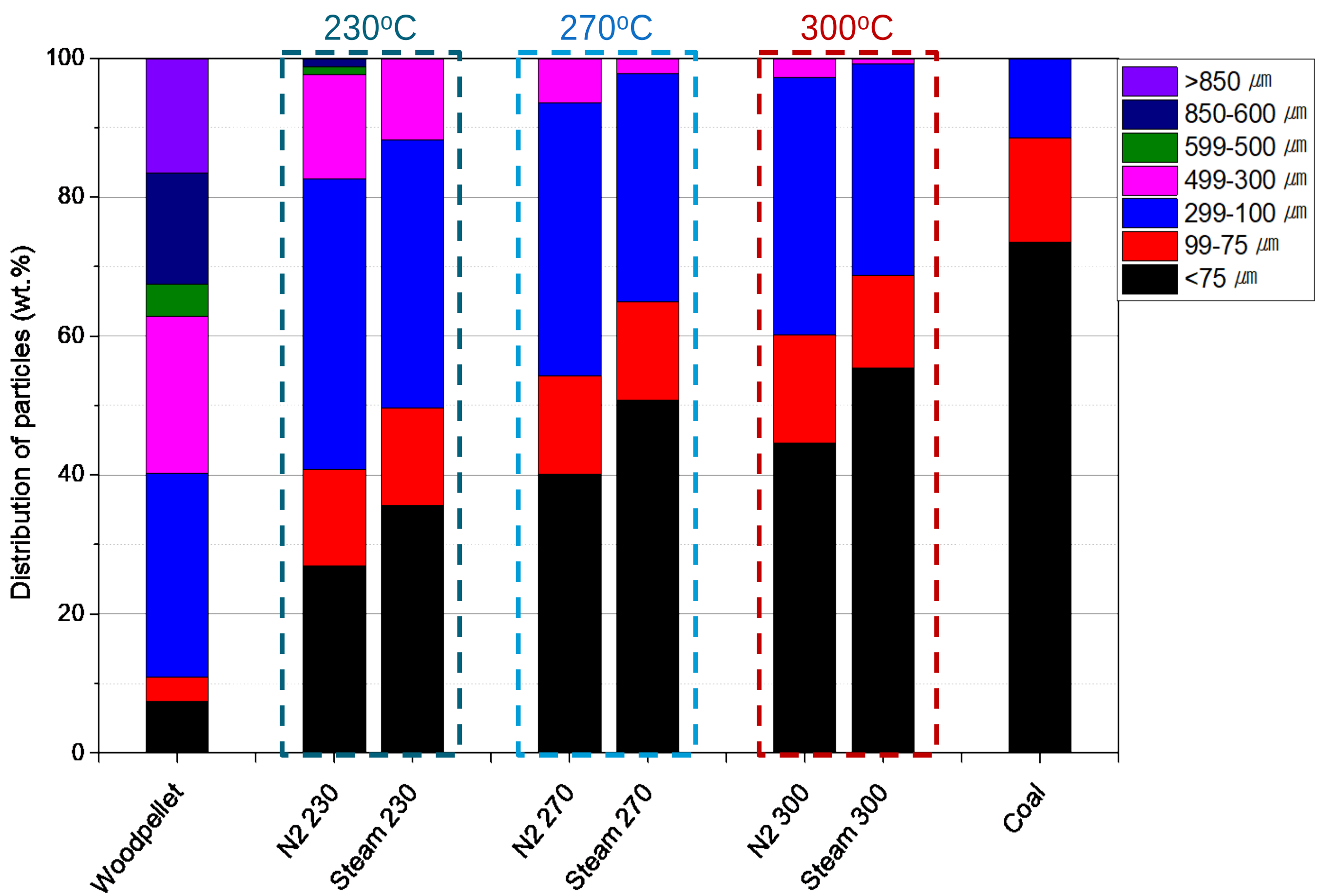
Yield



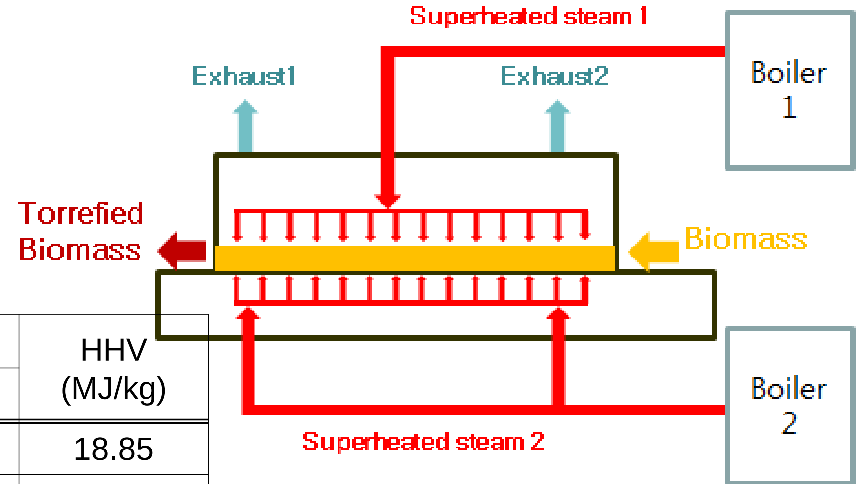
VM/FC

Lab-scale torrefaction experiment (2)

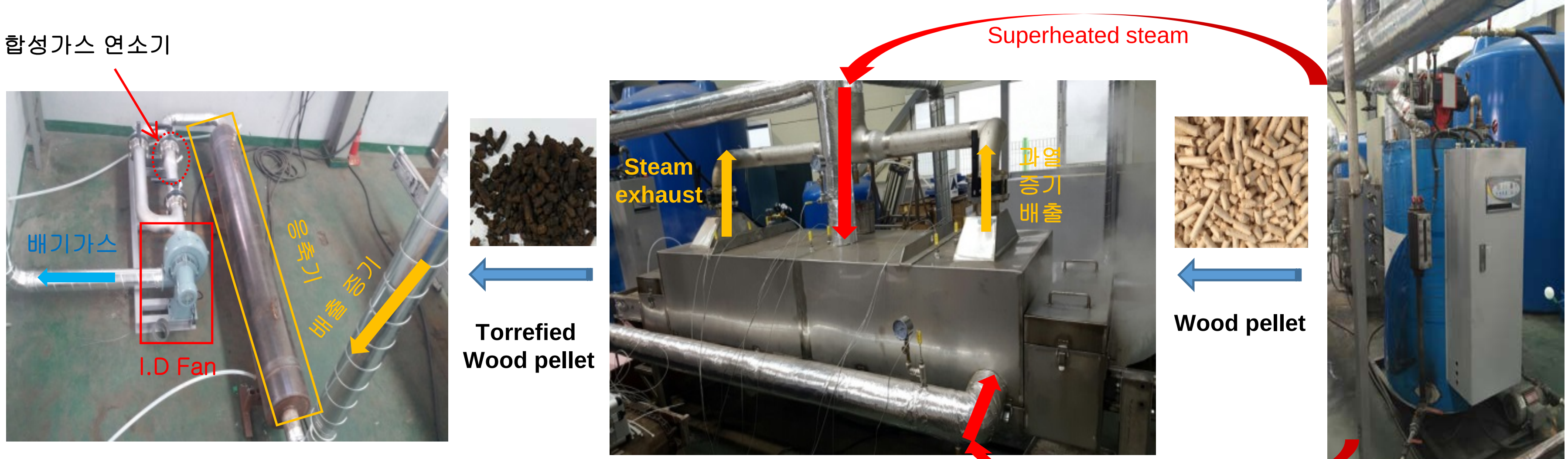
- Grindability of torrefied biomass – lab-scale pulverizer
  - When torrefied by steam, grindability was better
- Optimum torrefaction temperature:
  - Dependent on the object function
  - In this study: ~270°C



Pilot-scale experiments



	Proximate analysis (wt.%)				Elemental analysis (wt.%)				HHV (MJ/kg)
	M	VM	FC	Ash	C	H	N	O	
WP	5.6	78.6	15.4	0.4	48.8	5.6	0.59	39.0	18.85
TWP	1.7	75.5	22.4	0.4	54.5	5.8	0.3	37.3	21.53



Treatment system for exhausted steam

Torrefaction system

Boiler

Superheated steam

Conclusion

- Pilot-scale combustion tests were conducted for three direct co-firing methods: (1) Blending, (2) Blending + Air staging, (3) Reburning

- Low N content in biomass compared to coal reduces fuel NOx formation

- NOx emission decreases with increasing biomass co-firing ratio

- Reburning was the most efficient among the three direct co-firing technologies

- Torrefaction can be a feasible option for enhancing co-firing ratio of biomass without modification of the facility (e.g. biomass-dedicated mill)

- Other issues being studied
  - Slagging/fouling
  - Corrosion
  - PM generation in biomass co-firing