Oxygen Enrichment Combustion in Fluidized Bed with Optimal Torrefied Woody-Wastes

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Date:2019/06/25

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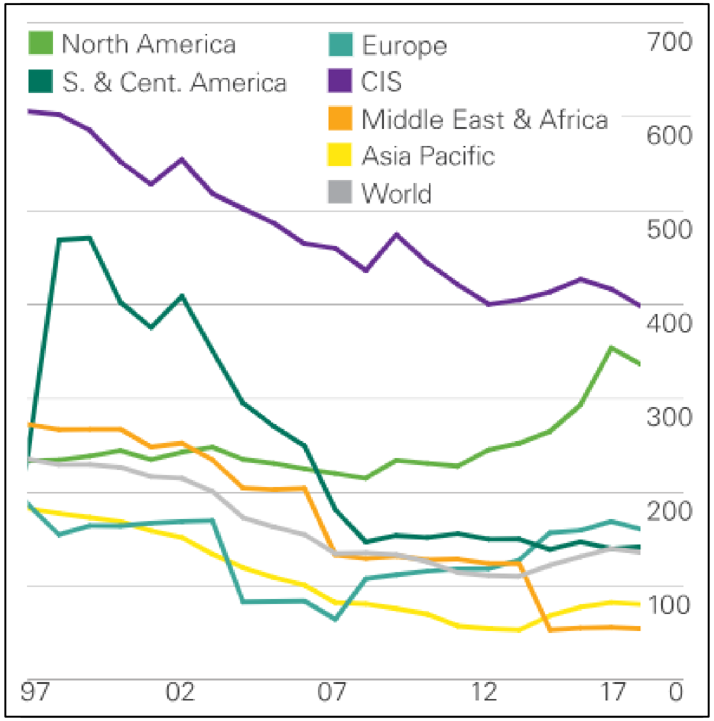
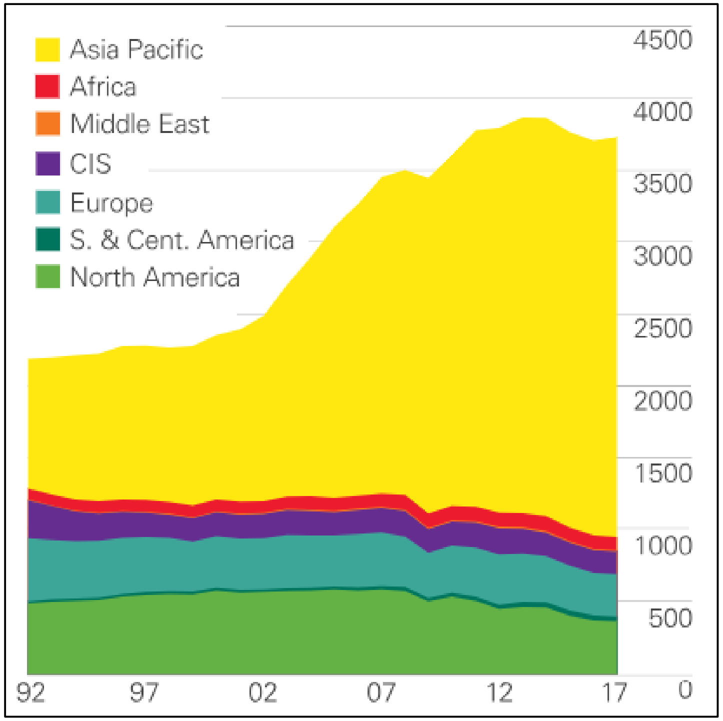
Background

- The reserve amount of coal is sufficient to meet 132 years
- The reserve amount of natural gas is sufficient to meet 50.9 years



R/P ratio for coal

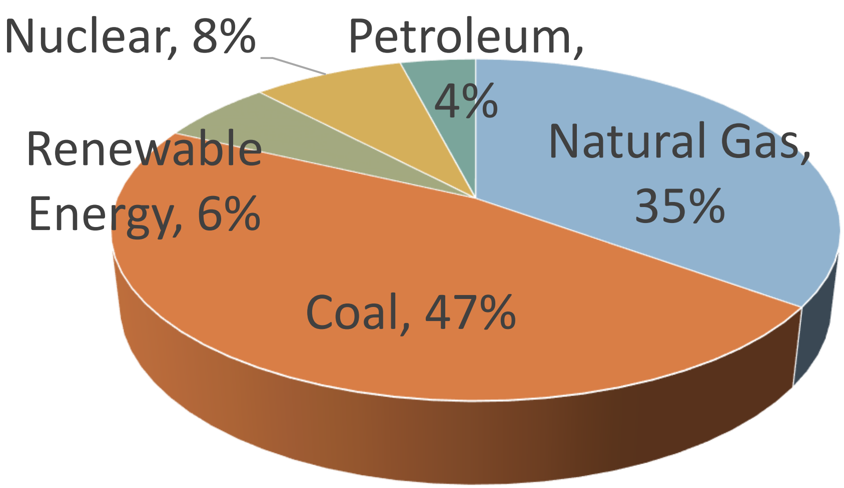


Consumption of coal

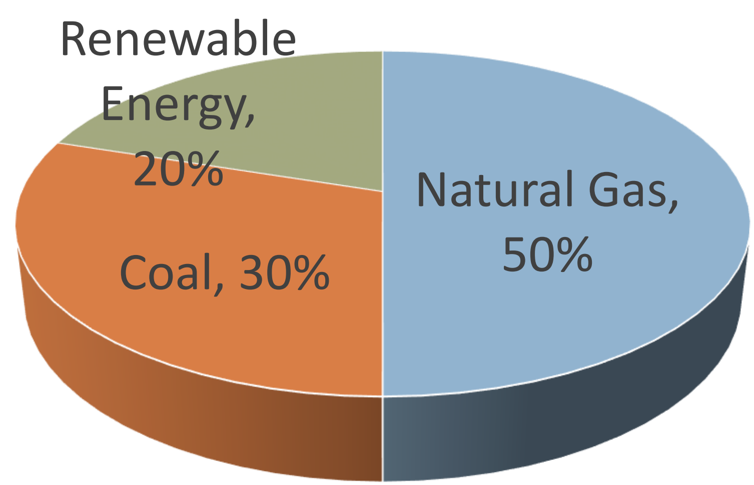
[1]BP Global, https://www.bp.com

Background

- 2030, greenhouse gas emissions reduce 50% (BAU)
- In 2025, the government has set a policy goal of 50% of natural gas and 20% of renewable energy



Power generation composition (2018)



Power generation composition (2050)

[2]Executive Yuan, R.O.C, https://www.ey.gov.tw/

Introduction

➢Waste-to-energy

The process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source[3].

Advantages[4]

- ✓ To decrease quantity of waste
- ✓ Nearly all biodegradable wastes are biomass
- ✓ To provide better control over odor and noise

Disadvantages

- ✓ To result in the contamination in the environment
- ✓ Waste-to-energy facilities are expensive to construct

[3]www.ema.gov.sg

[4]Luke Makarichi, The evolution of waste-to-energy incineration: A review (2018)

Introduction

➢ Pretreatment – Torrefaction

- ✓ Temperature between 200 – 300°C
- ✓ In an inert or limited oxygen environment
- ✓ $C_nH_mO_p$ + Heat → Char + CO + CO_2 + H_2O + condensable vapor + …

Raw Biomass

Biochar

Torrefied biomass[5]

- ✓ Reduce H/C & O/C ratios
- ✓ Enhance energy density
- ✓ Increase grindability
- ✓ Enhance hydrophobicity

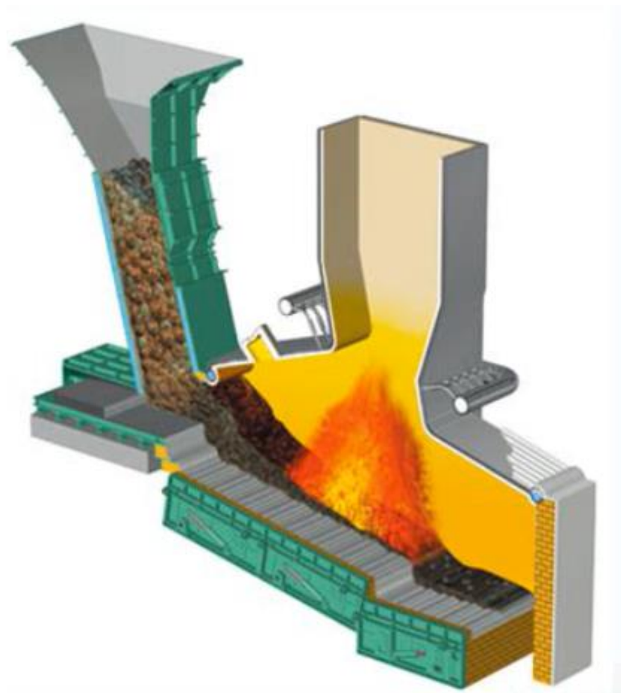
[5]Basu, “Biomass Gasification, Pyrolysis and Torrefaction-Practical Design and Theory.” Published by Elsevier Inc. (2013)

Introduction

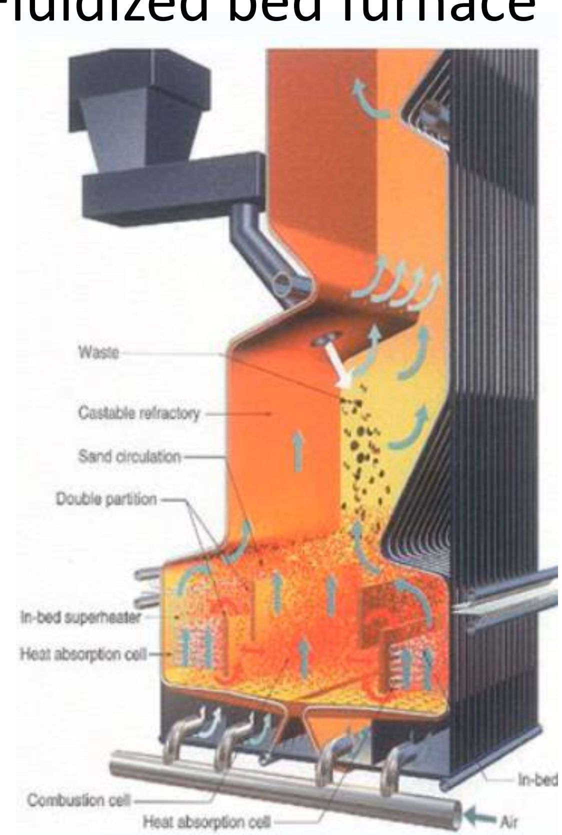
Fixed grate furnace

Rotary kiln furnace

Moving grate furnace



Fluidized bed furnace



Introduction

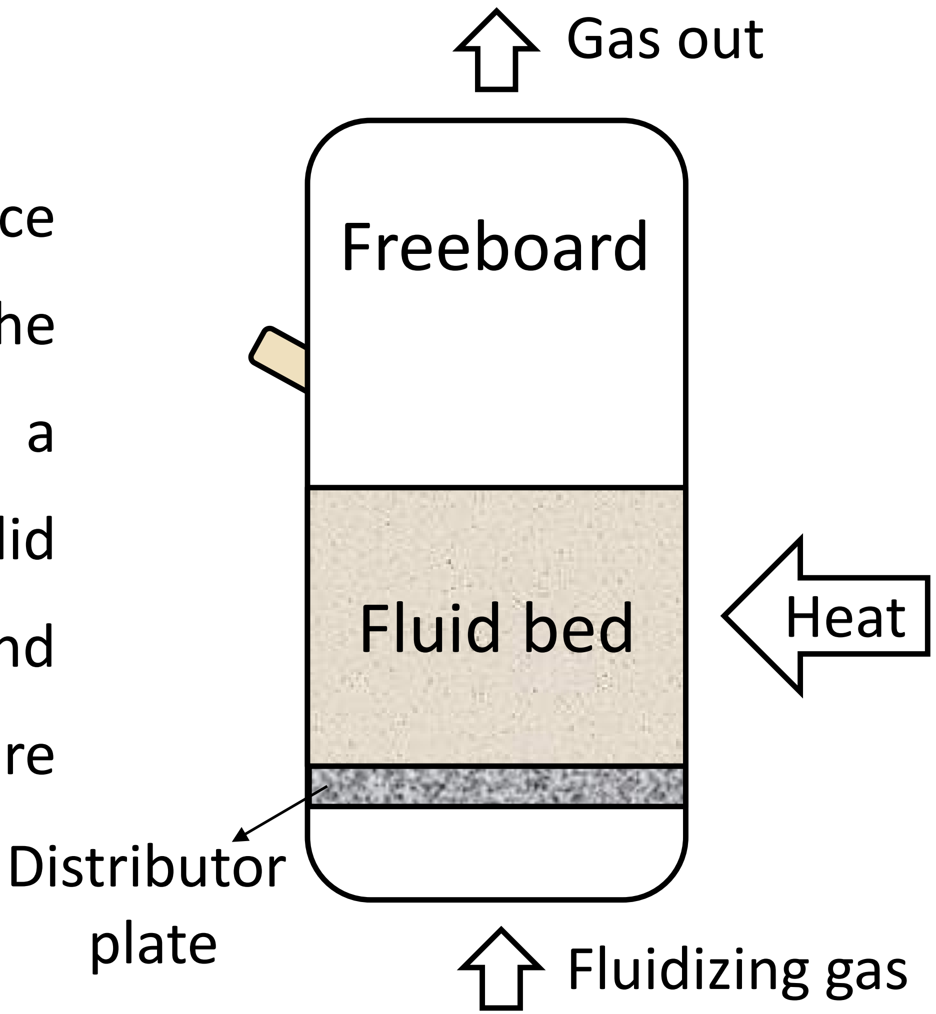
- Comparison between moving grate furnace and fluidized bed furnace

Feature	Moving grate furnace	Fluidized bed furnace
Flow of solid fuel	Transported on grate	Circulated through combustion chamber
Combustion zone	On the grate	Entire combustion zone
Excess air control	Difficult	Possible
Various fuel applicability	Fair	High
SO_x control	Difficult	Possible
NO_x control	Difficult	Possible

Introduction

➢ Fluidized bed

A type of combustion device in which a gas enters from the bottom of the burner into a reaction zone in which solid particles are suspended and combustion is completed there between.



Introduction

➢Oxygen enhanced combustion[6]

The process of burning a fuel using higher oxygen concentration.

Advantages

- ✓ Increased productivity
- ✓ Higher thermal efficiency
- ✓ Higher energy density
- ✓ Lower exhaust gas volumes

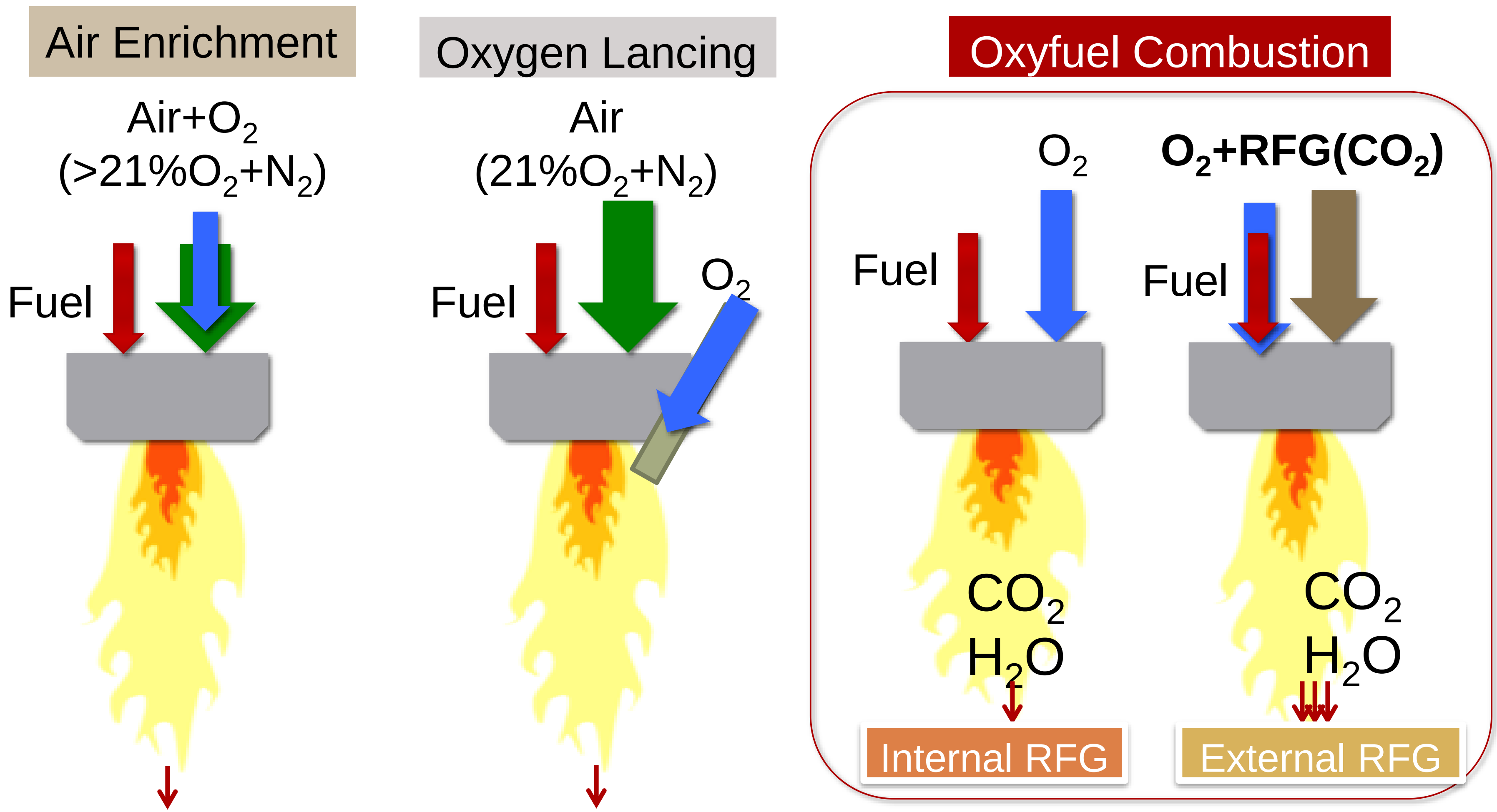
Disadvantages

- ✓ Air separation unit for oxygen production is expensive
- ✓ Needs of high heat resistant instruments

[6]H. I. Mathekga B. O. Oboirien, A review of oxy-fuel combustion in fluidized bed reactors (2016)

Introduction

➢ Oxygen enhanced combustion



Literature review

➢ Oxygen enhanced in Fluidized Bed

- ✓ Air enrichment in the atmosphere augments SO_2 and NO emission and reduces CO emission[7]
- ✓ As O_2 concentration increases, combustion efficiency is improved[7]
- ✓ High percentage of CO_2 and H_2O in the combustion gases can reduce the volume of flue gas emitted from power plant by 80%[8]
- ✓ Combustion activities is weaken as the oxygen concentration exceeds 40%[9]

[7]Lunbo Duan, Changsui Zhao, Wu Zhou, Chengrui Qu, Xiaoping Chen, O2/CO2 coal combustion characteristics in a 50 kWth circulating fluidized bed (2011)
[8]Terry Wall, An overview on oxyfuel coal combustion—State of the art research and technology development (2009)
[9]Siyi Luo, Bo Bo Xiao, Zhiquan Hu, Shiming Liu, Yanwen Guan, Experimental study on oxygen-enriched combustion of biomass micro fuel (2009)

Literature review

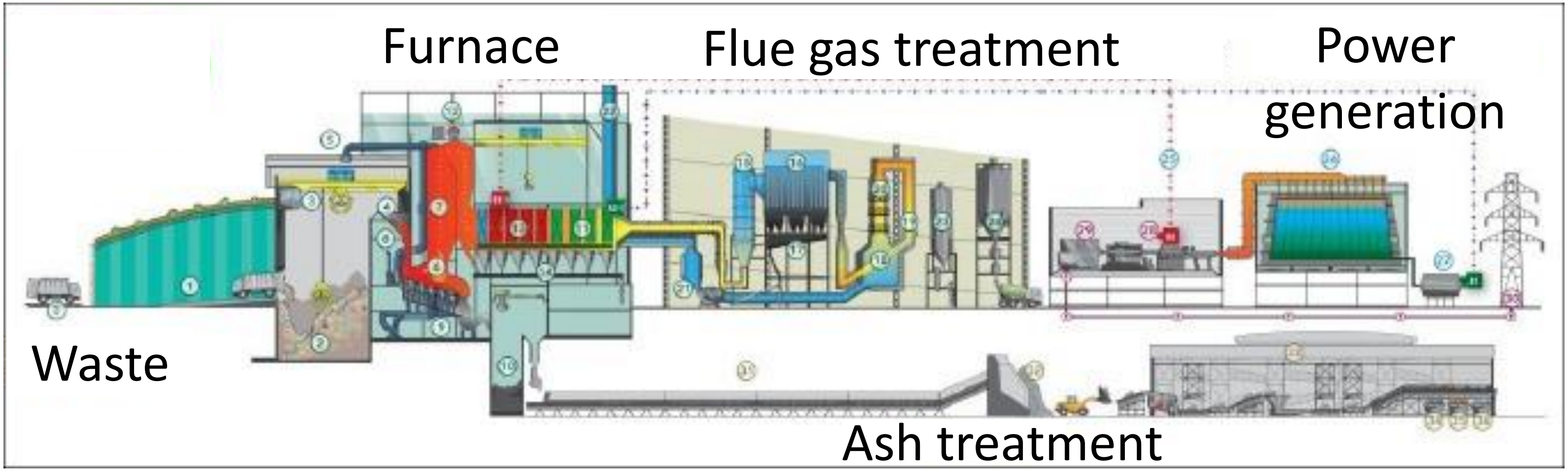
➢ Oxygen lancing

- ✓ No modifications to the existing air/fuel burner[10]
- ✓ NO_x emissions are lower compared to premixing[10]
- ✓ Flame shape may be lengthened by staging the combustion reactions[10]
- ✓ The lower the second air injection position, the higher the circulating rate[11]
- ✓ With proper selection of the oxygen lancing area, lancing can improve unit operation and reduce CO emission[12]

[10]Charles E. Baukal Jr., "Oxygen-Enhanced Combustion." Published by CRC Press. (2013)
[11]Weijia Zheng, The effect of the secondary air injection on the gas-solid flow characteristics in the circulating fluidized bed (2018)
[12]Corna, The use of oxygen in biomass and waste-to-energy plants: a flexible and effective tool for emission and process control (2010)

Motivation

- ✓ Develop waste-to-energy technology
- ✓ Higher combustion efficiency
- ✓ Lower cost



Objective

Biomass characteristic optimization

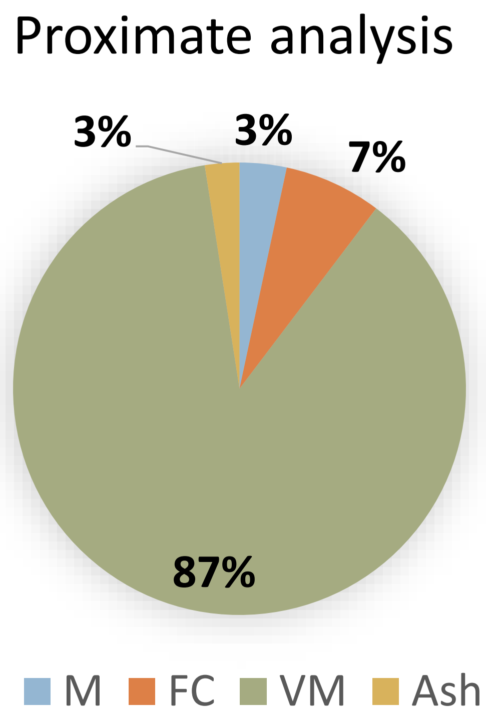
- Energy Yield Index
- Proximate Analysis-based Index
- Effective Combustion Comprehensive Index

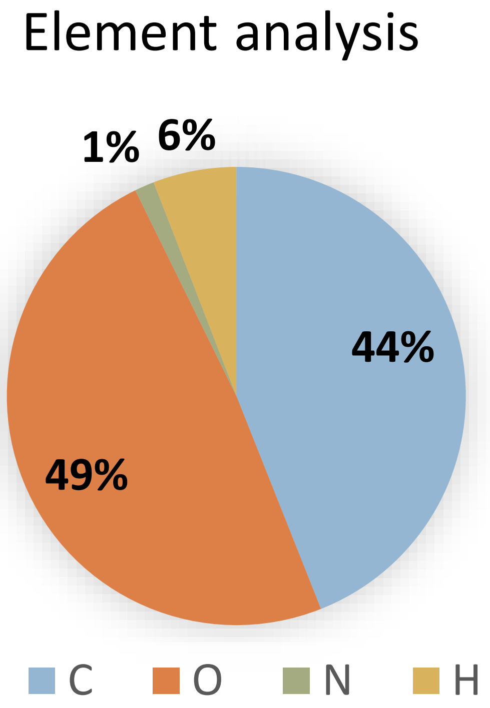
Biochar combustion optimization

- Total Fluidized Bed Efficiency
- Volatile Combustion Ratio

Experimental apparatus

Alee trees

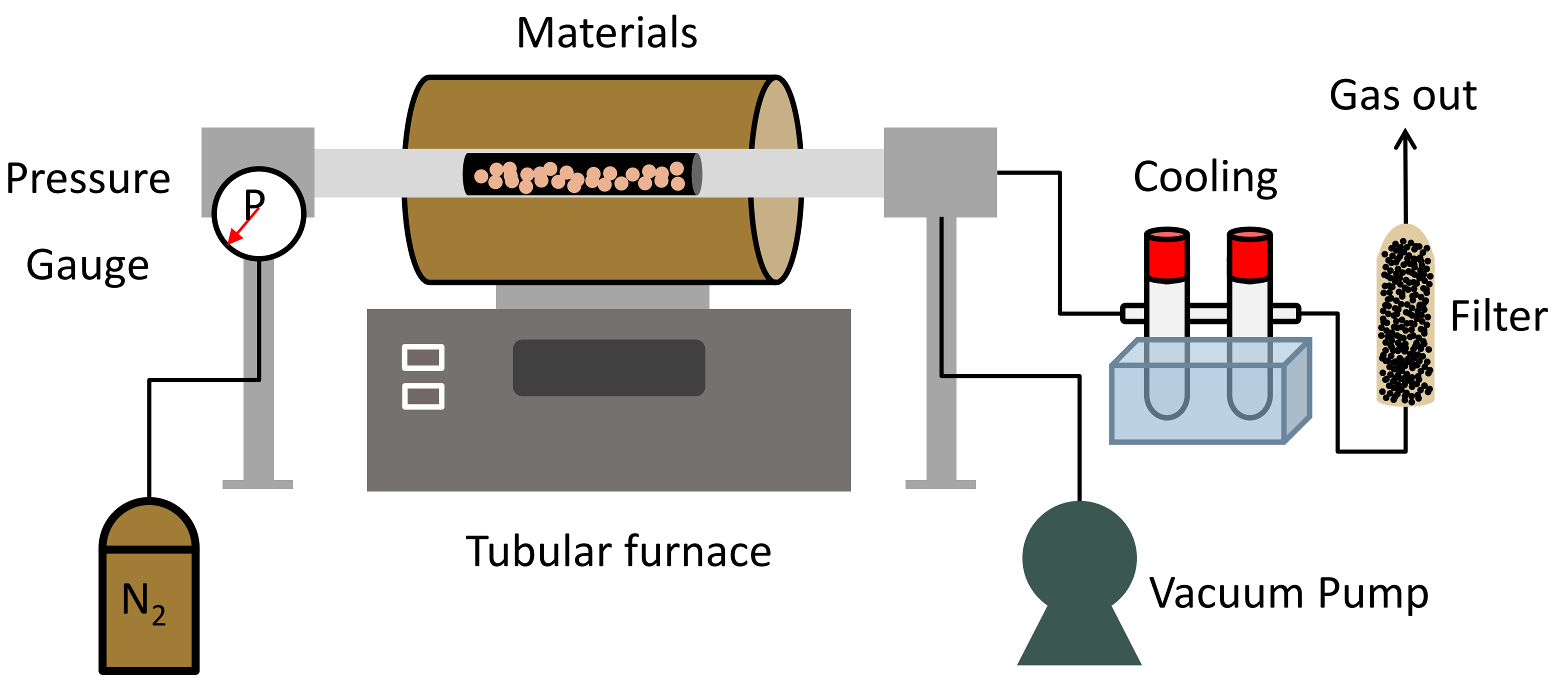




Heating value : 4400 Kcal/Kg

Experimental apparatus- Torrefaction system

- Sample: Alee trees
- Size : < 2.83 mm



Experimental apparatus-
Calorimeter

- About 1 g of materials is used
- By measuring the rising temperature of the calorimeter and the water inside, we can get the total heat release after combustion.

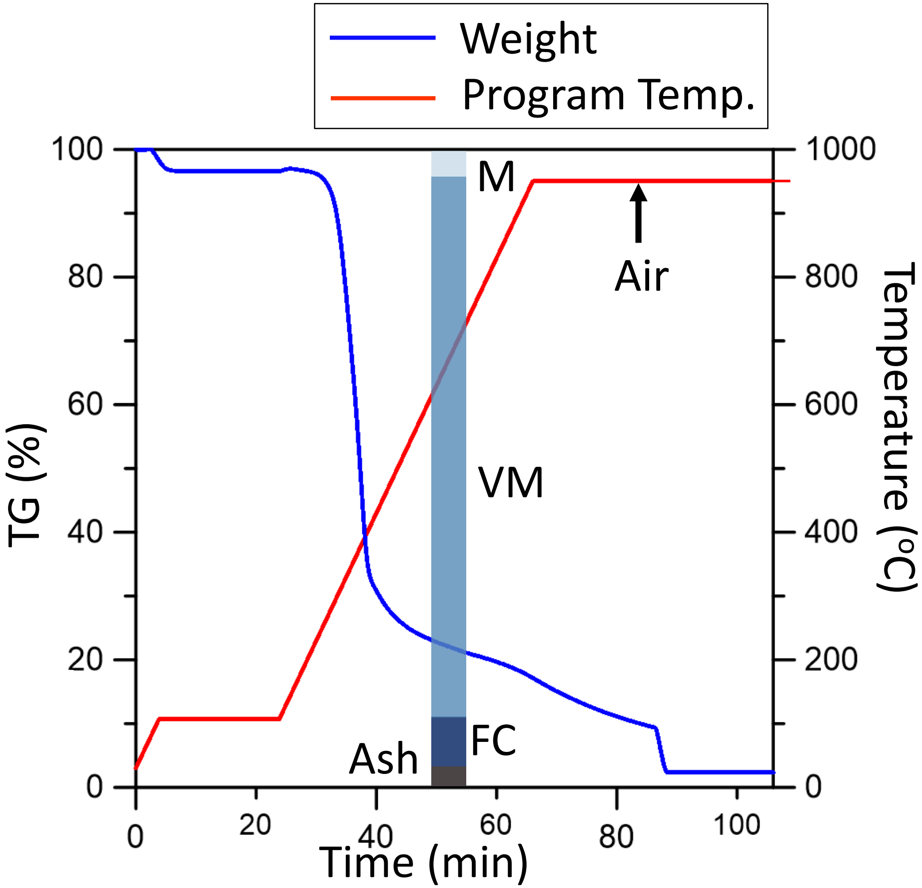
Calorimeter (Parr 6200)

$$Energy\ Yield = \frac{\text{mass of product } \times HV \text{ of product}}{\text{mass of biomass feed } \times HV \text{ of feed}} \times 100\%$$

Experimental apparatus-
Thermogravimetric analysis

- Model: Perkin Elmer (STA8000)
- Sample: Alee tree biochar
- Size: smaller than 74 μm
- Heating rate: 20 $^{o}C/min$
- Carry gas flow rate: 50 ml/min

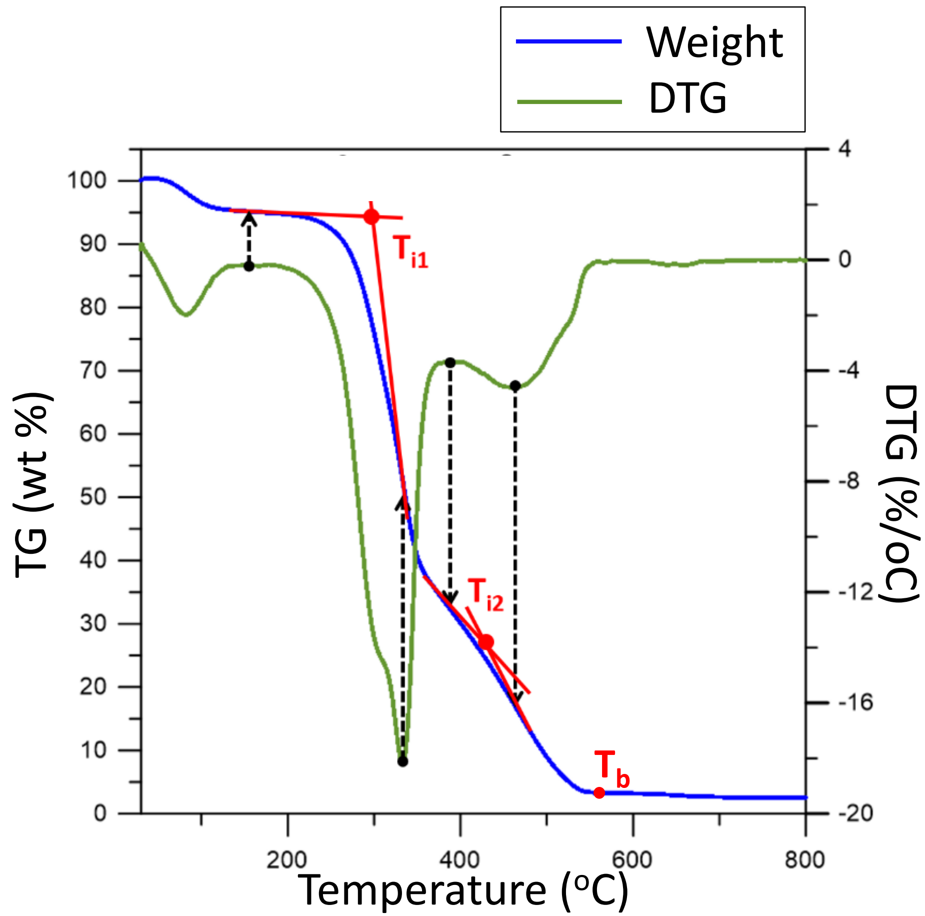
$$PA = \frac{VM \times FC}{M \times Ash}$$



Experimental apparatus-
Thermogravimetric analysis

- **Ignition temperature(T_{i1}&T_{i2})** was calculated by intersection method
- **Burnout temperature(T_b)** is identified at the temperature where the fuel conversion (α) reached 99%[13]

$$\alpha = \frac{W_i - W}{W_i - W_f} \times 100\%$$



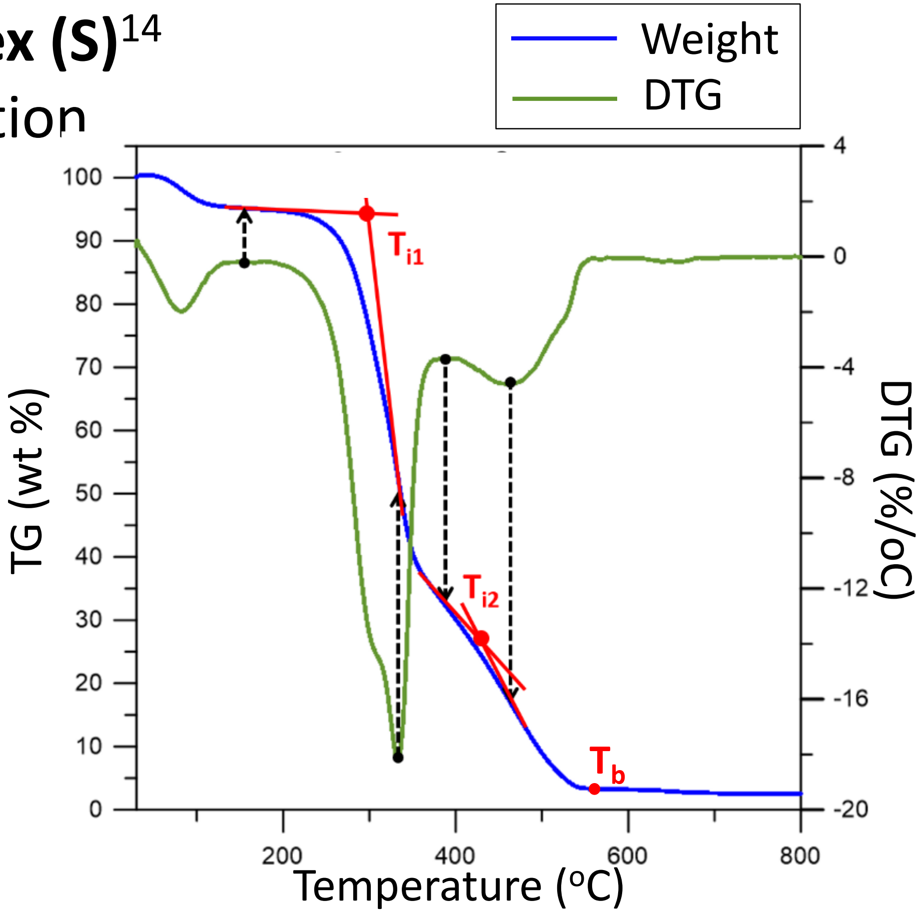
[13]Jau-Jang Lu, Wei-Hsin Chen, Investigation on the ignition and burnout temperatures of bamboo and sugarcane bagasse by thermogravimetric analysis (2015)

Experimental apparatus-
Thermogravimetric analysis

- **Combustion characteristic index (S)**[14] represents the level of combustion performance of solid fuels

$$S = \frac{(\frac{dW}{dt})_{max} \cdot (\frac{dW}{dt})_{mean}}{T_i^2 \cdot T_b}$$

$(\frac{dw}{dt})_{max}$: maximum mass-loss rate
$(\frac{dw}{dt})_{mean}$: average mass-loss rate

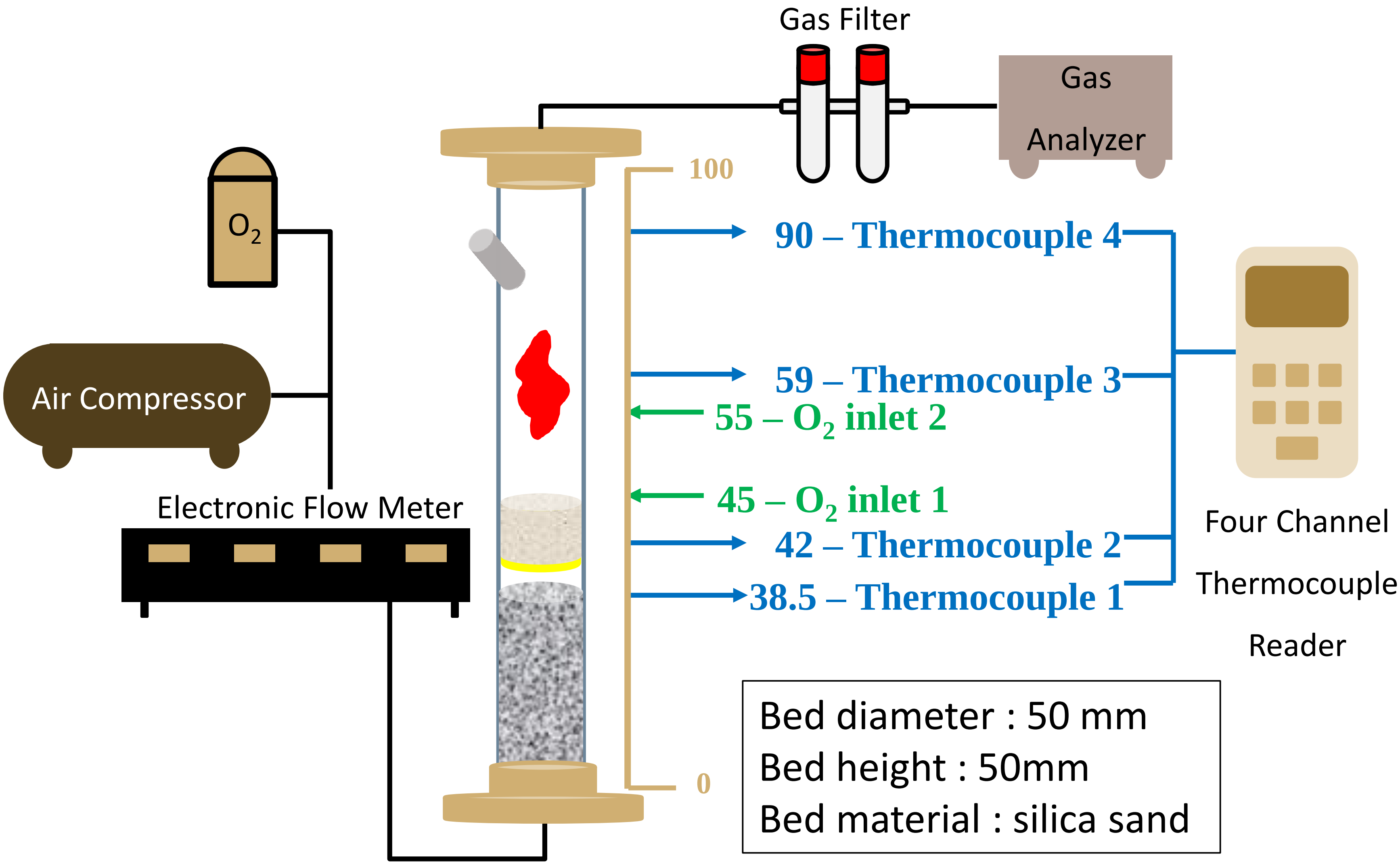


- **Effective Combustion characteristic index (S_{mix})**

$$S_{mix} = S_1 \times \frac{W_1}{W_1 + W_2} + S_2 \times \frac{W_2}{W_1 + W_2}$$

[14]Park. Et al. Bioresource Technology. (2014)

Experimental apparatus-
Bubbling fluidized bed reactor



Bed diameter : 50 mm
Bed height : 50mm
Bed material : silica sand

Experimental apparatus-
Taguchi method

- Orthogonal array

Experiments which give much reduced variance for the experiment with optimum settings of control parameters.

Orthogonal array $L_9(3^4)$

Series of Experiment	Factor 1	Factor 2	Factor 3	Factor 4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

81 sets → 9 sets

- S/N ratio

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right]$$

n: the number of tests

y_i: the value of the indicators

Experiment procedure

Biomass Optimization

1. Construct L18 orthogonal array for biomass characteristic optimization
2. Conduct 18 sets of experiments
3. Analyze the results according to S/N ratio
4. Get optimal results for biomass characteristics

→

Biochar Combustion

1. Construct L9 orthogonal array for combustion behavior optimization
2. Conduct 9 sets of experiments
3. Analyze the results according to S/N ratio
4. Get optimal results for fluidized be combustion behavior

Results and Discussion-
Biomass optimization

Temperature

- 200 ºC
- 220 ºC
- 240 ºC
- 260 ºC
- 280 ºC
- 300 ºC

Resident Time

- 20 min
- 40 min
- 60 min

N2 Flow Rate

- 30 ml/min
- 50 mi/min
- 70 ml/min

NO.	Temperature (ºC)	Residence Time (min)	Carrier Gas Flow Rate (cc/min)	Sample	Size (mm)	Heating rate (ºC/min)	Weight (mg)
1	200	20	30	Alee Trees	<2.83	20	15
2	200	40	50				
3	200	60	70				
4	220	20	30				
5	220	40	50				
6	220	60	70				
7	240	20	50				
8	240	40	70				
9	240	60	30				
10	260	20	70				
11	260	40	30				
12	260	60	50				
13	280	20	50				
14	280	40	70				
15	280	60	30				
16	300	20	70				
17	300	40	30				
18	300	60	50				

Taguchi's Orthogonal Arrays – $L_{18}(6^1 \times 3^6)$

Results and Discussion-
Biomass optimization

	EY Index			S_{mix} Index			PA Index		
	Temp. (°C)	Res. Time (min)	N_2 Flow Rate (ml/min)	Temp. (°C)	Res. Time (min)	N_2 Flow Rate (ml/min)	Temp. (°C)	Res. Time (min)	N_2 Flow Rate (ml/min)
L1	-0.713	-2.554	-2.672	25.017	42.313	42.117	36.747	96.427	99.887
L2	-0.651	-2.793	-2.463	24.987	41.887	41.487	43.710	100.823	98.770
L3	-0.824	-2.360	-2.572	26.483	42.380	42.977	48.290	103.387	101.980
L4	-1.287	-	-	22.290	-	-	54.753	-	-
L5	-1.844	-	-	19.727	-	-	56.957	-	-
L6	-2.389	-	-	8.077	-	-	60.180	-	-
S/N difference	1.739	0.433	0.209	18.407	0.493	1.490	23.433	6.960	3.210
Ideal	220	60	50	240	60	70	300	60	70

Results and Discussion-
Biochar combustion

Bed Temp.

- 550°C
- 650°C
- 750°C

Materials

- EY
- SI
- PA

O_2 position

- 0 cm
- 45 cm
- 55 cm

O_2 Concentration

- 23%
- 27%
- 30%

No.	Bed Temp.	Materials	Oxygen Position	Oxygen concentration
1	550°C	EY	0 cm	23%
2	550°C	SI	45cm	27%
3	550°C	PA	55cm	30%
4	650°C	EY	45cm	30%
5	650°C	SI	55cm	23%
6	650°C	PA	0cm	27%
7	750°C	EY	55cm	27%
8	750°C	SI	0cm	30%
9	750°C	PA	45cm	23%

Taguchi's Orthogonal Arrays – $L_9(3^4)$

Results and Discussion-
Biochar combustion

- **Total fluidized bed efficiency**

$$Poison\ Index\ (PI\%) = \frac{CO}{CO_2} \times 100\%$$

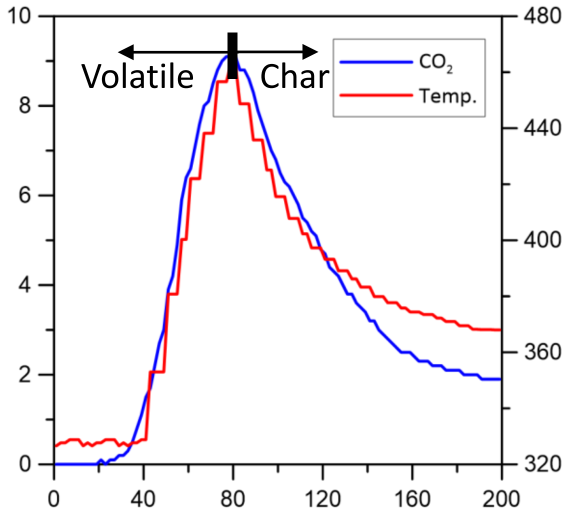
PI% < 0.4% → boiler clean

0.4% < PI% < 0.8% → boiler need of cleaning

0.8% < PI% → boiler need of repair

- **Volatile combustion ratio**

$$V - CR\ (\%) = \frac{(CO + CH_4)}{(CO + CH_4 + CO_2)} \times 100\%$$



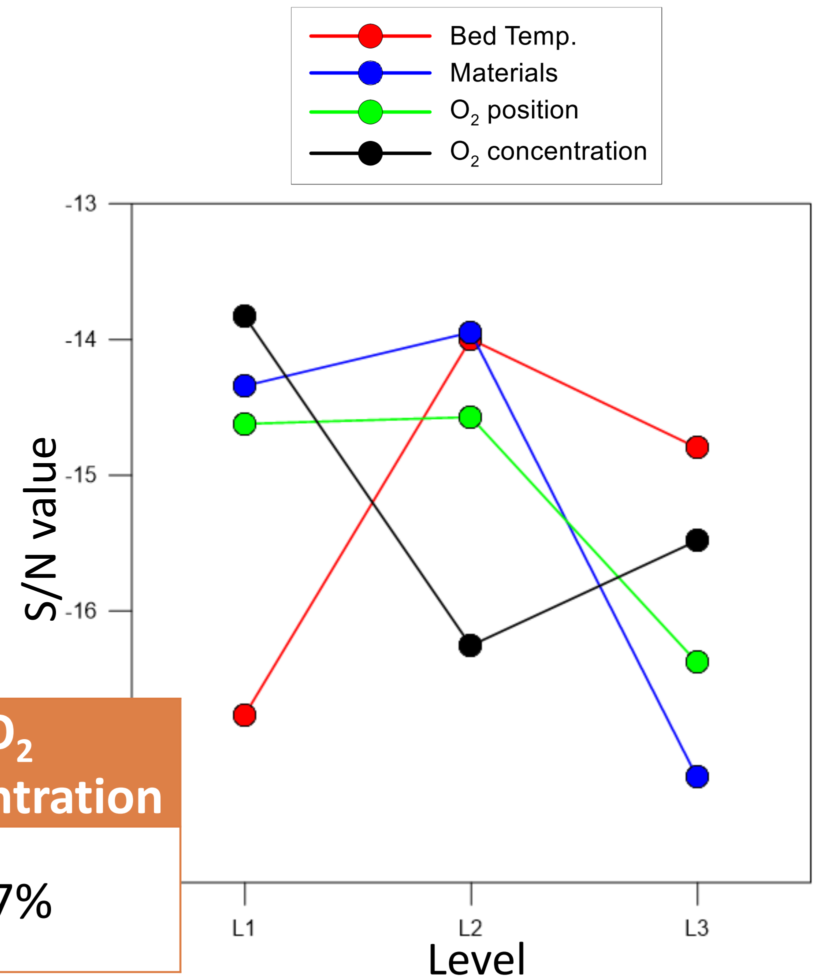
[15]Kane International Ltd, https://www.kane.co.uk

Results and Discussion-
Biochar combustion

- Total fluidized bed efficiency

	CO (ppm)	CO_2 (%)	PI (%)	S/N for PI
1	1288021	645	0.20	-13.98
2	1494872	945.8	0.16	-15.92
3	1176454	1216.4	0.10	-20.00
4	1862043	815.1	0.23	-12.77
5	2202569	942.7	0.23	-12.77
6	1012813	679.4	0.15	-16.48

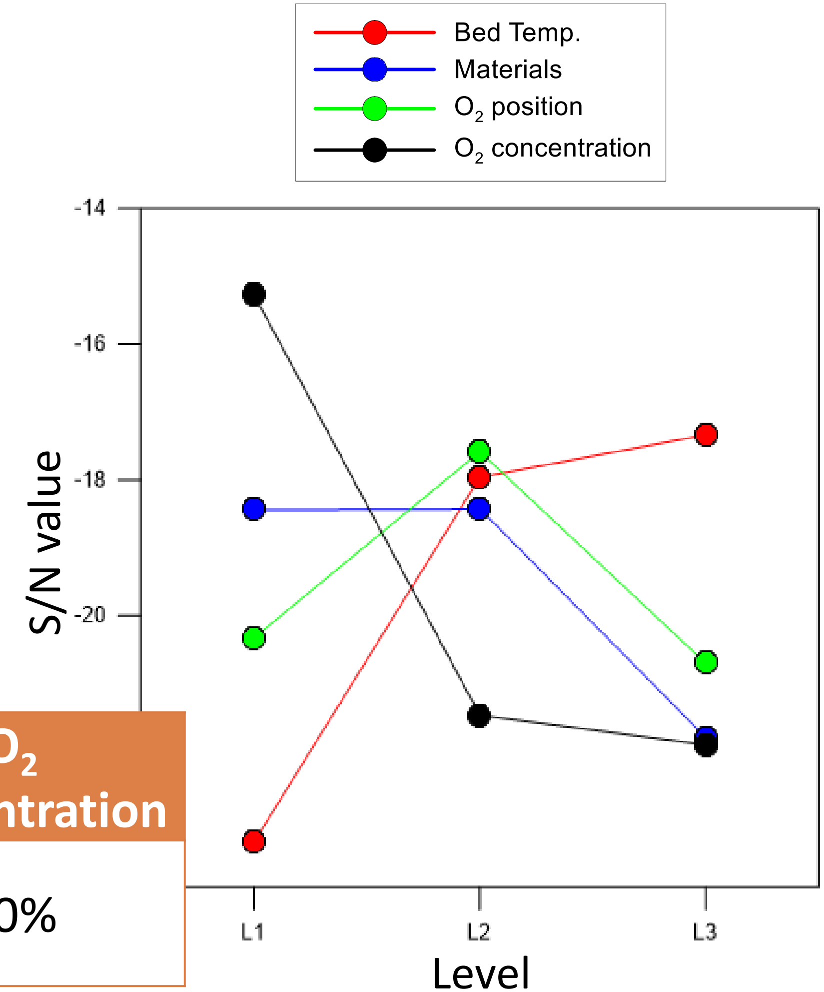
Bed Temp.	Torrefied Materials	O_2 Position	O_2 Concentration
550°C	PA	Downstream	27%



Results and Discussion-
Biochar combustion

- Volatile combustion ratio

	CO (ppm)	CO_2 (%)	CH_4 (%)	V-CR (%)	S/N
1	675605	121.7	15.2	0.12	-18.74
2	580849	147.6	11.9	0.08	-22.18
3	232708	213.5	7.5	0.04	-29.11
4	823620	163.9	25.2	0.14	-17.25
5	1016494	209.4	53.3	0.21	-13.72
6	255522	77.9	5.7	0.07	-22.92



Bed Temp.	Torrefied Materials	O_2 Position	O_2 Concentration
550°C	PA	Downstream	30%

Conclusions

- Biomass optimization

✓ Torrefaction temperature was the dominant factor

✓ The resident time showed the same trend that longer torrefaction time is better

✓ Flow rate of N_2 carry gas shows no significant influence on the conversion of biochar.

	Temperature	Residence time	N_2 flow rate
EY	220°C	60 min	50 ml/min
S_{mix}	240°C	60 min	70 ml/min
PA	300°C	60 min	70 ml/min

Conclusions

- Biochar combustion

✓ For total combustion efficiency, materials accounted for the most influence. Oxygen inlet position had the least influence

✓ For volatile combustion ratio, bed temperature and oxygen concentration were important, while materials and oxygen inlet position were both less important.

<table>
<tr><th></th><th>Bed Temperature</th><th>Torrefied Materials</th><th>Oxygen Position</th><th>Oxygen Concentration</th></tr>
<tr><th>Fluidized Bed Efficiency</th><td rowspan="2">550°C</td><td rowspan="2">PA</td><td rowspan="2">Downstream</td><td>27%</td></tr>
<tr><th>Volatile Combustion Ratio</th><td>30%</td></tr>
</table>

Thank you for your attention!