Fuel and Combustion Laboratory (F&C)
Department of Aeronautics and Astronautics

International Energy and Environment Conference

Plasma-assisted Gasification for Turning the Solid Residue into Hydro-gen Energy

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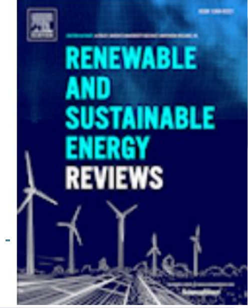
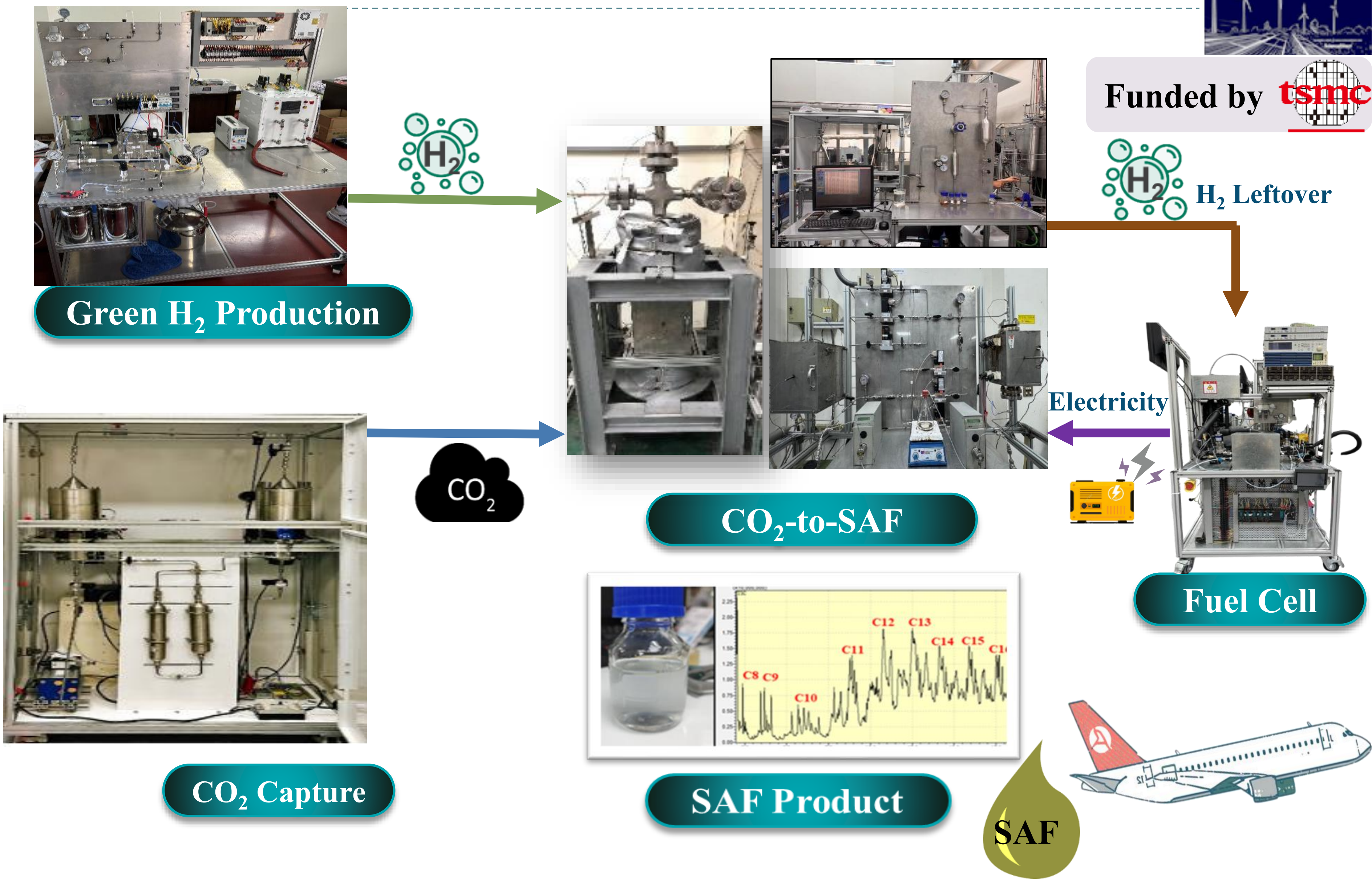
國立成功大學
National Cheng Kung University

Electrolyzed Sustainable Aviation Fuel (e-SAF)





Test Benches/Facilities in F&C for Developing SAF

Fuel Production

Fuel Combustion

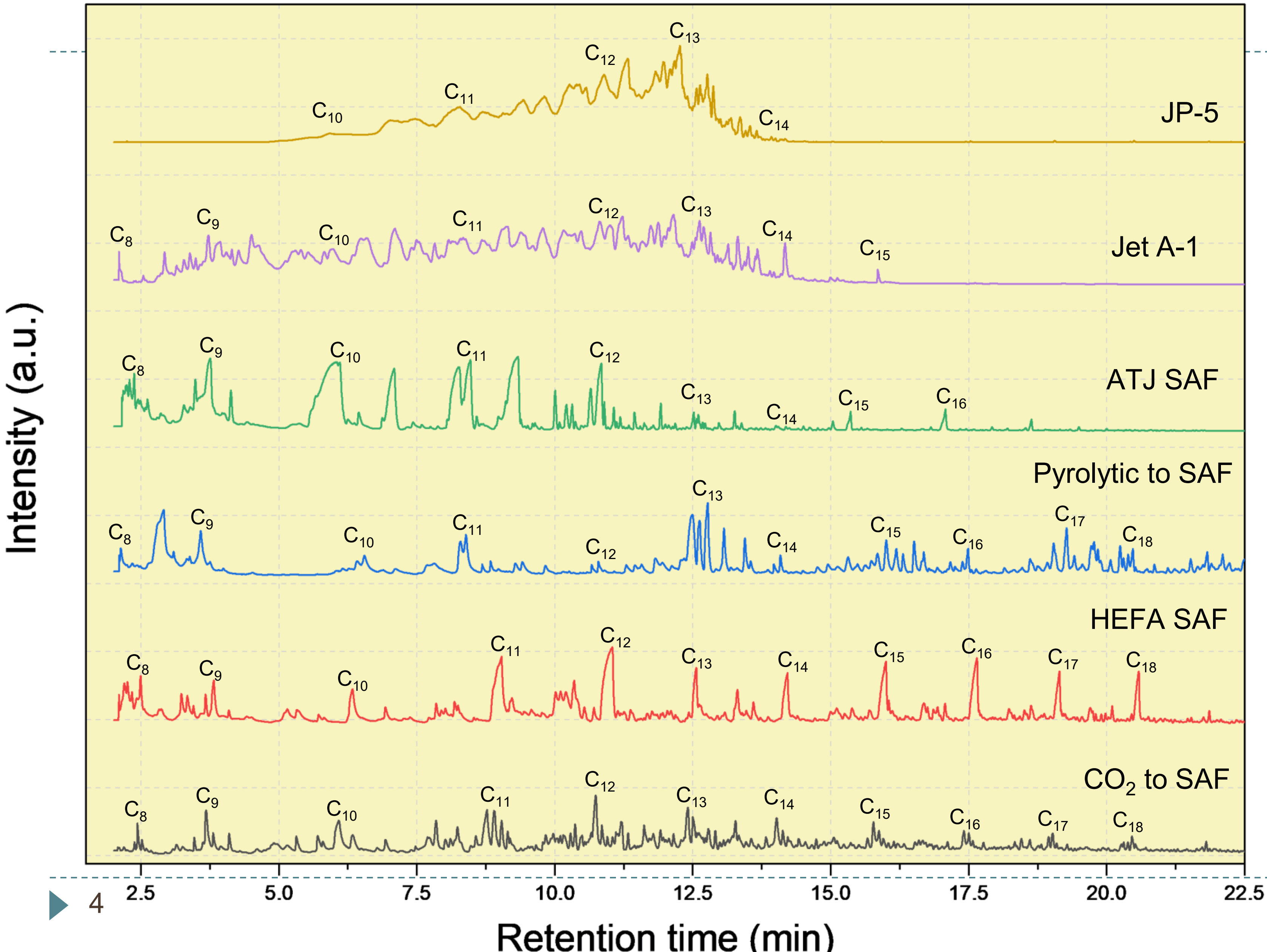
Engine Performance

Demonstration Plant Site

Electrolyzed Hydrogen and Fuel Cell

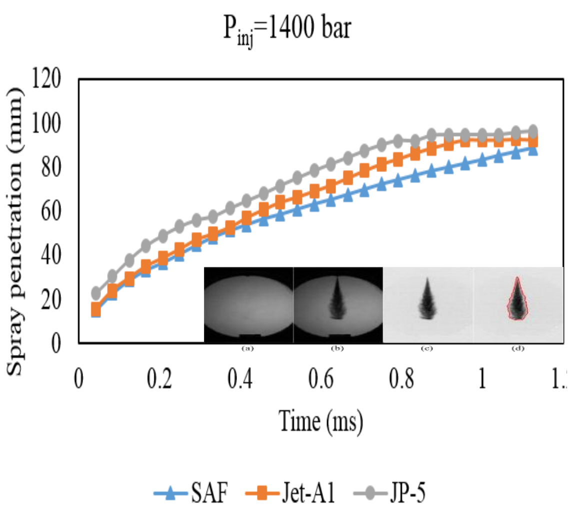
F&C, NCKU has the best potential for developing SAF across Taiwan

SAFs from Various Pathways Produced in F&C

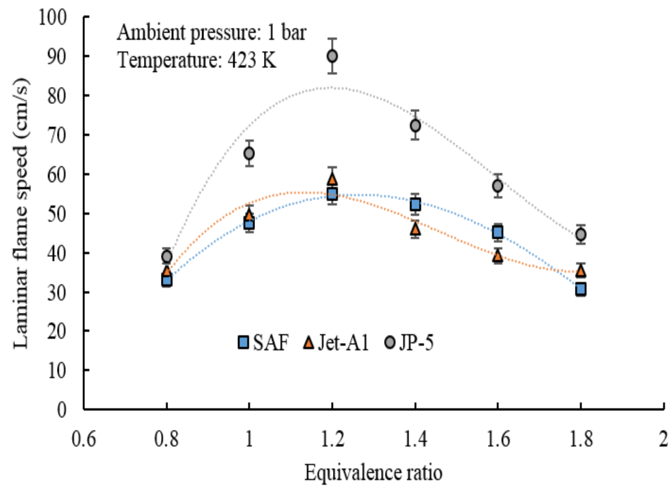


Combustion-
1. Constant Volume Combustion Combustor

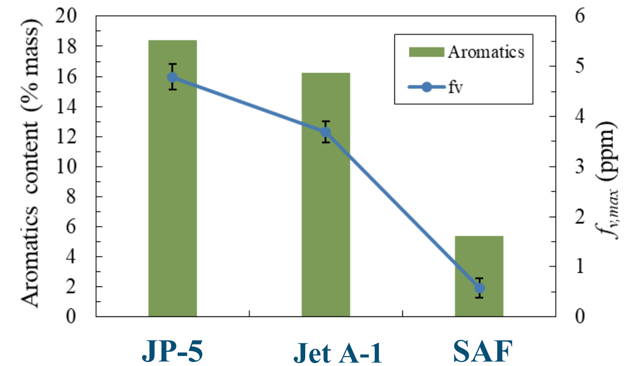
Funded by CSC Group

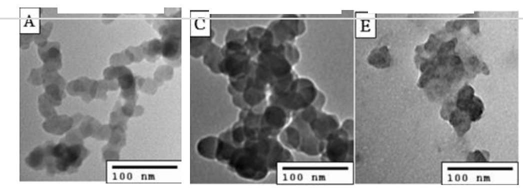


Spray Characteristics



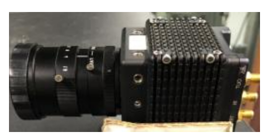
Laminar Flame Speed





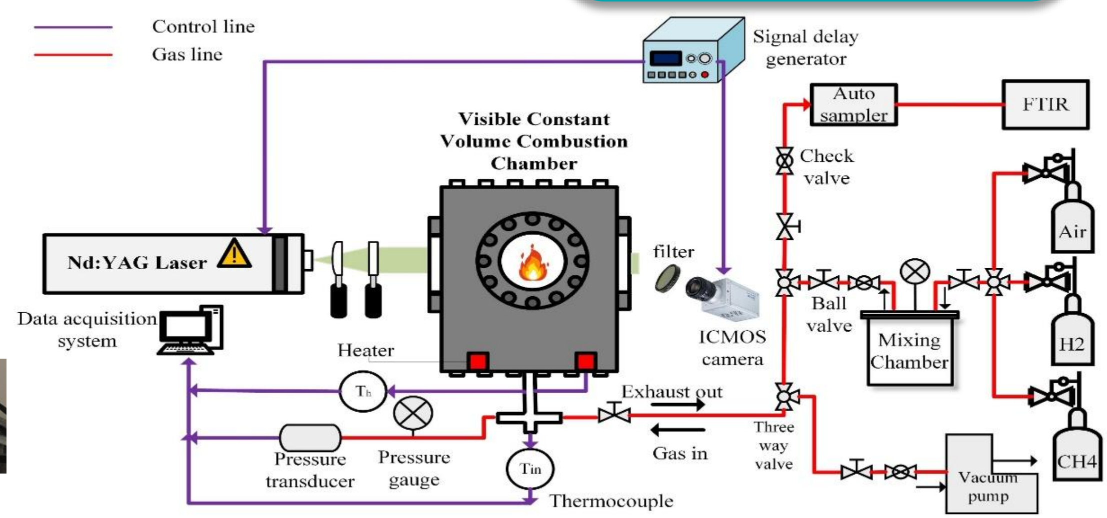
Soot Formation

ICMOS Camera

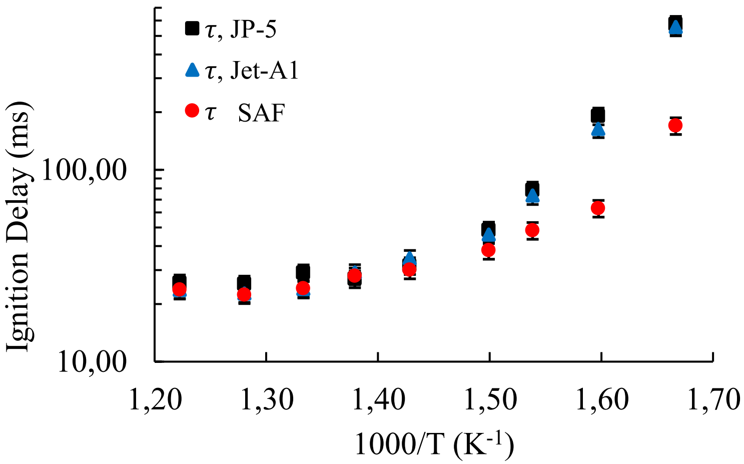


ICCD Camera

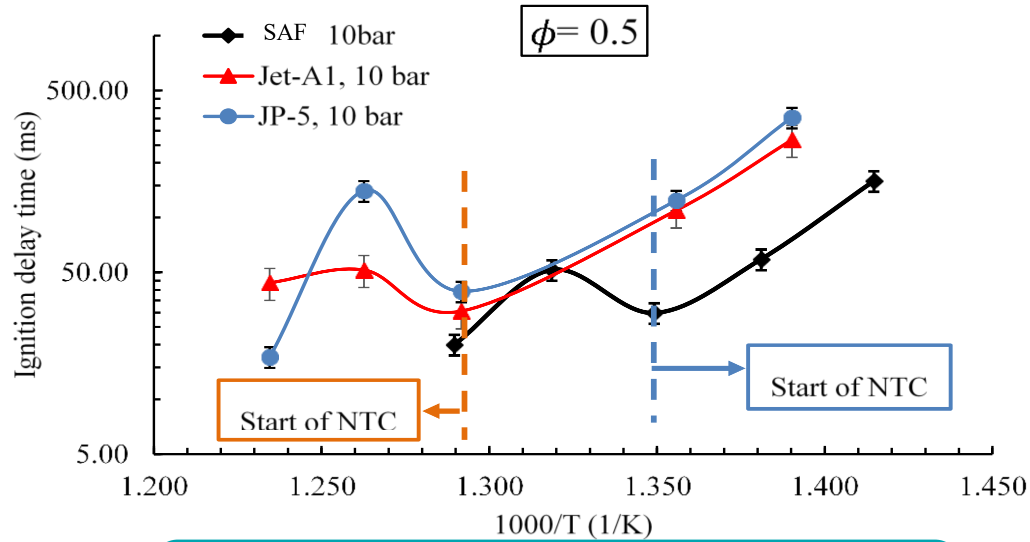
Nd: YAG Laser



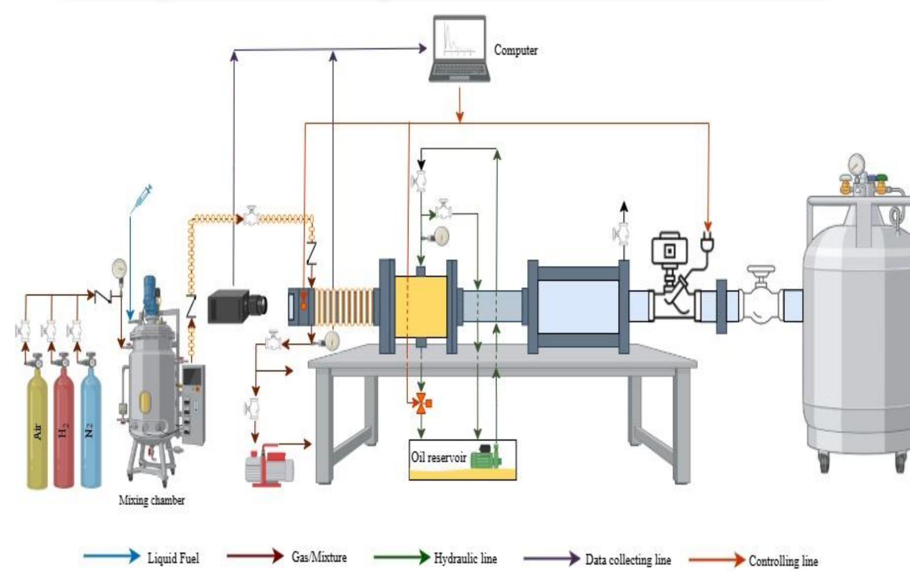
Combustion-
2. Rapid Compression Machine



Ignition Delay

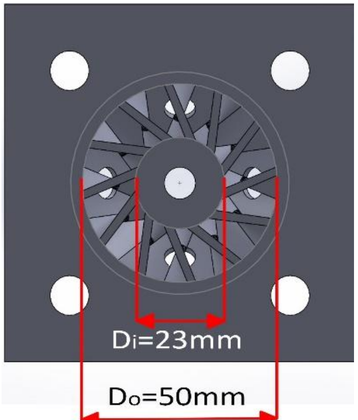


Negative Temperature Coefficient

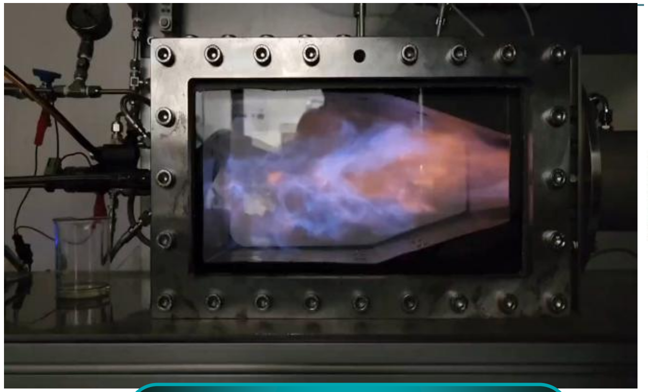


Combustion-
3. Gas Turbine Combustor (Swirl Combustor)

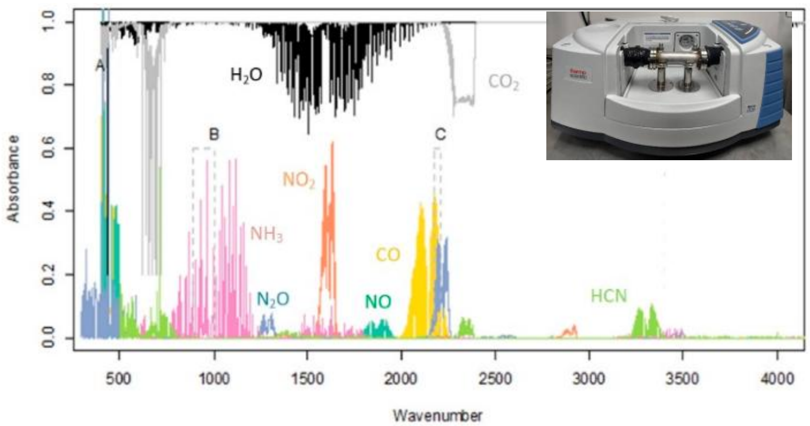
Funded by CSC Group



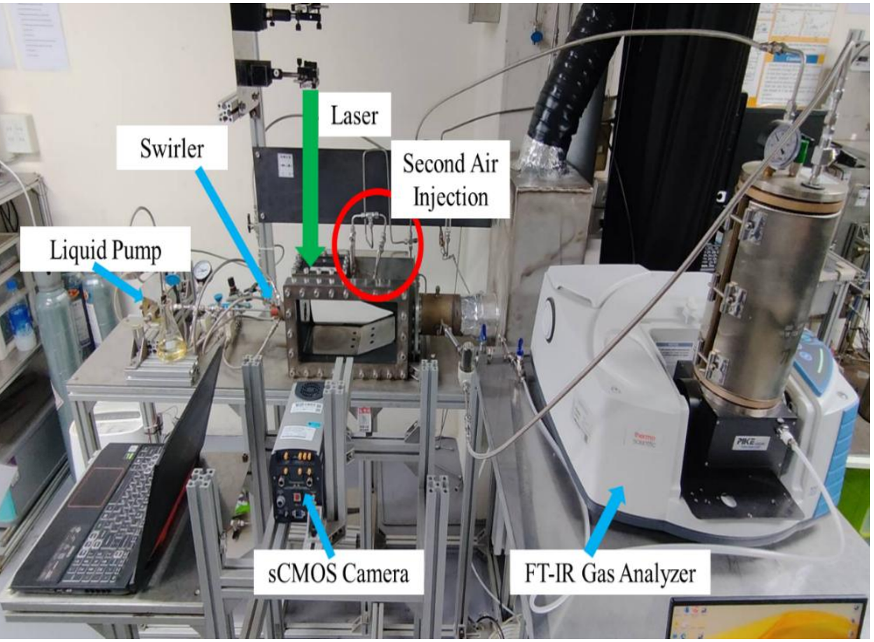
Effects of Swirler

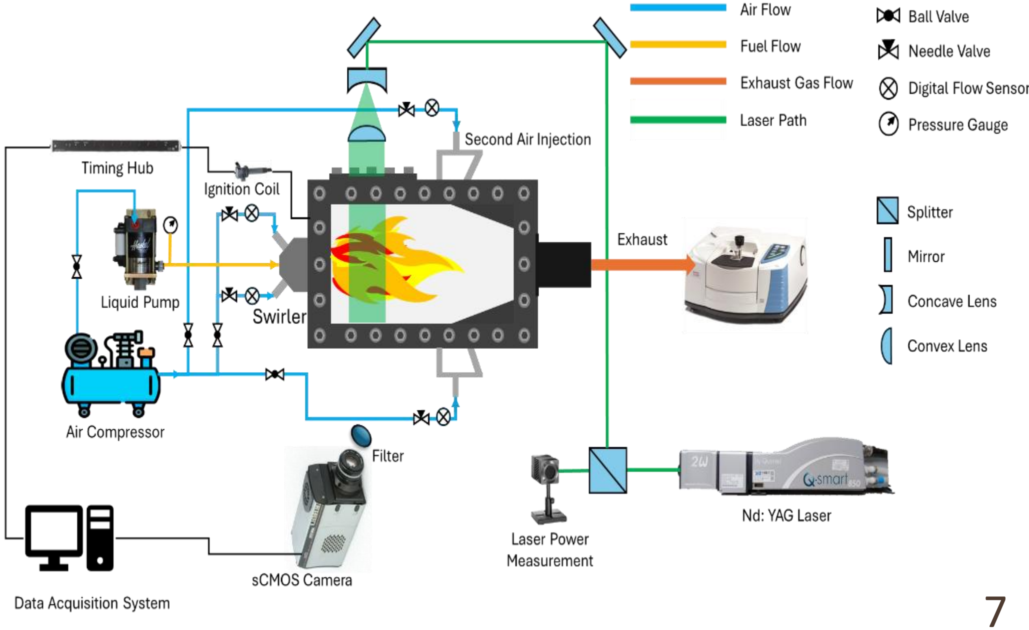


Flame Structure



FTIR Emission Analysis





Objective

Waste Processing

Problem - 1

- Industrial or Agriculture Waste has been a costly issue
- Illegal treatment for industrial waste leads to criminality
- Self-processing consumes energy and emits pollutions
- Self-processing occupies spaces
- Carbon Tax

H_2 for Net Zero Century

Problem - 2

- H_2 production for Net Zero
- A distributed prototype model applied for Industrial H_2 production
- H_2 Production either consumes energy or emits carbons

Sustainable Decarbonization

Benefit

- Occupy 6.6 m^2
- H_2 or H_2-to-fuel cell electricity
- Residue -> Negative electrode of Li battery or active carbon
- Recovered CO_2 can be sold or future be utilized

System Overview

Funded by NSTC 國科會

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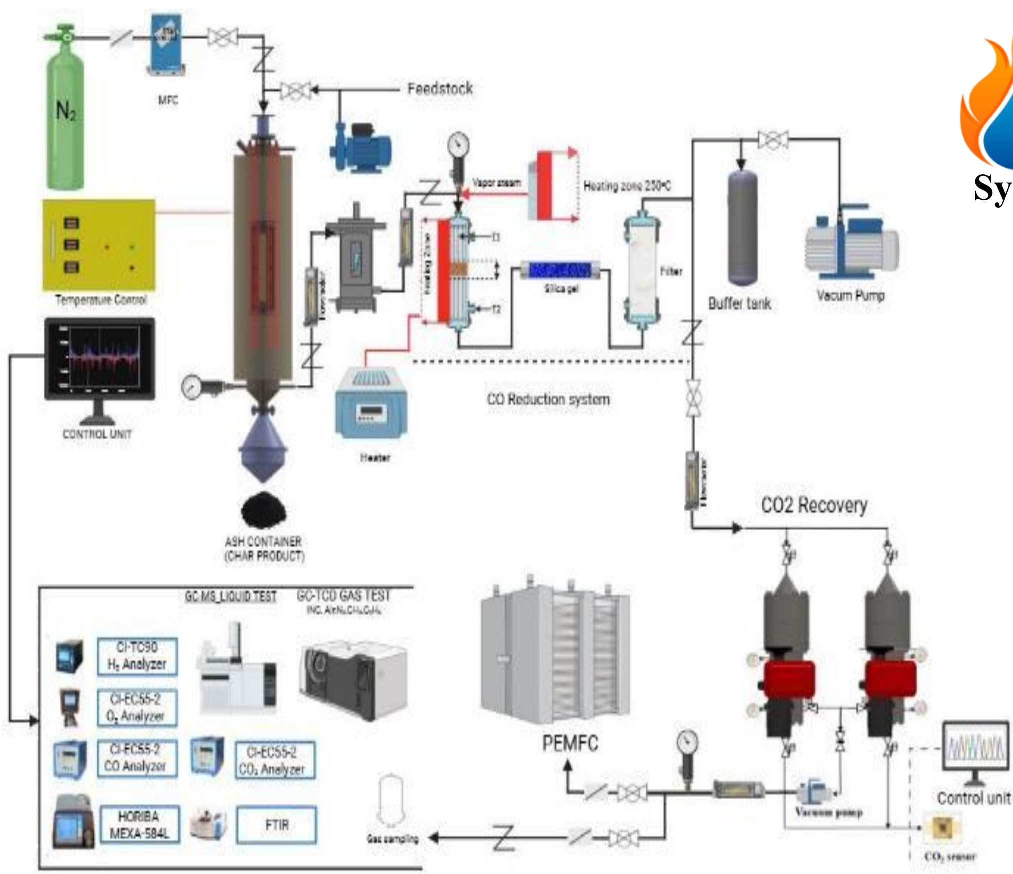
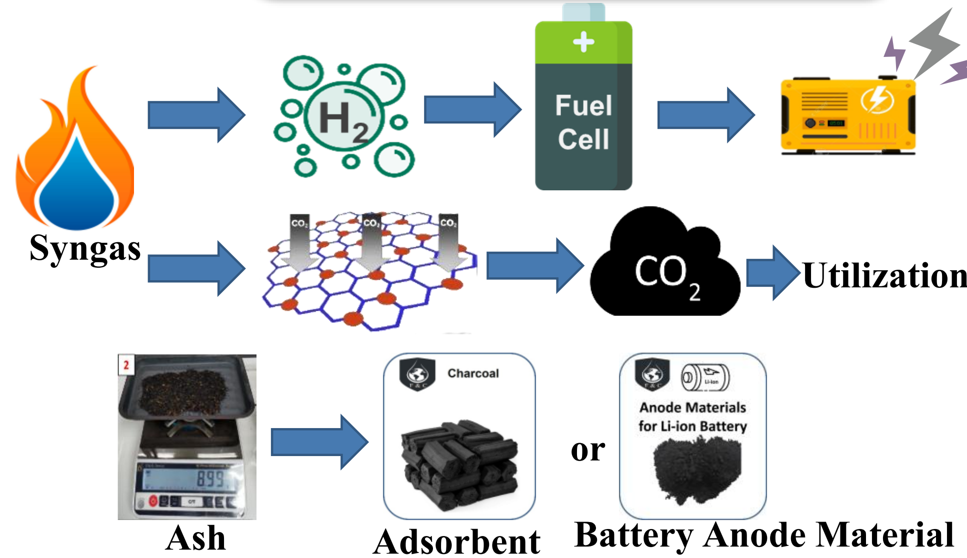
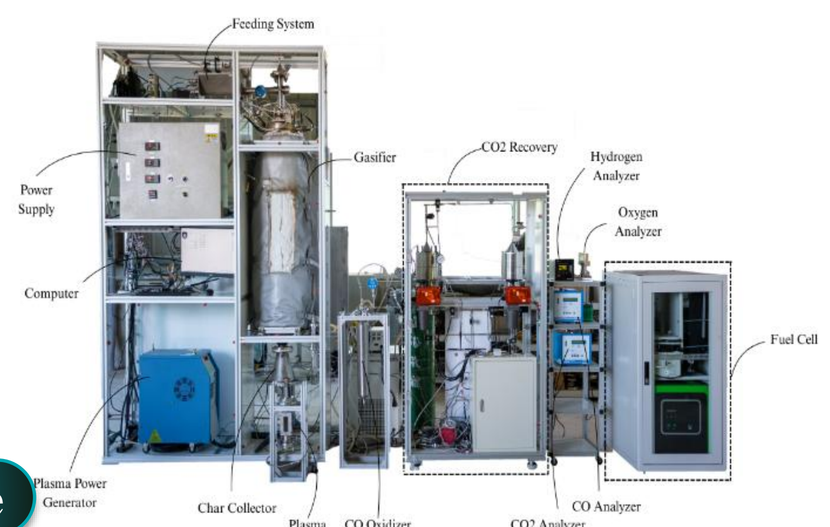
Hydrogen Production and power generation system



Applications of the Product

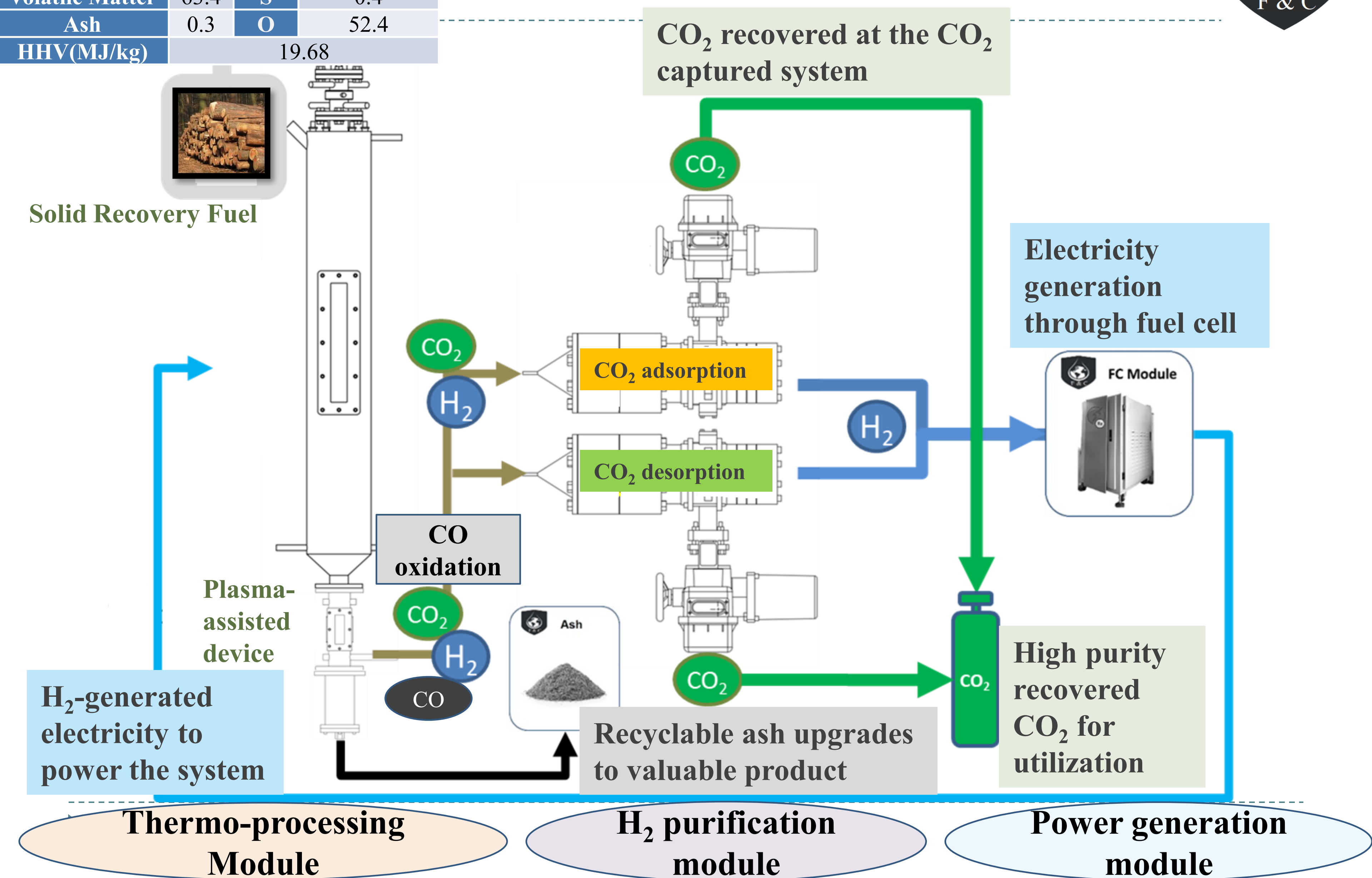




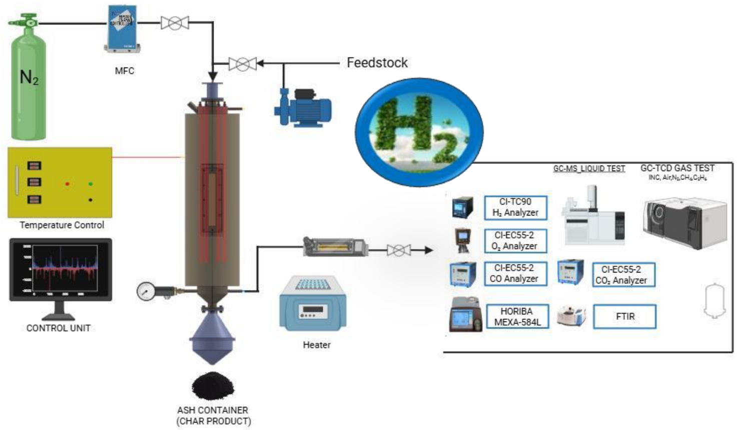
System Prototype

Mixed Pine and Cedar Wood, size: 0.3 mm

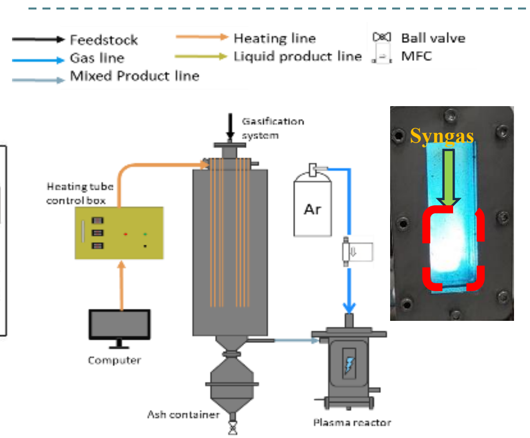
Proximate (wt.%)		Ultimate (wt.%)	
Moisture	9.8	C	46.6
Fixed Carbon	26.5	H	6.0
Volatile Matter	63.4	S	0.4
Ash	0.3	O	52.4
HHV(MJ/kg)	19.68		



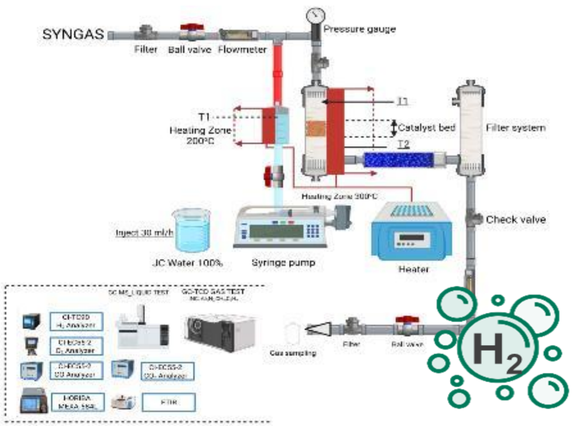
Hydrogen Production and Fuel Cell Power Generation-Related Studies



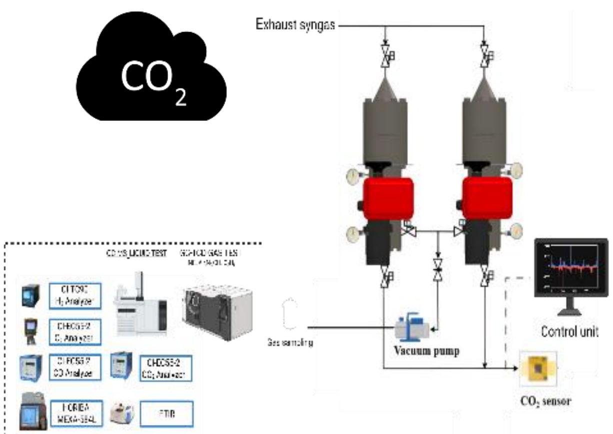
Thermo-processing Module



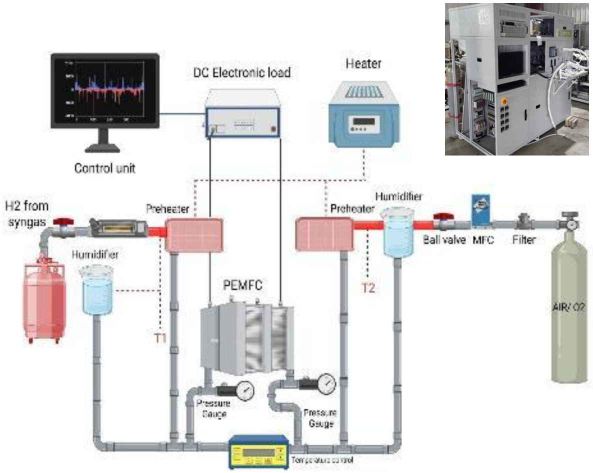
Plasma-assisted Module



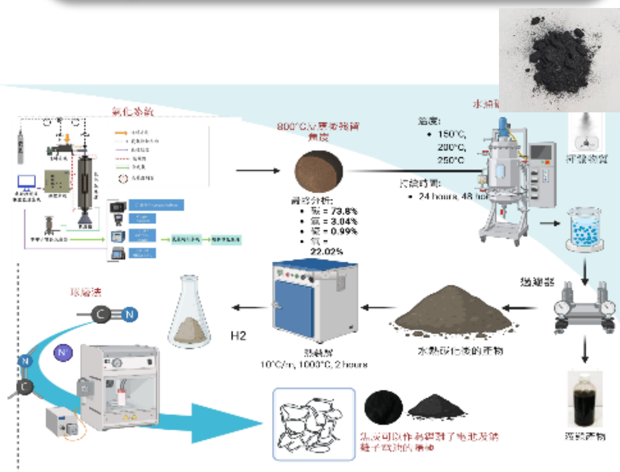
H2 Purification Module



Carbon Recovery Module



Fuel Cell Module

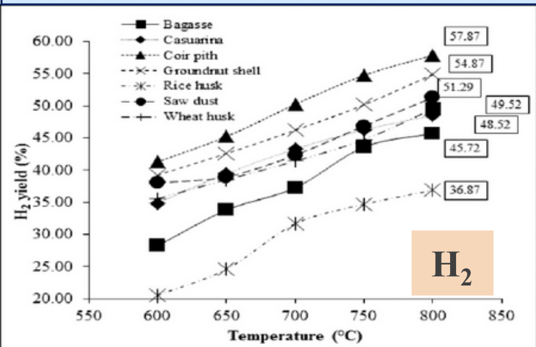


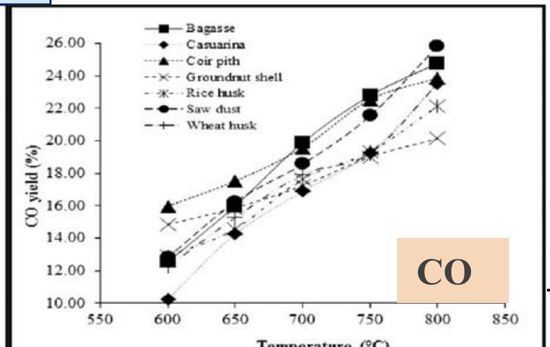
Ash-to-Battery Module

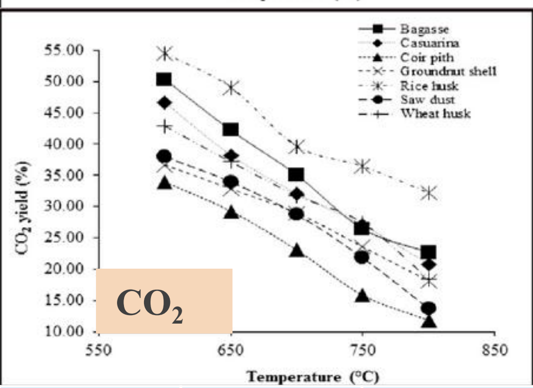
Thermo-processing Module: Plasma-assisted Gasification

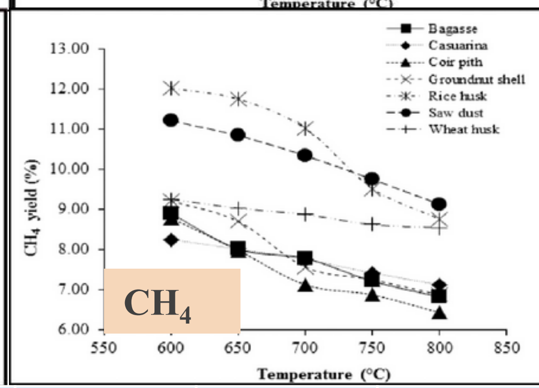
Literature Survey

Choosing the right temp.



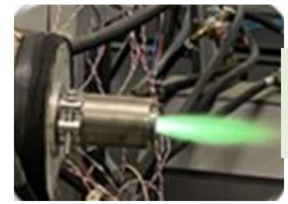






	Mixed Wood Chips	Softwood Pellets	Rape Straw Pellets	Poultry Litter Pellets	Sewage Sludge Sawdust Pellets
H_2	16.4	14.0	14.4	14.6	14.0
CO	22.6	24.3	14.6	17.4	16.4
CO_2	11.1	10.3	11.8	13.5	9.2
CH_4	4.8	4.1	4.1	1.3	1.1
N_2	44.9	47.1	55.0	53.1	59.2

Choosing plasma



With Plasma Torch (71 kW)

Syngas	Conc. (%)
H_2	43.86
CO	30.93

H_2: CO : 1.42
Syngas: 81.5%
Char: 5.8 % ;
Tars: 1.4% ;
Condensate: 11.3 %

With Plasma Arc (1.9 kW)

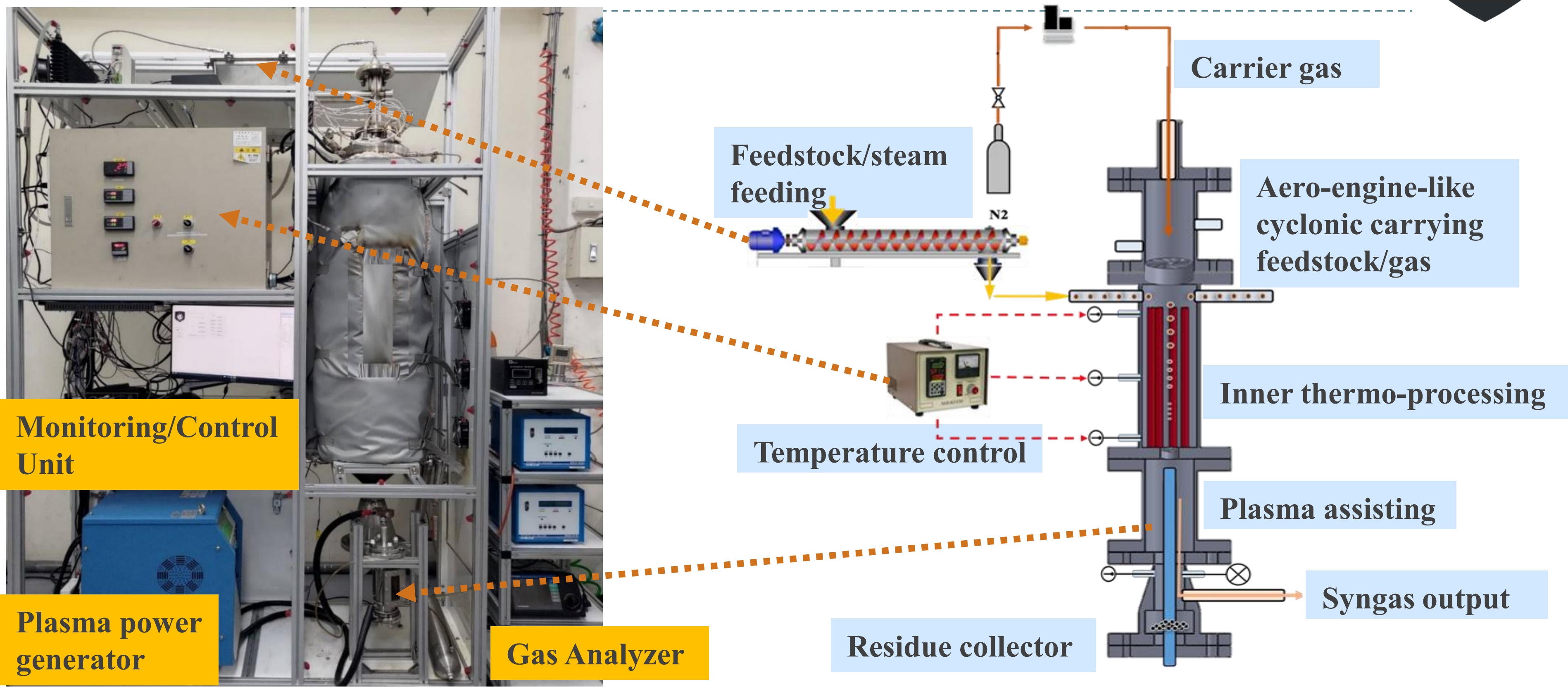
Syngas concentration (%)	Thermal case	Plasma case
H_2	38.9% ± 3%	38.5% ± 2%
CO	32.8% ± 3%	38.4% ± 2%
CH_4	10.2% ± 3%	10.3% ± 2%
CO_2	17.7% ± 3%	12.7% ± 2%

(With N_2 removal)

Low power of plasma makes no difference ? ?!

1. Pang (2020)
2. Tamošiūnas et al. (2023)
3. Striūgas et al. (2014)
4. Parthasarathy et al. (2017)

Thermo-processing System



1. Continuous Cyclonic Downdraft Plasma-assisted thermo-processing System
2. Feeding: 10 kg/hr
3. Feedstock moisture is injected into system as steam: increase H_2
4. Plasma-assisted process: for reducing tar and hydrocarbons
5. Syngas: H_2 ; CO ; CO_2 ; CH_4
6. Residue collected: can be materials for Negative electrode of Li battery or active carbon

Plasma-assisted device

Power Supply: PLA-TIG 301P , Maximum 9.6 kW

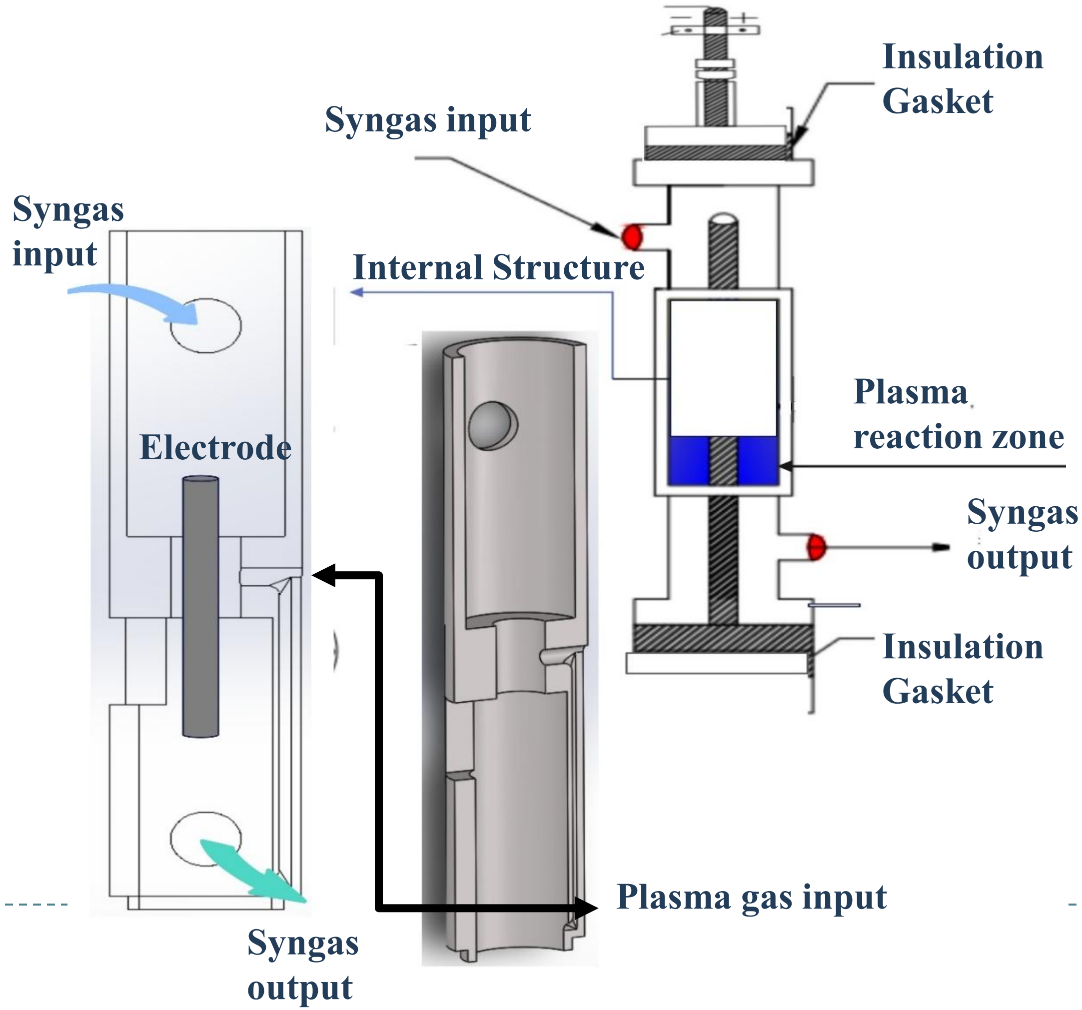
Electrode: Ø12mm graphite electrode

Distance between electrode and ignition surface: 2 mm

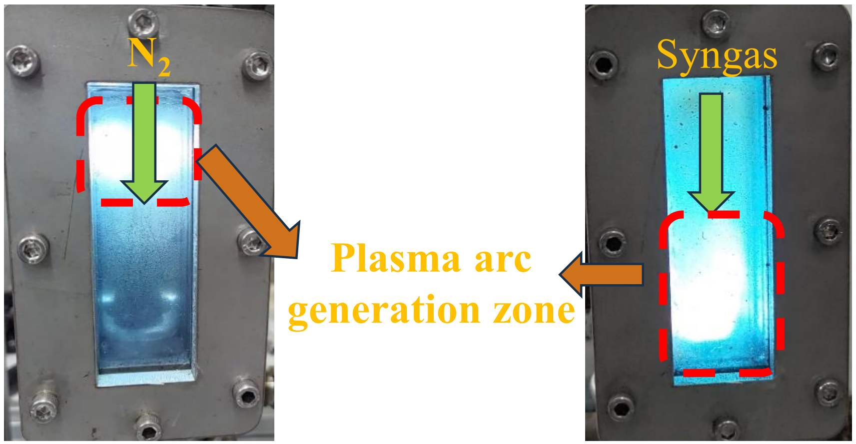
Current: 30 A

Output DC voltage: 20 ~ 30 V

Rated power: 2.1 ~ 2.4 kW



Plasma-assisted device

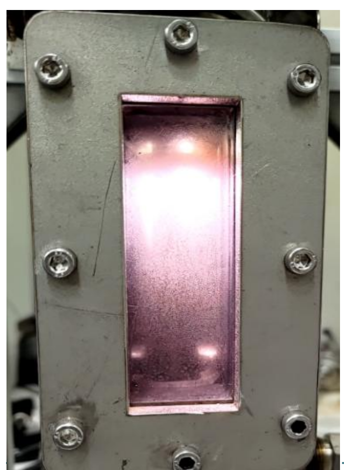


N_2 Initiate

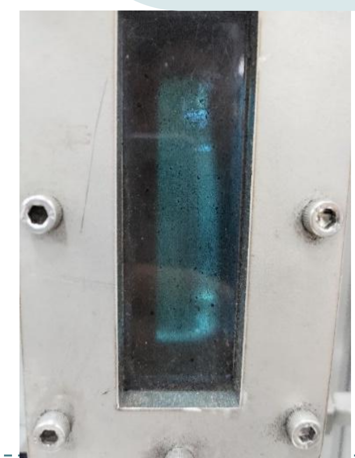
Syngas Initiate

1. Plasma arc distributed in the gas channel
2. Temperature in the plasma zone: 800~1200 °C
3. The color of plasma depends on the gas passing through

Fail to initiate



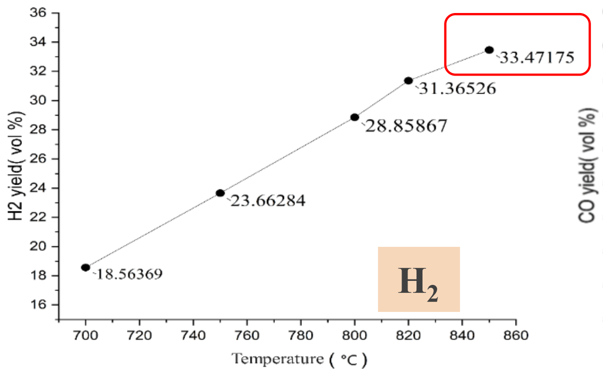
With tungsten electrode

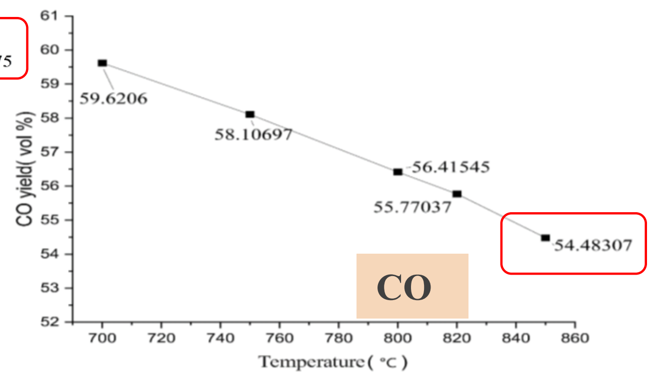


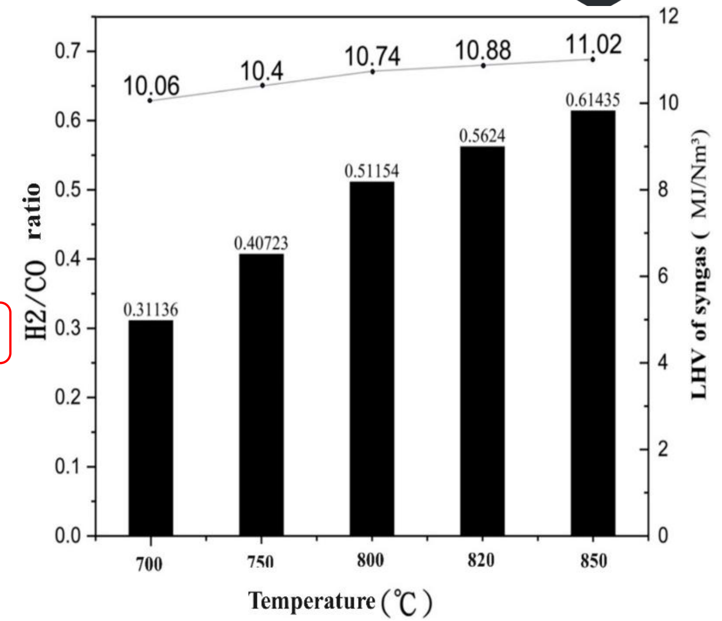
With graphite electrode

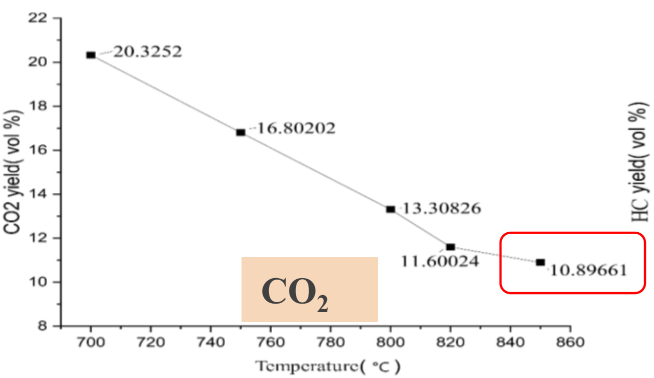
Results

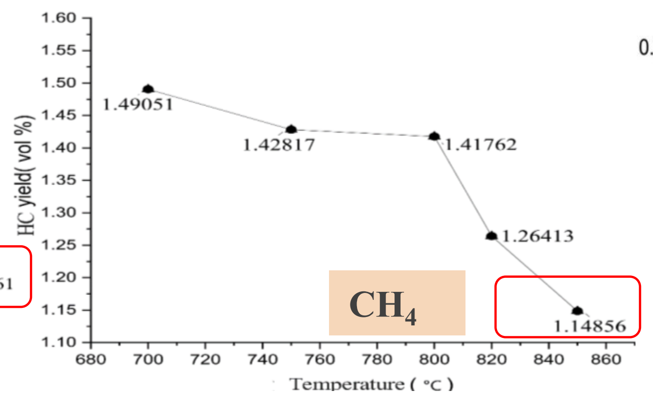
Temperature effects

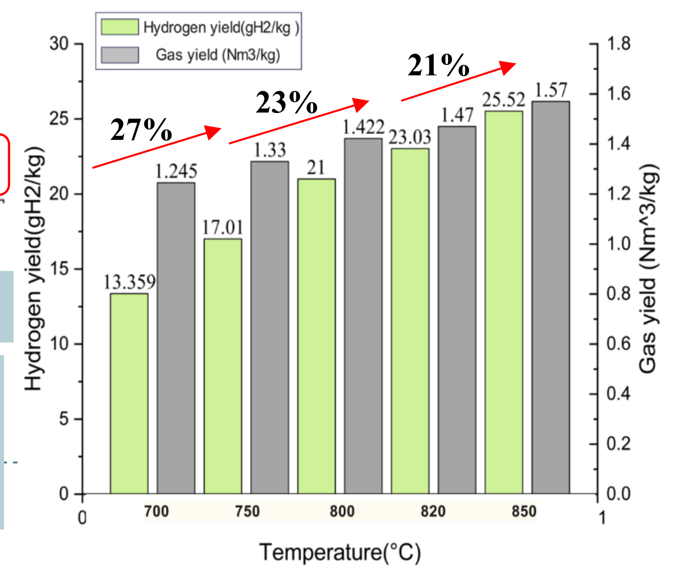












Syngas yield goes up with temp.

H_2/CO ratio goes up with temp.

LHV goes up with temp., due to the increase of H_2

H_2 yield goes up with temp. (700 ~ 750 °C), due to the enhance of water-gas shift

Feeding effects

Feeding rate	0.6 (kg/hr)	3.8 (kg/hr)	7.9 (kg/hr)
H_2 (vol%)	20.31	20.07	19.53
CO (vol%)	38.51	38.12	39.20
CO_2 (vol%)	10.53	11.33	12.12
HC (vol%)	0.71	0.85	0.83
N_2 (vol %)	29.94	29.63	28.32
Ash (%)	18.3	20.1	22.1
Syngas yield (Nm^3/hr)	0.474	3.002	6.241

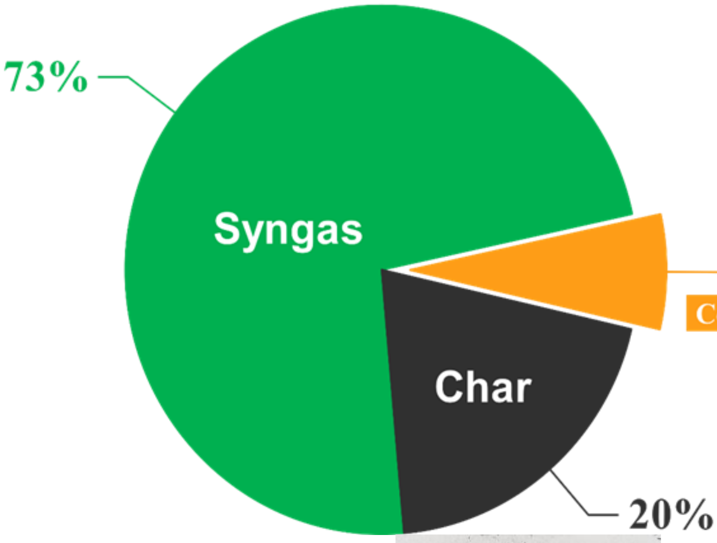
Plasma effects

Temperature (°C)	800		850	
Plasma	Off	On	Off	On
H_2 (vol%)	28.86	29.74	33.47	35.04
CO (vol%)	56.42	56.27	54.48	53.65
CO_2 (vol%)	13.30	13.71	10.90	11.18
HC (vol%)	1.428	0.42	1.14	0.25

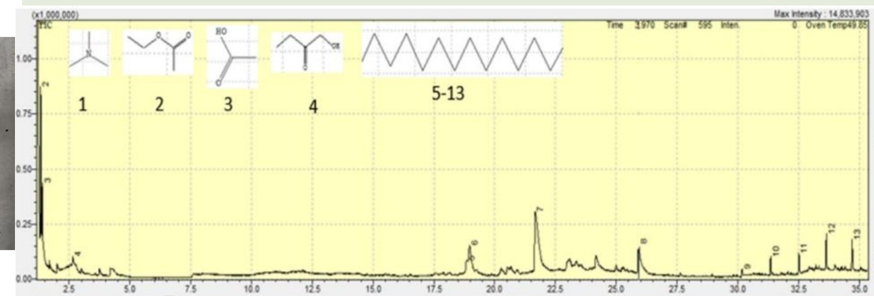
F & C

Syngas composition remains consistent with different feeding rate

Co-product



* Tar contains mostly long-chain HC
* 7% of condensed tar includes 3.4 % of tar of 3.6 % of condensed products
* Glass wool in the filter with plasma is cleaner => Heavy hydrocarbon is decomposed by plasma



Char contains mostly carbon

70~89% of H_2 in feed goes to syngas

92% of water in feed is gasified

Proximate (wt.%)		Ultimate (wt.%)	
Moisture	3.78	Carbon	73.8
Fixed Carbon	60.59	Hydrogen	3.04
Volatile Matter	32.8	Sulfur	0.99
Ash	2.83	Oxygen	22.02
CCE (%)	76		
HHV (MJ/Kg)	26.60		

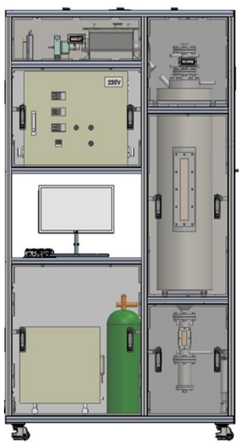
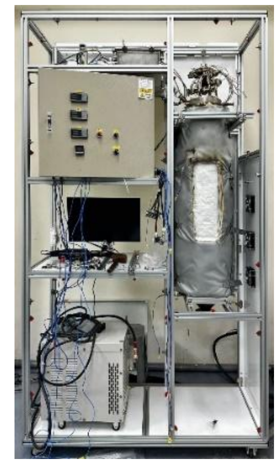
Glass wool in Filter

Without plasma

With plasma

From Design to Prototype

F & C

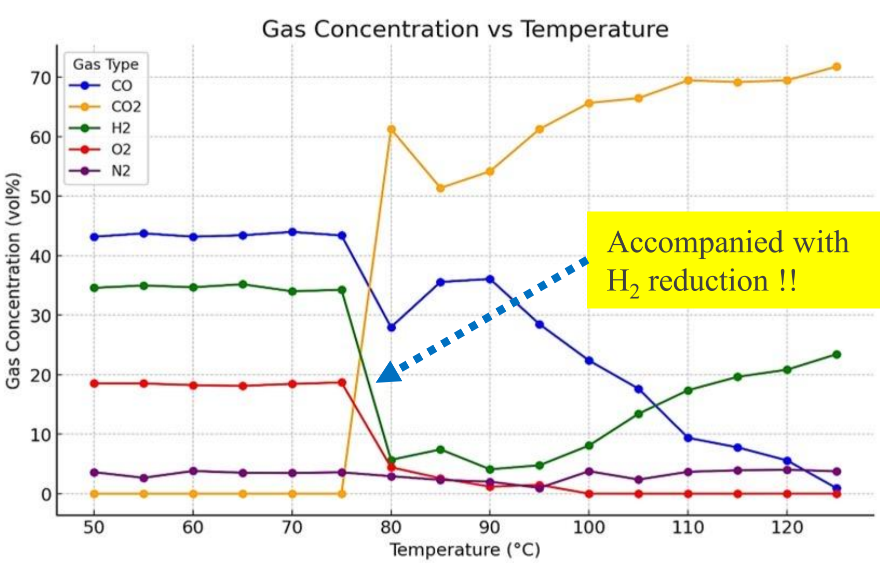
Design	Assembling & Test	Prototype
	   	 

H_2 purification module-1
Turn CO into CO_2

Selective Oxidation of CO

1. CO in syngas should be limited for fuel cell
2. Selective oxidizing CO to CO_2
3. Recover CO_2 at the next step
4. Oxidant can be supplied by Air

NO.	Catalyst	CO (%)	CO_2 (%)	H_2 (%)	O_2 (%)
Initial		45	0	35	20
1	CZT3008585C45	**0.20**	**76.40**	**20.90**	**0.01**
2	Fe-CuC5W	2.40	90.50	0.01	0.18
3	Fe-G4C8	26.50	7.40	20.01	21.82
4	Fe-CuC6	28	7.60	20.72	19.69
5	Fe-G4C8	30.50	7.01	19.74	20.51
6	5FCuA04Cu	16.80	34.50	7.51	10.37
7	5FAO4Cu	13.80	44.00	1.58	6.56
8	FeAl-Cu	24	11.00	17.00	23.77
9	5FCoAo5Co	16.20	42.00	4.59	1.46
10	5FAO4Cu	2.20	61.50	0.01	0.50
11	Fe-C20116	24	18.40	0.00	23.70
12	FZ00	0.40	12.20	27.90	23.77



CO oxidation with various temperature

H_2 purification module-2
CO_2 Recovery

CO_2 recovery

Funded by tsmc

Recovery Efficiency: 95%

Adsorption Capacity: 0.6857 mmol/g

Desorbed CO_2 purity: 97%

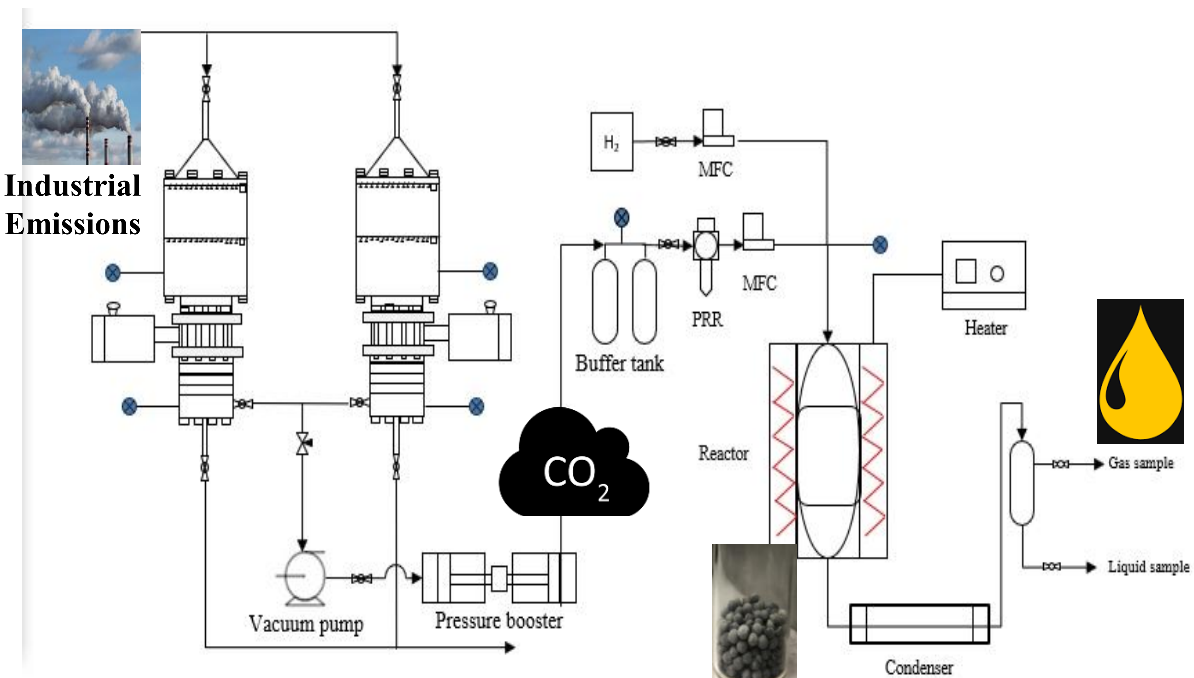
CO_2-to-Fuel Conversion: 92%

Aerodynamic Chamber Design : High efficiency

Room temperature and atmospheric pressure : Low energy consumption

Home-made absorbent and catalyst (for CO_2 utilization) : Low cost, life-time usage, and no waste treatment needed

High conversion and selectivity for recovered-CO_2-to-Fuel



Performance Calculation

Adsorption process

1. CO_2 adsorption efficiency :

$$CO_2 \text{ adsorption efficiency} = \left(\frac{\%CO_{2,in} - \%CO_{2,out}}{\%CO_{2,in}}\right) \times 100$$

2. CO_2 adsorption capacity :

$$CO_2 \text{ adsorption capacity} = \frac{Q_{tot} * \rho_{CO2}}{100 * M_w * w} \int_{t_0}^{t_1} (C_0 - C_t)\,dt$$

$\%CO_{2,in}$ = Concentration of CO_2 at inlet (%)

$\%CO_{2,out}$ = Lowest concentration of CO_2 at outlet (%)

Q_{tot} = Total feed flow rate (cm^3/min)

ρ_{CO2} = Density of CO_2 (g/cm^3)

Mw = Molecular weight of CO_2 (g/mol)

w = Weight of adsorbent (g)

C0 = Concentration at inlet

Ct = Concentration at that time at outlet

Desorption process

3. CO_2 Purity :

$$CO_2 \text{ purity} = \left(\frac{\%CO_{2,des}}{Total\ gas}\right) x\ 100\%$$

4. CO_2 Recovery :

$$CO_2 \text{ recovery} = \frac{\int_0^{t_{cycle}} Q_{des}\, y_{CO_2}^{des}\, dt}{\int_0^{t_{cycle}} Q_{feed}\, y_{CO_2}^{feed}\, dt}\ x\ 100\%$$

$\%CO_{2,des}$ = CO_2 concentration in desorption process (vol%)

Q_{des} = Flow rate of desorbed CO_2 gas (l/min)

$y_{CO_2}^{des}$ = Desorbed CO_2 concentration (vol%)

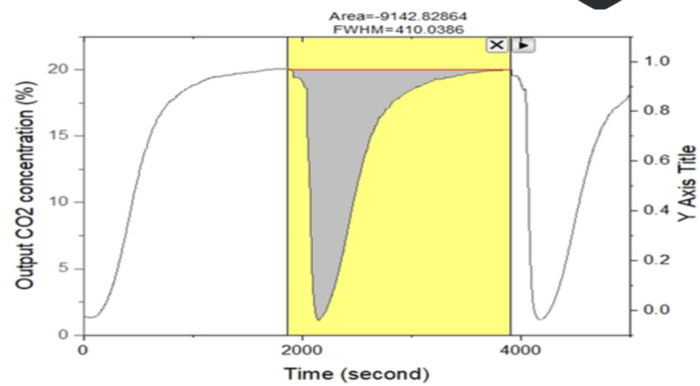
Q_{feed} = Feeding flow rate of CO_2 gas (l/min)

$y_{CO_2}^{feed}$ = Inlet feeding CO_2 concentration (vol%)

CO_2 Recovery

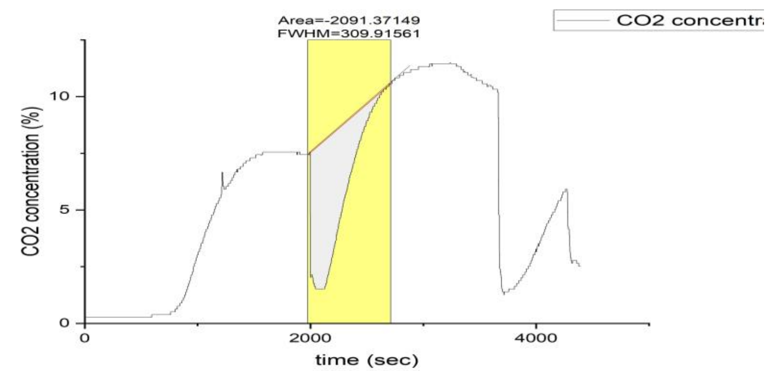
Pure test: with N_2 and CO_2

CO_2 adsorption efficiency (%)	CO_2 purity (%)	CO_2 recovery (%)	Adsorption capacity (mmol/g)
94.7	97.0	85.2	0.91



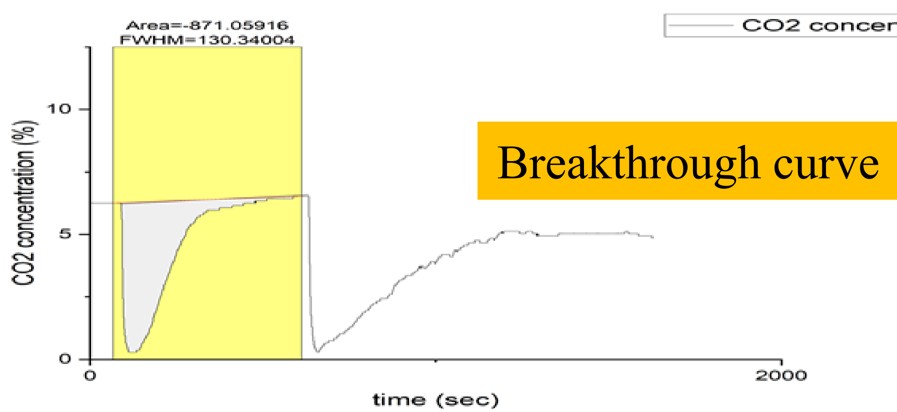
Integrate with thermo-processing of agriculture residue

CO_2 adsorption efficiency (%)	CO_2 purity (%)	CO_2 recovery (%)	Adsorption capacity (mmol/g)
88.6	45.5	41.0	0.26



Integrate with thermo-processing of industrial slurry

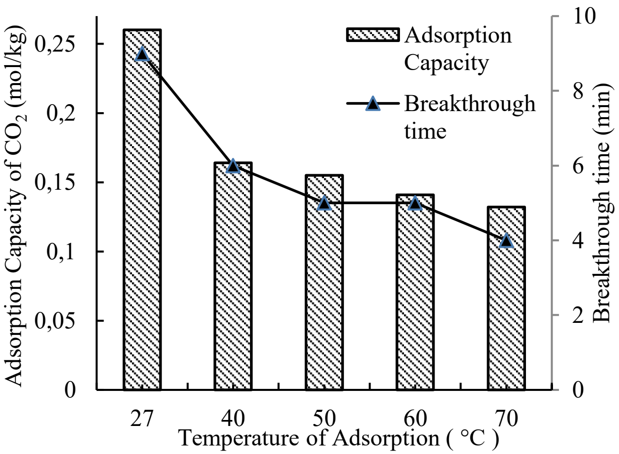
CO_2 adsorption efficiency (%)	Adsorption capacity (mmol/g)
95.8	0.097



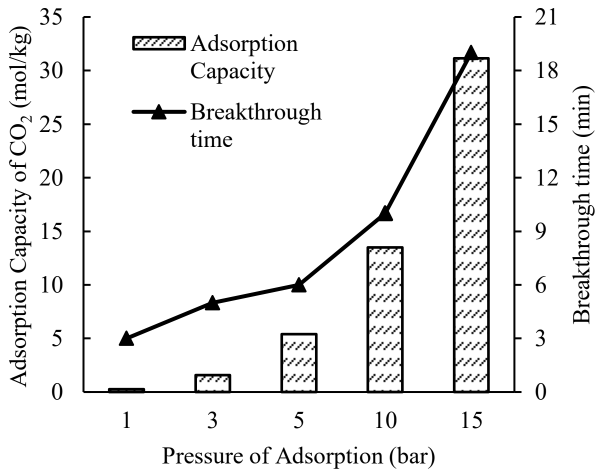
Breakthrough curve

Impact of parameter

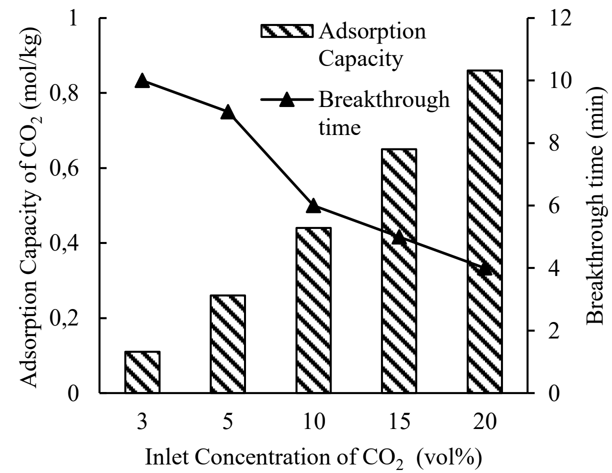
Temperature of Adsorption



Pressure of Adsorption



Inlet CO_2 concentration



- ↑ Adsorption Temperature
- ↓ Adsorption capacity
- ↓ Breakthrough time

Van Der Waal force decrease

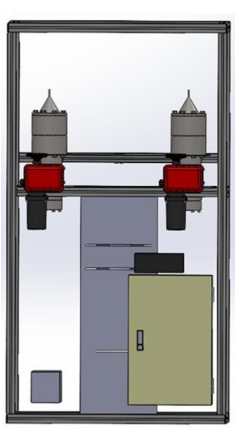
Exothermic

- ↑ Adsorption Pressure
- ↑ Adsorption capacity
- ↑ Breakthrough time

Increase of Molecular Collision

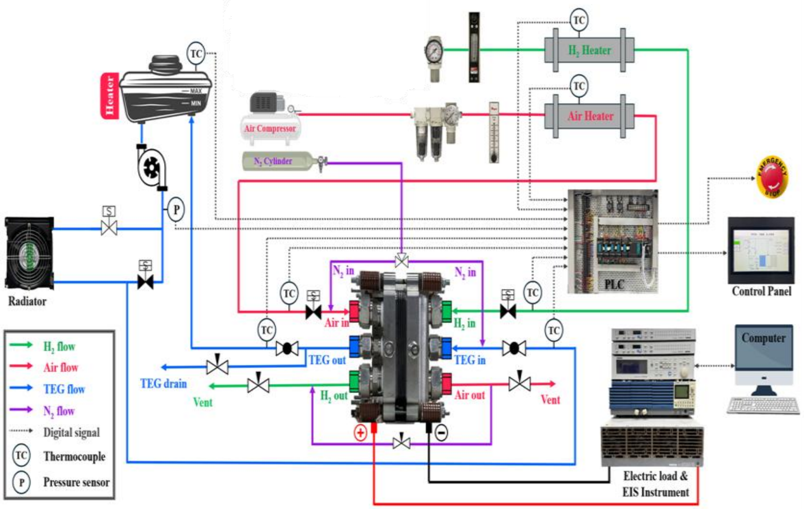
- ↑ Inlet CO_2 concentration
- ↑ Adsorption capacity
- ↓ Breakthrough time

From Design to Prototype

Design	Assembling & Test	Prototype
	   	 

Power generation module

H_2-to-Electricity

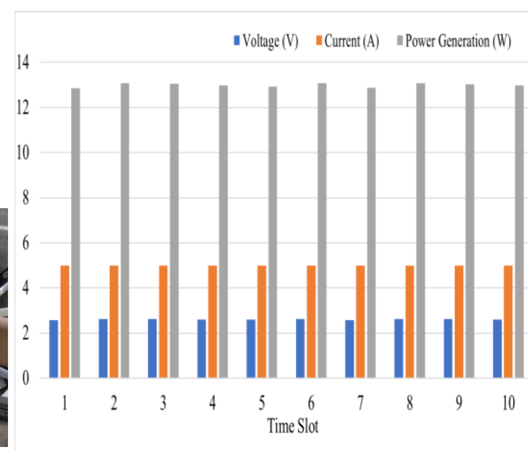


HT-PEMFC Test Bench Specifications

Parameter	Unit	Value
Operating Temperature	ºC	140 – 200
Power	kW	Up to 3
Voltage	V	0 – 150
Cell measurement	Cell	Up to 64 (simultaneously)
Impedance range	Ω	0.01 – 10
Measuring frequency	Hz	0.01 – 20 x 10^3
Measuring AC current	-	0 – 10 %
Protection Function	-	UVP, OVP, OPP, REV, and OHP

High Temperature Proton Exchange Membrane Fuel Cell

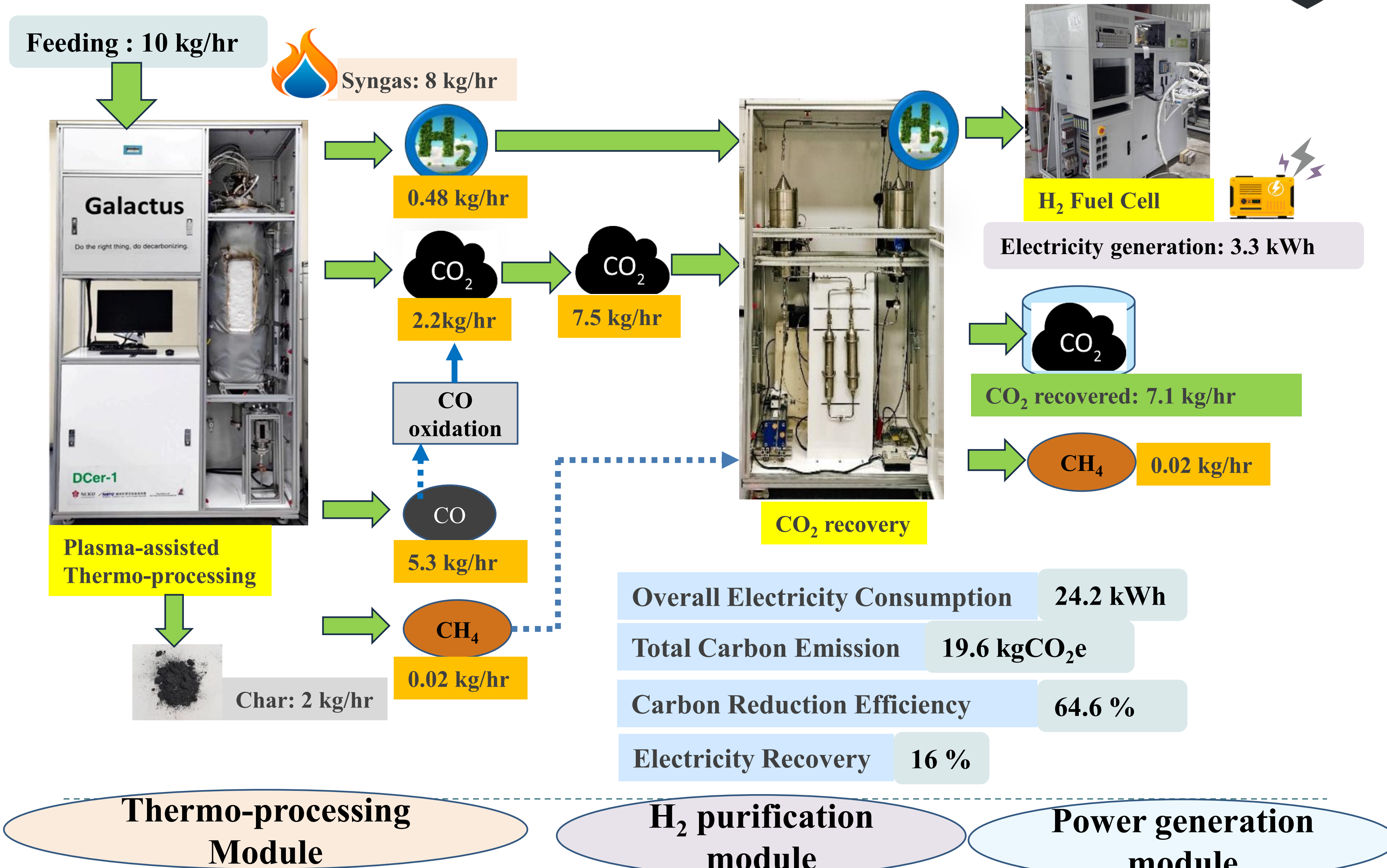
Test Bench



System power consumption	24 kWh
H_2 Production	0.48 kg/hr
H_2-to-electricity Production	3.3 kWh

Providing 14 % system electricity requirement

Overall Evaluations



Field Test

Prototype	Field Assembling	Field Test
 	 	 

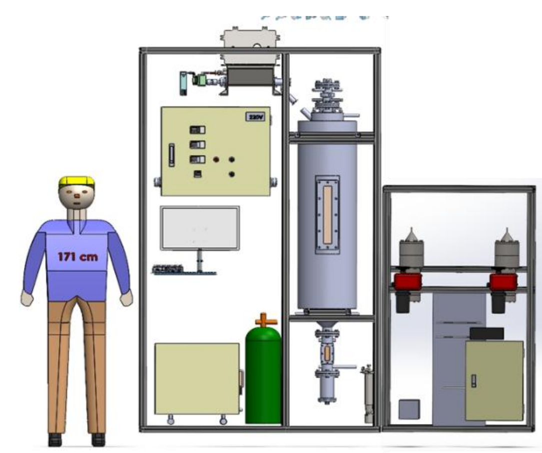
Prototype

H_2 production is low → High energy consumption, carbon emission, and cost

→ Maximum 0.6 kg/hr hydrogen can be extracted

→ Can select another feedstock with high hydrogen content

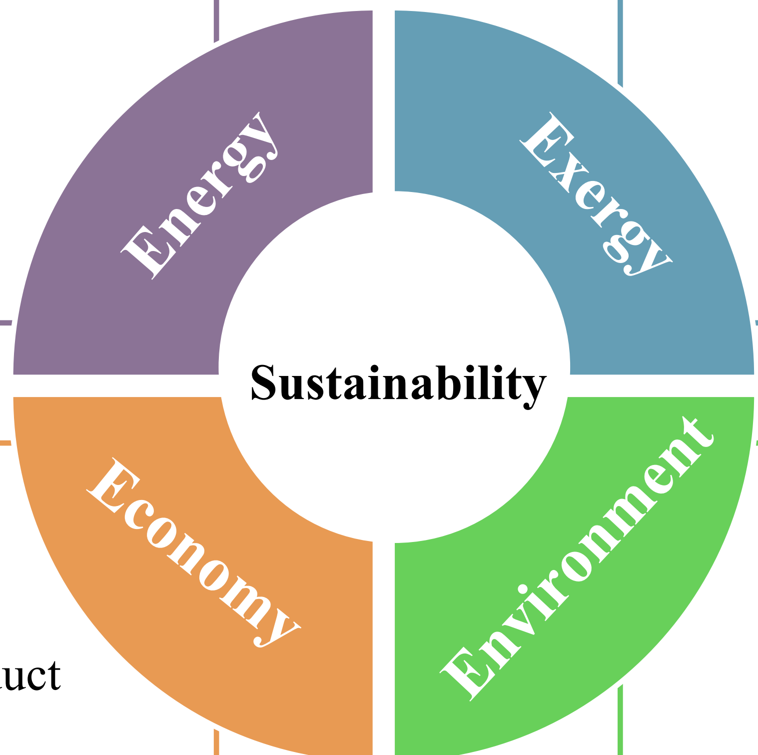
	H_2	Energy Consumption (MJ/kg H_2)	H_2 production (kg H_2 / hr)	Carbon Emission (kg CO_2 / kg H_2)	Cost (\$/kg H_2)	Process Efficiency (%)
Electrolysis	Green	9.1	2.52	8.9 ~ 12.9	10.3	70
Steam reforming	Gray	143	7.78	13.7	2.9	74–85
Pyrolysis	Turquoise	0.0015	10.40	0.0356	1.6	42.5
Gasification	Black	0.163	0.143 ~ 0.71	0.02	0.3	35
Biological	NA	NA	NA	NA	2.83	0.1
Plasma Gasification	Turquoise	6.58	1.73	0.055	400	79.22 ~ 83.46
Coal gasification	Black	186	12.6	29.33	1.91	75
Decarbonizer	**Blue**	**352**	**0.48**	**75.9**	**31.72**	**65.77**



What's Next ?

- Energy Efficiency
- Pinch analysis for energy integration
- Thermo-economic analysis

- Exergy flow and exergy efficiency
- Cost of exergy destruction



- Minimize H_2 production cost
- Maximize co-product credit

- Carbon Intensity
- Other potential pollutions

Thank you

Contact

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