

Imperial College
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“Laboratory techniques for screening biomass gasification feedstocks”

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Overview

- Research Group introduction
- Research Group objectives
- Experimental bench-scale reactors – design aspects; operating conditions; selected data.
- The “hot rod” fixed bed reactor
- The wire-mesh reactor
- The fluidised bed reactor in the context of oxy-fuel fluidised bed gasification

Energy Engineering Research Group

Personnel:

Professors Denis Dugwell and Rafael Kandiyoti [both part-time]

Dr Marcus Millan-Agorio, Dr Paul Fennell

Dr Nigel Paterson, Dr Graham Reed, Dr Nick Florin

Plus many PhD students – Nicolas Spiegl [FBR & WMR],

Yatica Somrang [WMR] Staineth Monteiro-Nunes [HRR]

Objectives:

To enhance the efficiency, and reduce the environmental impact, of energy utilisation through the study of pyrolysis, combustion, gasification and liquefaction of coal, petroleum residues, waste fuels and biomass.

Emphasis on fundamental aspects such as solid, liquid and gaseous by-product yields and composition; heteroatom partitioning; trace element partitioning. Carbon capture by calcium looping.

Gasification studies focussing on quality and quantity of gas and tar. Study of tar characteristics and means of tar minimisation. Down-draft gasification and fluidised bed gasification.

Hot Rod Reactor

Specification:

Fixed bed reactor.

100-200 mg sample
ground to 150-800 μ m

Temperature up to 1000 $^{\circ}$ C

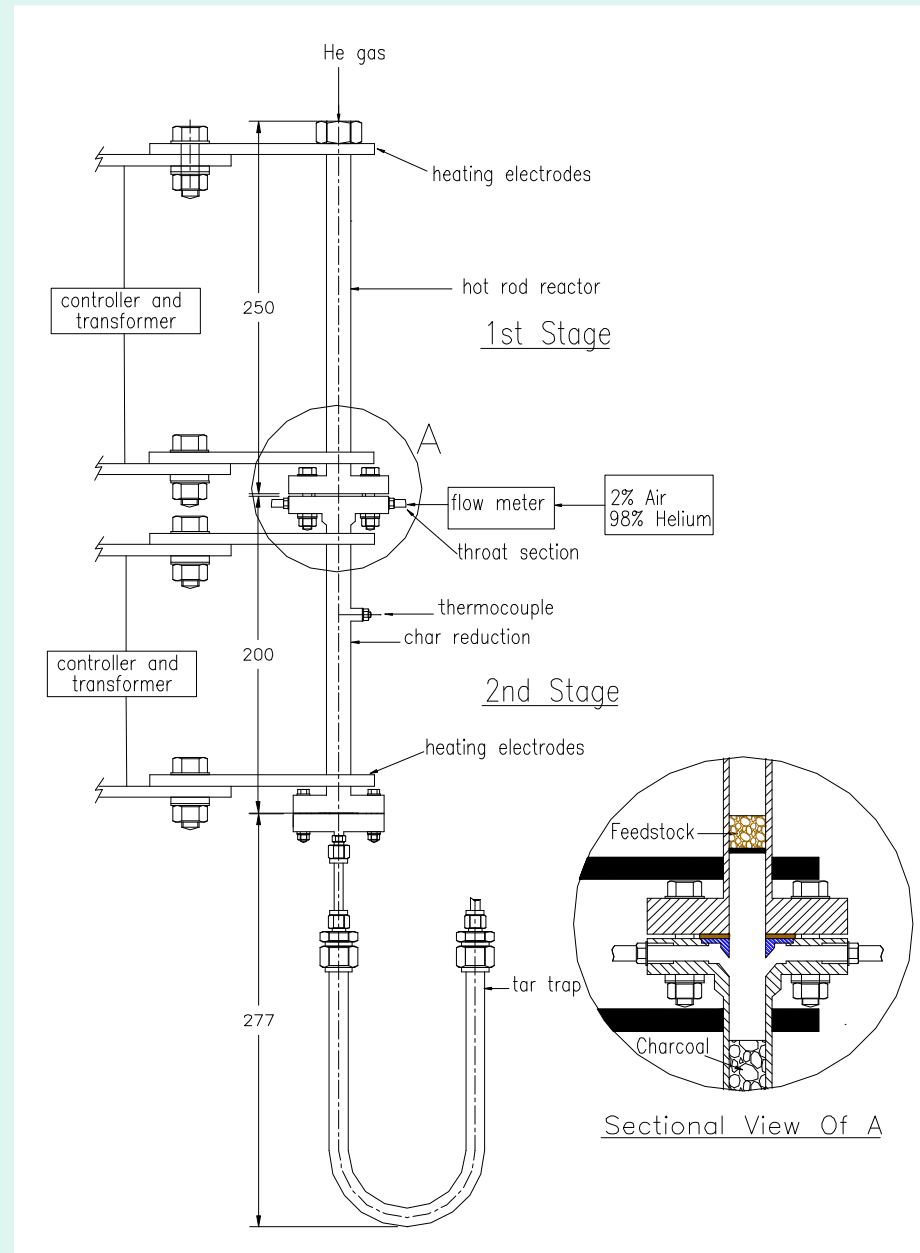
Pressure: atmospheric
up to 100 bar

Simulation of down-draft
biomass gasifier

12 mm i.d. 316 s.s

Throat: O₂ injection

12 mm i.d. Incoloy 800HT



Test Objectives & Conditions

To examine reactor operating parameters that would reduce the residual tar content in the fuel gas in a downdraft gasifier and ideally eliminate it altogether.

The laboratory scale, two-stage fixed bed reactor has been developed to simulate and enable study of aspects of the operation in downdraft gasifiers that influence tar cracking.

Tar is generated by pyrolysis in the first stage and cracking and gasification take place in the second stage.

Intermediate injection of O₂ in He can simulate the throat of an operating gasifier.

1st Stage. Feed: beechwood [106-150 μm]; superficial velocity 0.1 m/s; Inlet pressure 2.2 barg; T 500 °C. 48% tar in raw pyrolysis gas
2nd Stage. Empty, superficial velocity 0.4 m/s, inlet pressure 2.1 barg

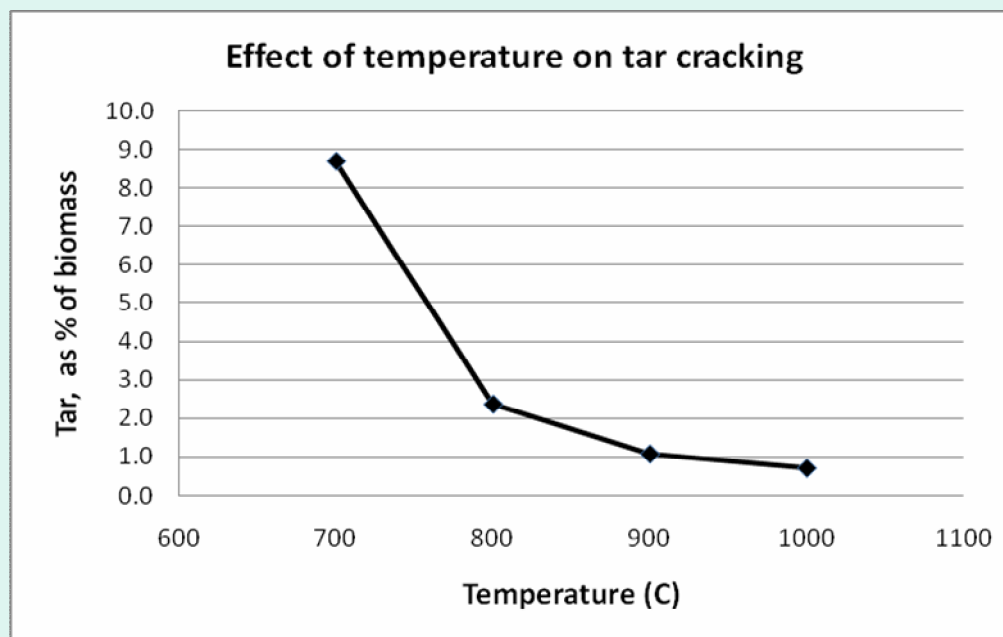
Measurements and Feedstock

- **Measurement of tar yield by weight – wash into Chloroform-Methanol [4:1 by vol.] mixture, filter and evaporate off solvent [90°C then 35°C]. Weigh residue.**
- **Characterisation of light tars by GC: C2 – C5 alkanes and alkenes [packed alumina F-1 60/80 column] and CO₂ [molecular sieve 5A 60/80 column].**
- **Methane and CO measured online by ADC infra red analysers.**
- **Heavy tar characterisation by SEC, MALDI-ms, UVF, NMR etc.**

Feedstock - Beechwood

Ultimate Analysis (wt %)							Proximate, (wt %)	
C	H	N	O	S	Cl	Ash	Moisture	Volatiles
43.4	4.8	0.26	39.9	<0.04	0.01	0.5	11.6	75.0

Effect of Empty 2nd Stage temperature on tar yield and quality



Yields expressed as weight % of raw biomass

T, °C	Tar	Char	c2 – c5	CH4	CO	CO2	H2O	% of Σ
700	8.7	22.4	2.9	2.6	14.4	7.7	23	82
800	2.4	22.3	3.4	4.7	18.8	7.8	23	82
900	1.1	22.9	2.6	4.9	19.6	10.3	25	87
1000	0.7	22.8	0.8	4.7	20.6	13.2	15	78

Effect of char-filled 2nd Stage temperature on tar yield and quality

1st Stage set as previously.

2nd Stage: Superficial velocity and pressure as before, T variable
Filled with spruce char – 4 g [212 – 500 μm material].

Yields expressed as weight % of raw biomass

T, °C	Tar	Char	c2 – c5	CH4	CO	CO2	H2O	% of Σ
700	3.5	22.4	2.5	3.7	12.1	10.1	25.0	80
800	1.0	22.3	3.1	4.9	15.7	10.3	20	77
900	0.3	22.9	1.0	3.7	30	7.8	10.0	75
1000	0.3	22.8	0.0	2.3	34	0.1	0.0	59

* Tar effectively eliminated by small flow of 2 % air in He at 800C

Wire-Mesh Reactor

Specification:

Mono-layer fixed
bed reactor

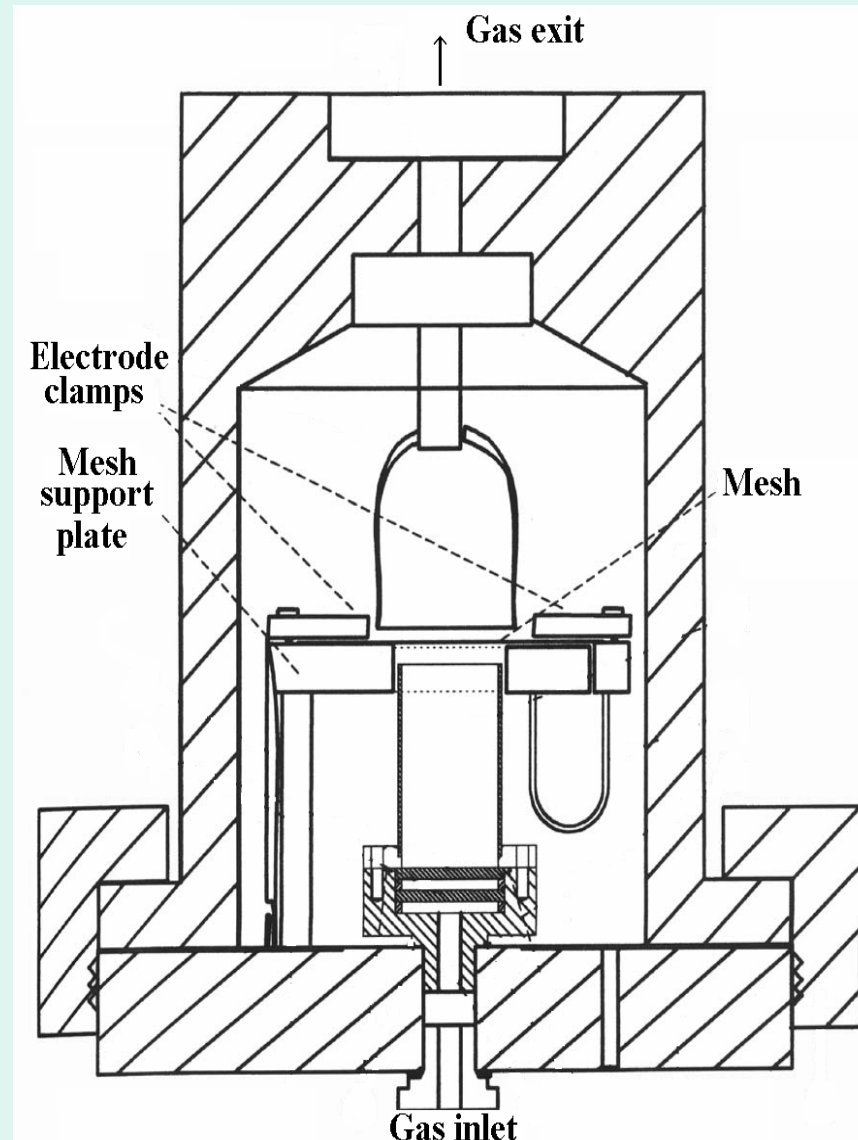
5-7 mg sample
ground to 106 -150 μ m

Temperature up to 2000C
HR to 10⁴ K/s, hold to 30s

Pressure: atmospheric
or up to 150bar – N₂ , He,
H₂, CO₂, steam.

Simulation of devolatilisation
stage of pf combustor or
fluidised bed combustor

Gasification studies



Wire – Mesh Reactor Fuels

German Lignite

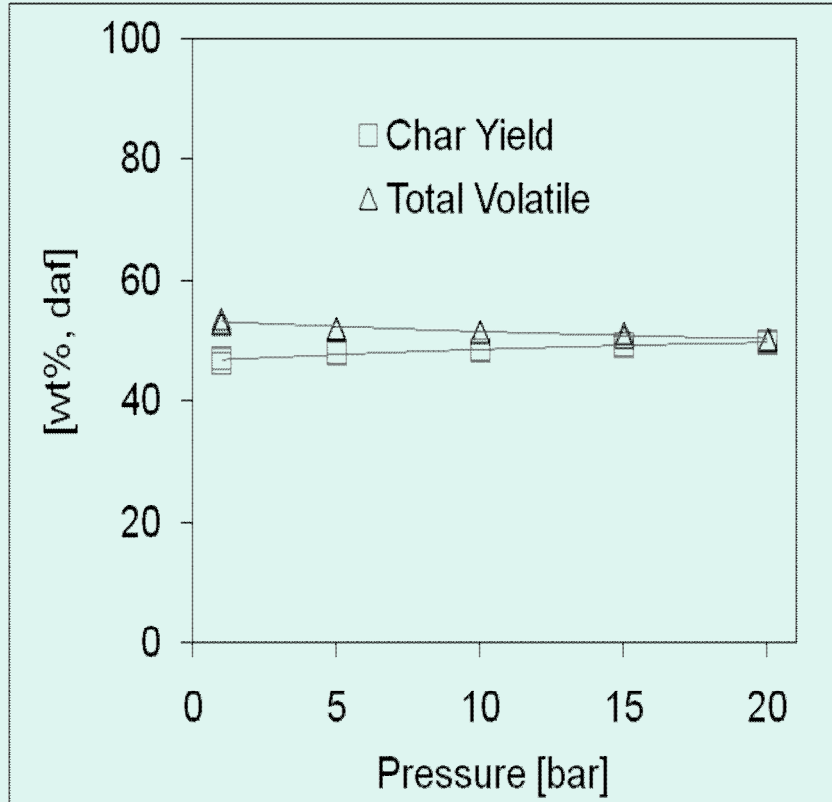


Moisture: 3.2%, Ash: 4.1%, Volatile Matter: 44.0%, Fixed Carbon: 38.7%

Rice Husk from Thailand

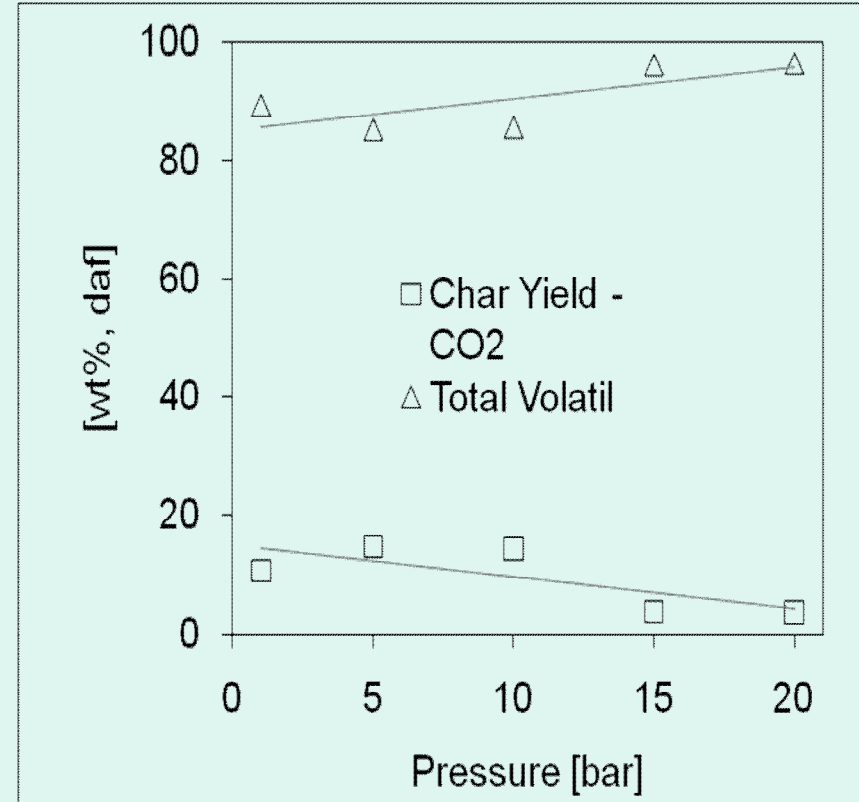
Composition,	%			Calorific value, kJ/kg	
Total moisture	10.1	Carbon	35.14	GCV	14,456
Ash	16.8	Hydrogen	4.38	NCV	13,310
Volatile Matter	58.0	Nitrogen	0.60	CV [daf]	19,780
Fixed Carbon	15.1				
Sulphur	0.04				
Chlorine	0.27				

Results: Wire Mesh Reactor - Lignite



Pyrolysis [850C] :

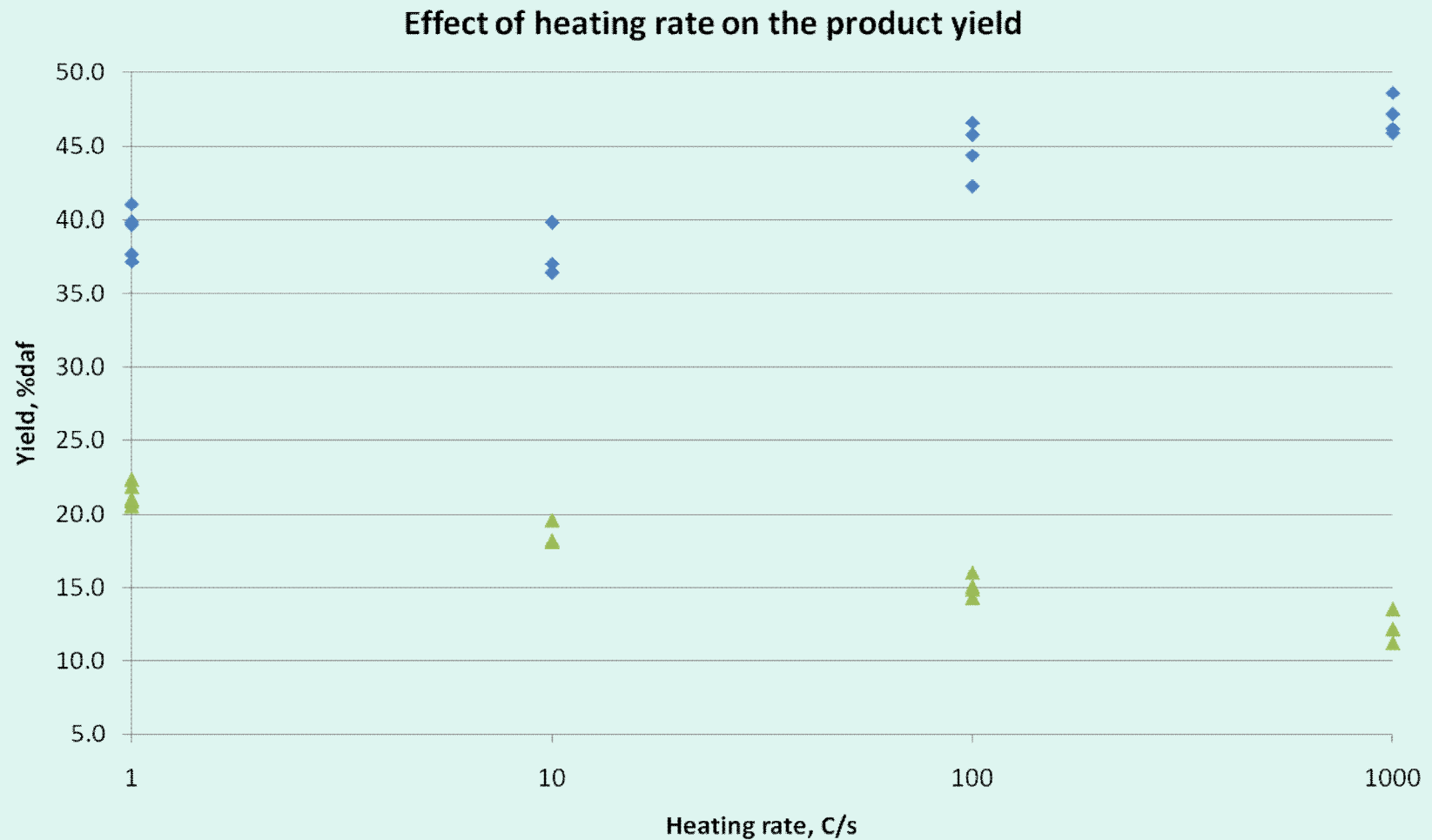
- ❑ Decrease in total volatile yield
- ❑ Increase in char yield



Gasification [850C]:

- ❑ Increase in total volatile yield
- ❑ Decrease in char yield
- ❑ Increase in extent of gasification

Effect of heating rate on bio-oil yield



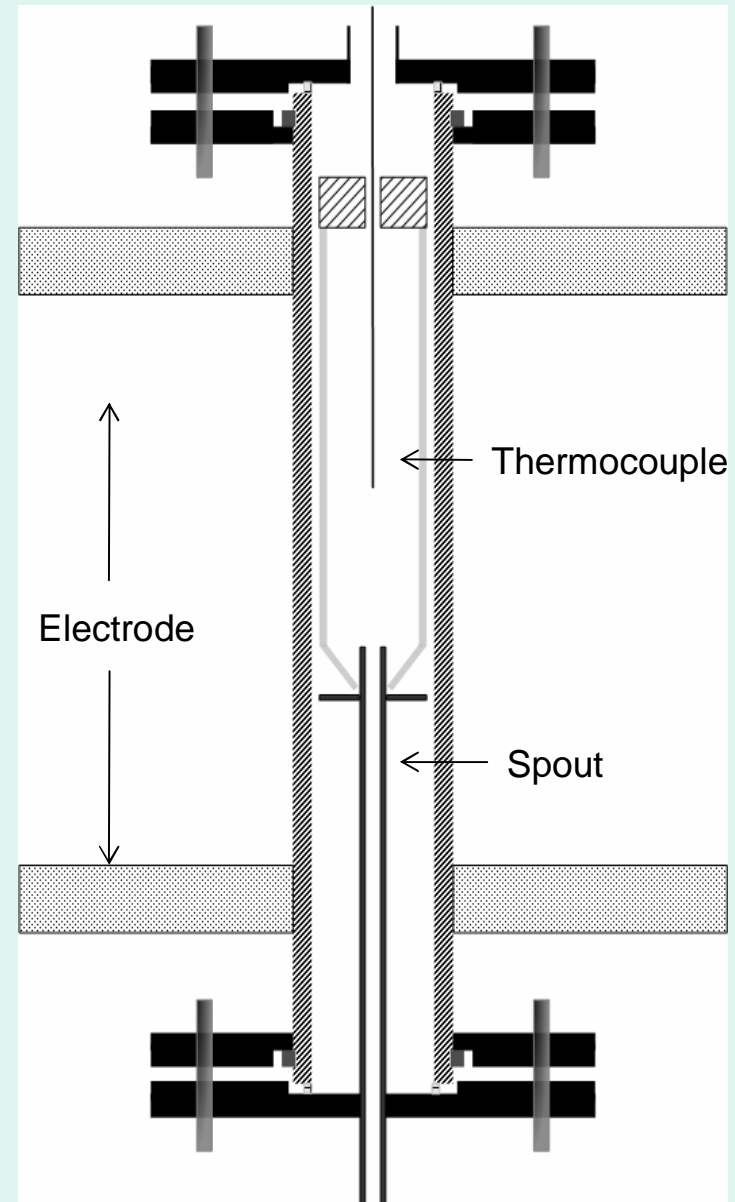
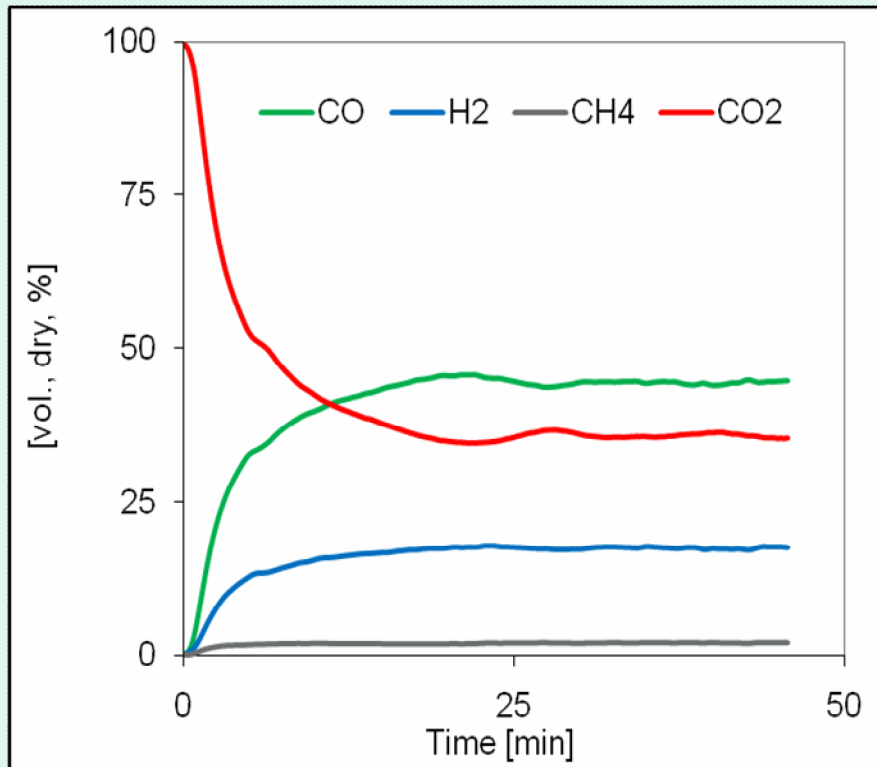
Pyrolysis at 500°C
30s holding time

◆ Bio-oil ▲ Char

Rice husks

Pressurized Fluid Bed Reactor

- ❑ Up to 1000°C and 20 bar
- ❑ Resistance-heated reactor shell
- ❑ Solid feed rate of up to 6 g/min
- ❑ Constant fuel gas composition for up to 30 min

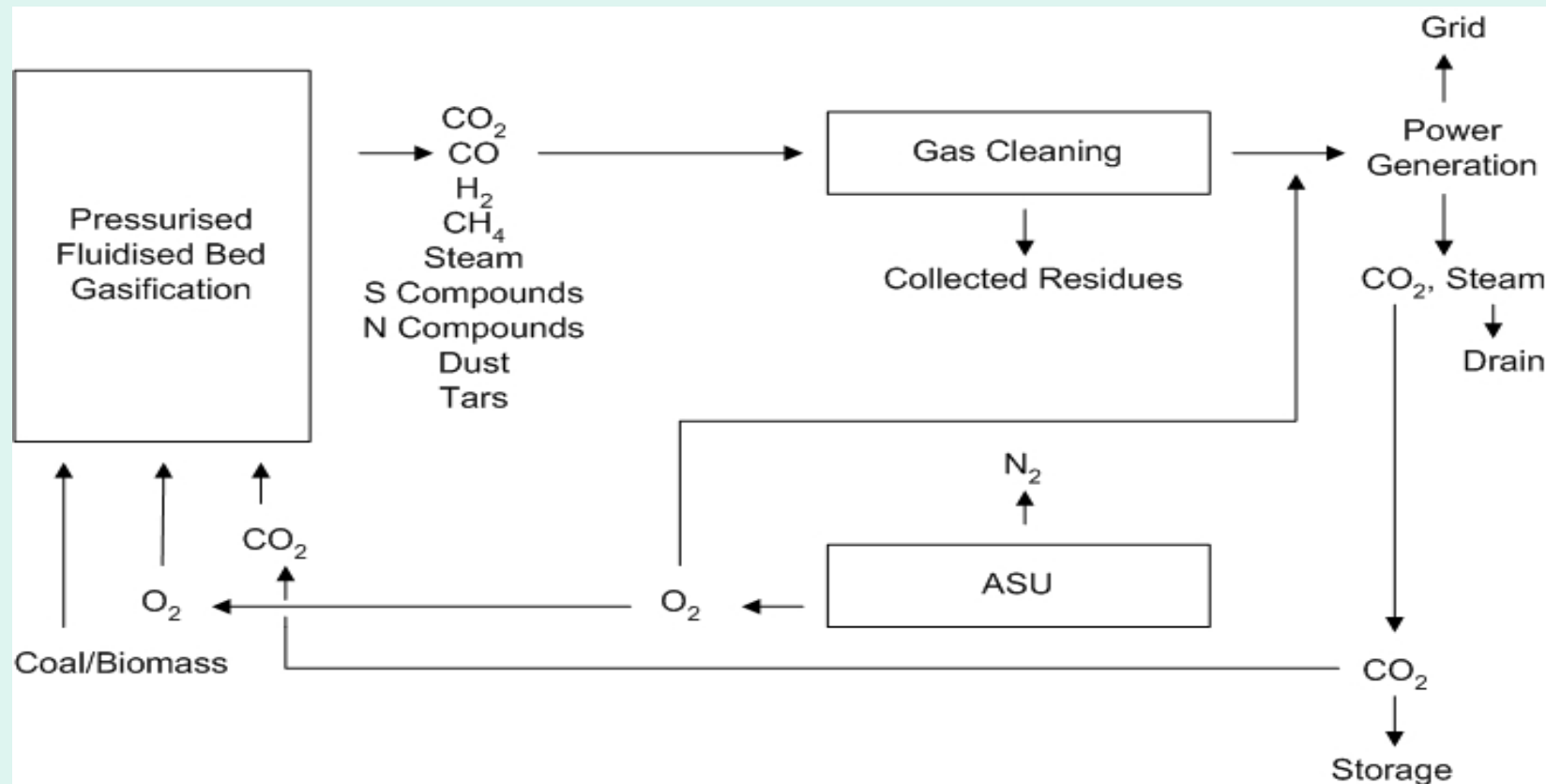


Pressurised Oxy-Fuel Gasification

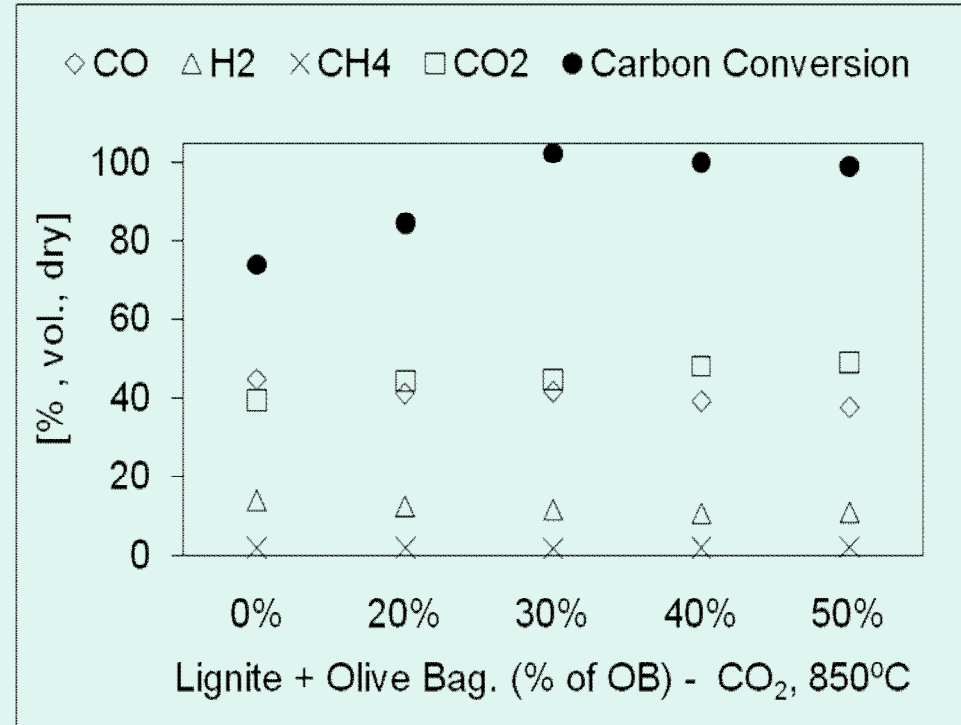
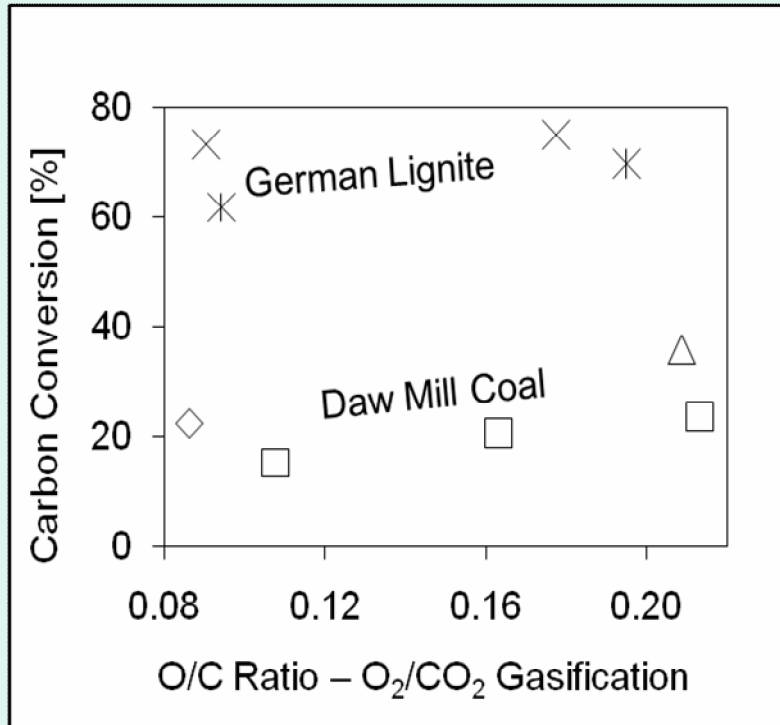
Part of EU Flexgas Project:
Near Zero Emission Advanced
Fluidized Bed Gasification

- * Novel concept for power generation: FBR + IGCC + CCS
- * Adapting the oxy-fuel concept from pf – combustion to fluidised bed gasification

- * Operating a fluidised bed gasifier on **O₂/CO₂** instead of O₂/steam or air/Steam

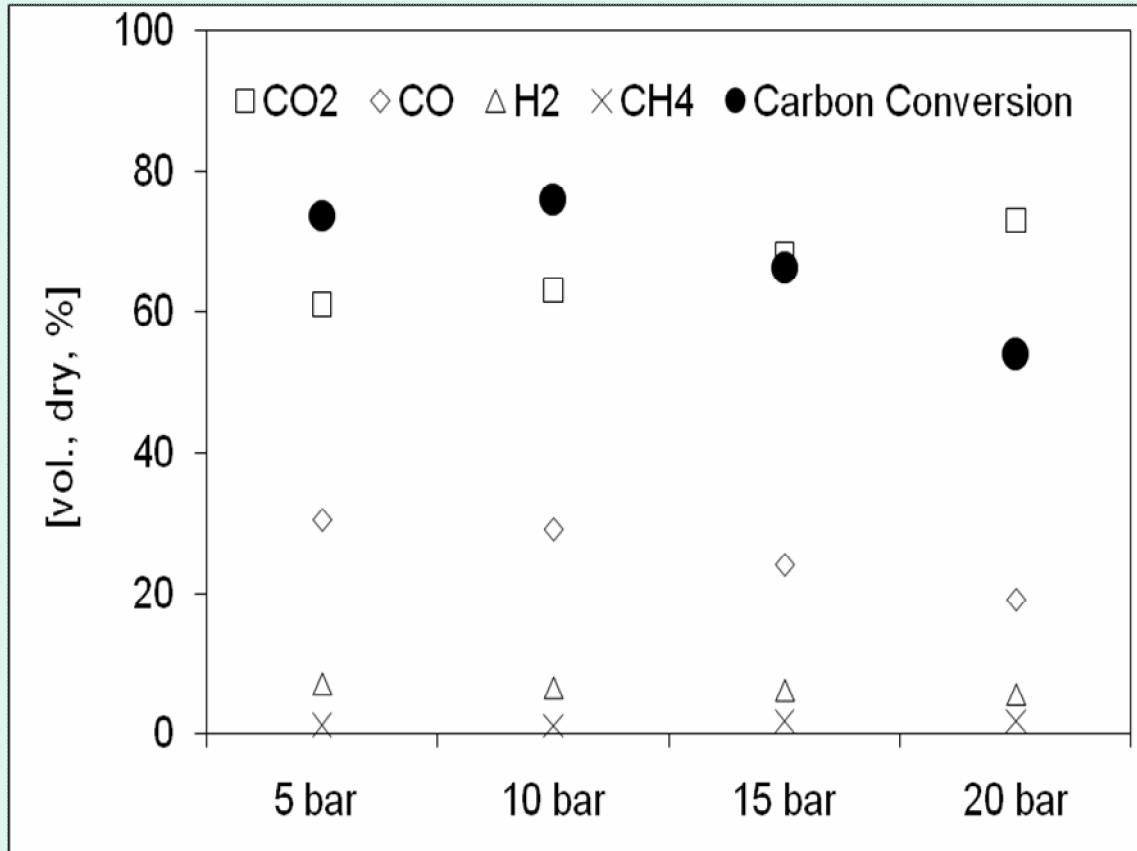


Performance of Different Fuels and Fuel Mixtures



- ❑ 40 - 50 % higher carbon conversion with Lignite compared to bituminous coal
- ❑ Complete carbon conversion with 30% OB/Lignite and similar fuel gas composition
- ❑ Fuel reactivity: Daw Mill < Lignite < Olive Bagasse [3.7% moisture, 5.2% ash, 67.2% VM, 23.9% Fixed Carbon]

PFBR Results on Lignite



Fuel: German Lignite

(Moisture:3.2%, Ash: 4.1%, Volatile: 44.0%, Fixed Carbon: 38.7%)

Temperature: 850°C

Gasification Agent: 3.7% O₂/CO₂

(O/C ratio = 0.2)

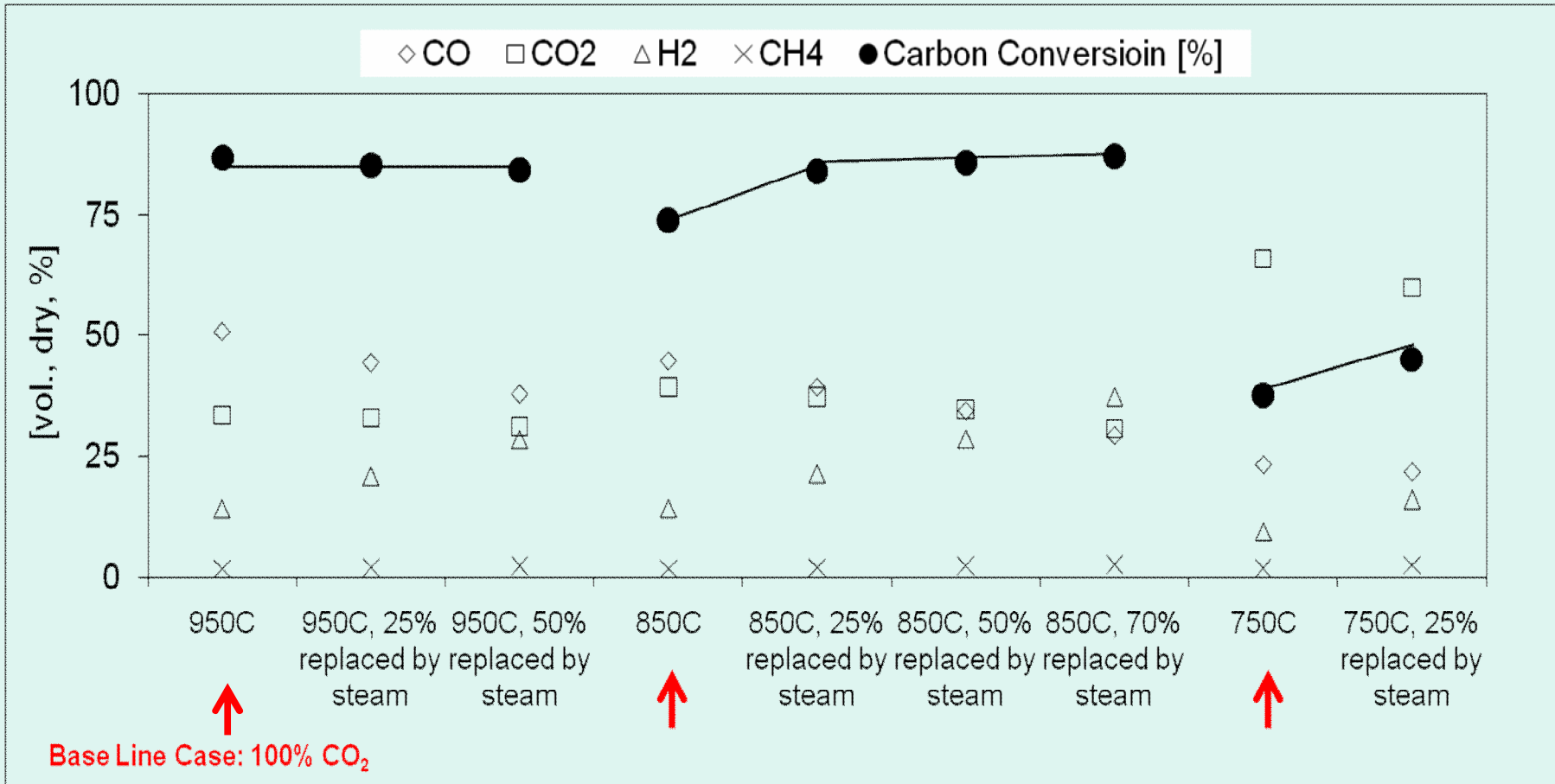
Fuel Feeding Rate: 1.5 – 6 g/min

(constant Gas/Fuel Ratio)

Gas Velocity: 0.08 m/s

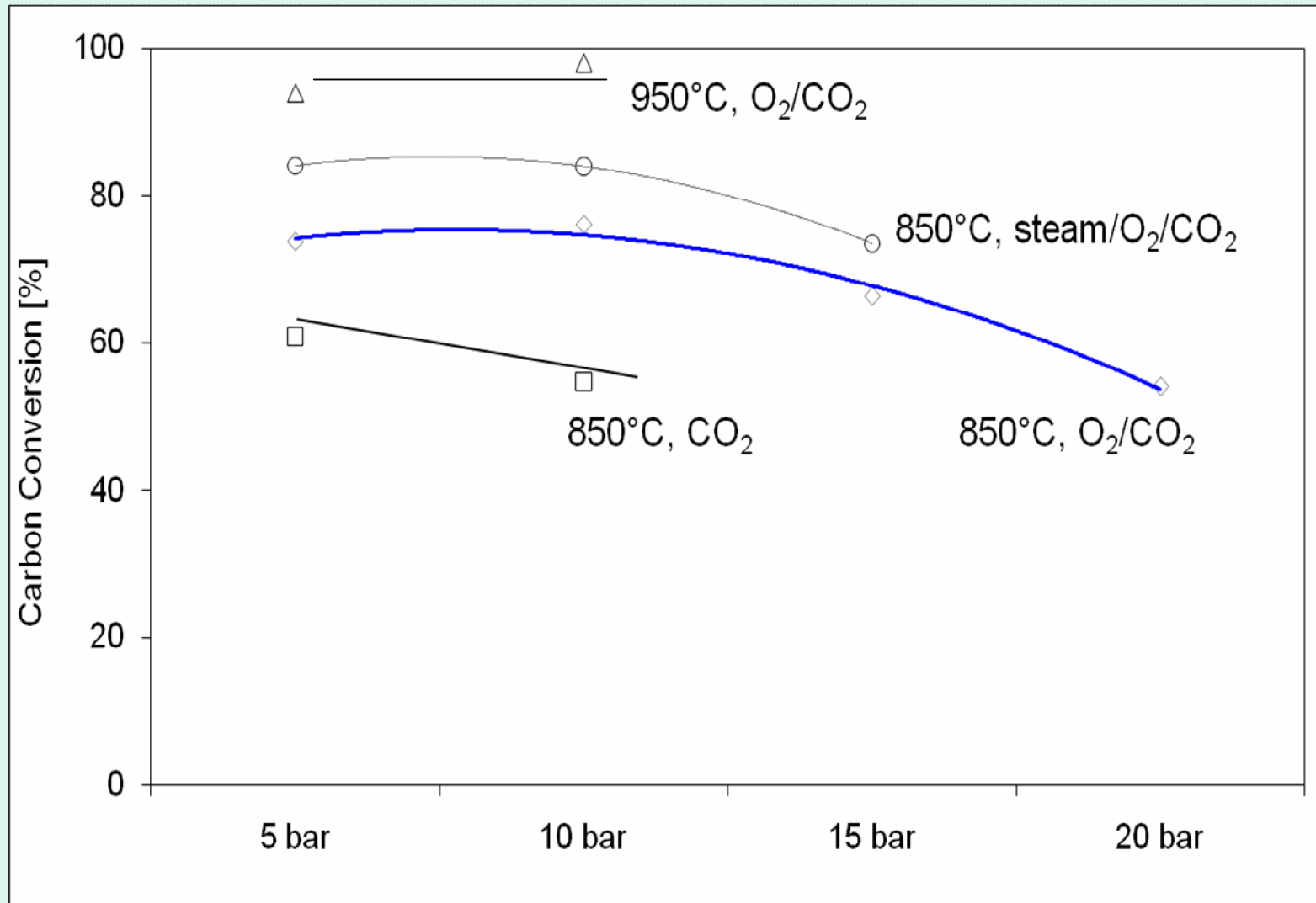
- ❑ Pressure increased from 5 – 20 bar while keeping gasification conditions constant
- ❑ Simulating increased throughput with increasing pressure
- ❑ **Result: Decrease in Carbon and Energy Conversion and Fuel Gas Heating Value**

Effect of steam addition: Lignite

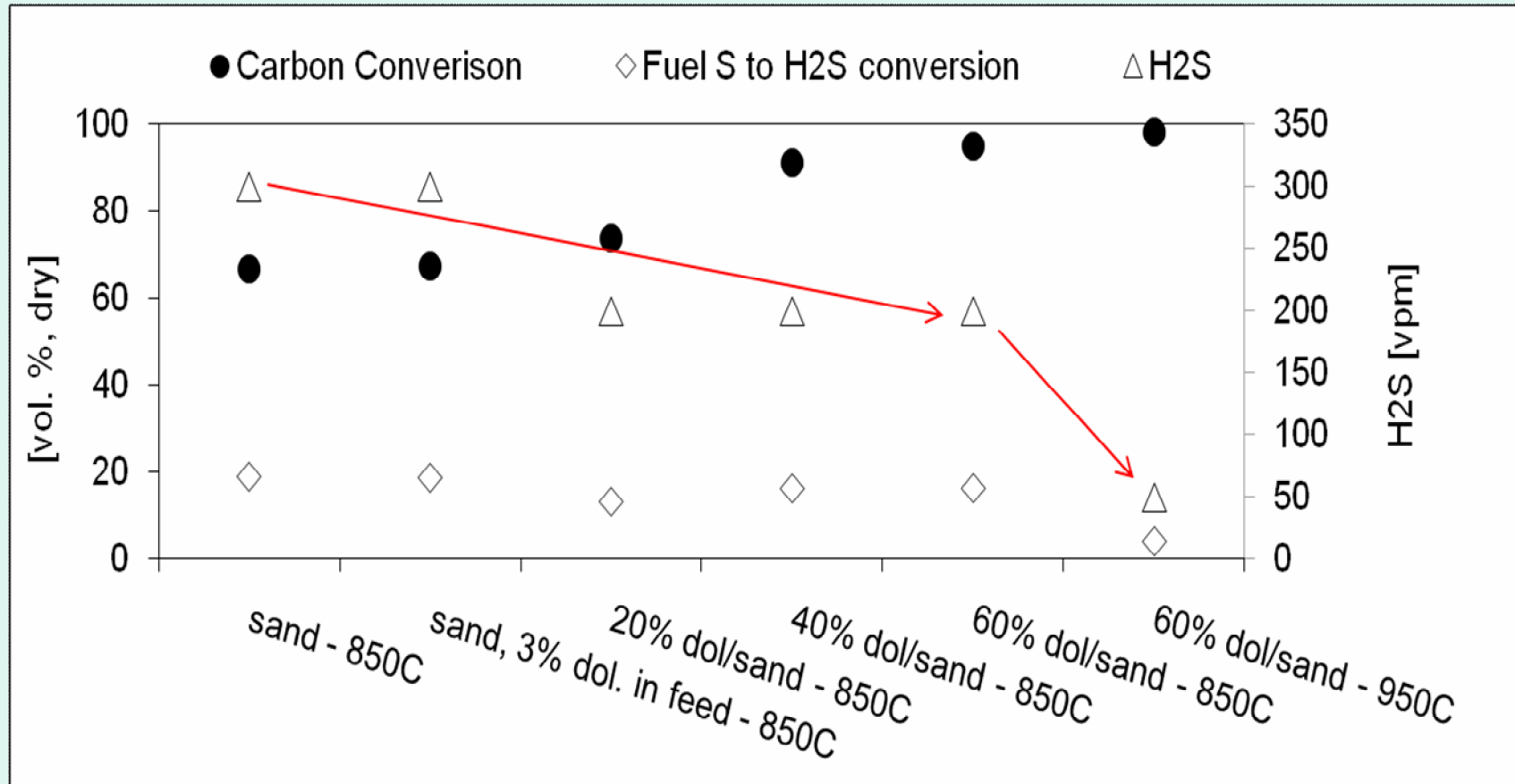


- Maximum carbon conversion 85% (large amount of fines entrained in the fuel gas stream)
- 950°C: CO₂-char reaction fast enough to achieve similar results as steam-char reaction
- 850°C: maximum conversion can be achieved with 25% steam

Increasing Gasification Performance for Lignite by steam, O₂ addition



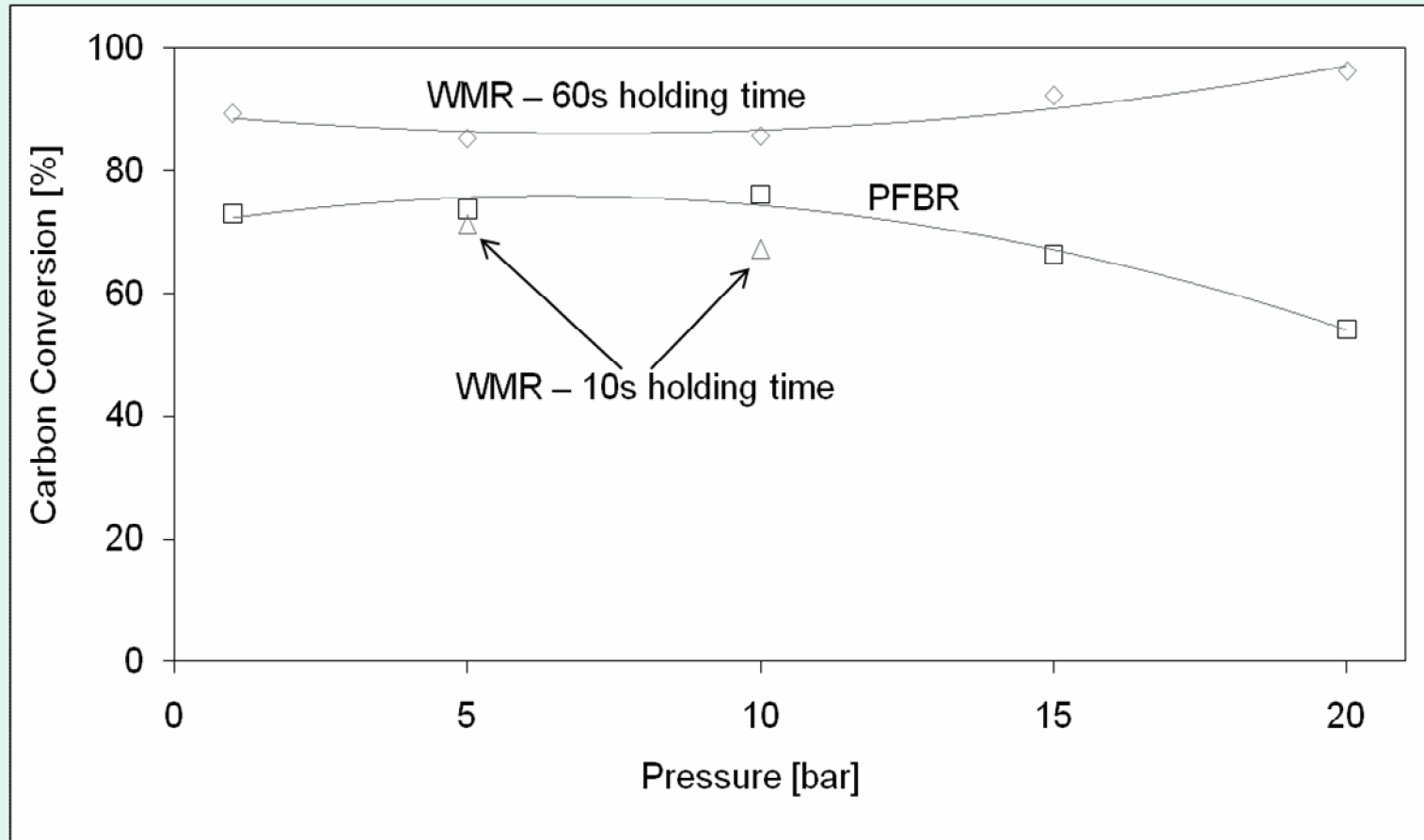
Sulphur Retention with Dolomite



- ❑ H₂S content of the fuel gas can be reduced to 200 ppm (850°C) and 50 ppm (950°C)
- ❑ Catalytic activity of limestone: Carbon Conversion increases to 100%

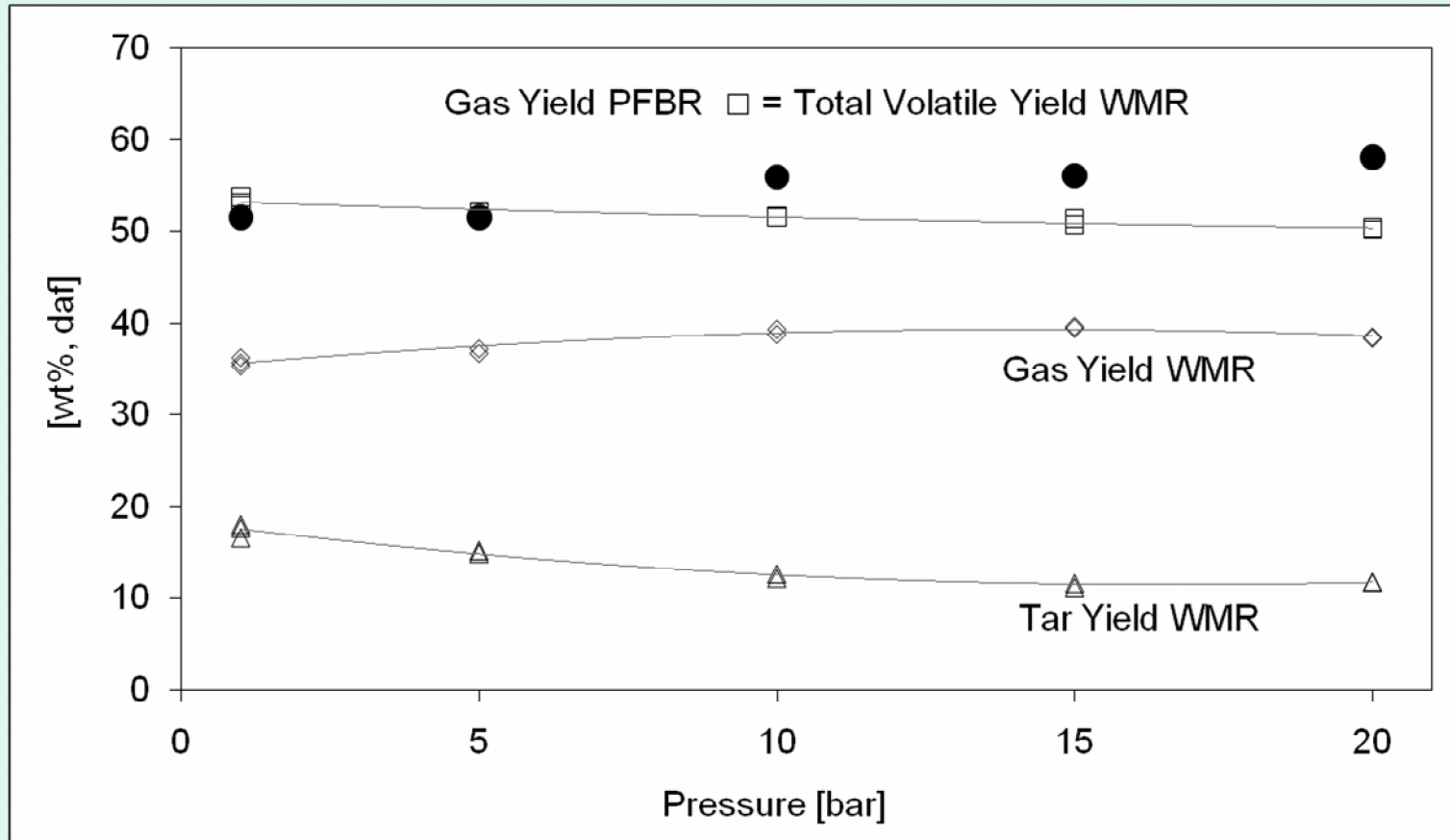
Conclusion: Higher temperature for effective sulphur capture necessary under oxy-fuel conditions [Lignite S content – 0.23%]

Comparison: Gasification 850°C (WMR CO₂, PFBR O₂/CO₂)



- ❑ WMR: Carbon Conversion Increased with Pressure
- ❑ PFBR: Carbon Conversion Decreases with Pressure
- ❑ WMR - 10s holding time similar to PFBR

Comparison: Pyrolysis – 850°C (WMR He, PFBR N₂)



- Gas Yield PFBR is similar to total volatile yield WMR
- Tar is effectively destroyed in the bed of the PFBR

Conclusions

- The laboratory operates a suite of bench-scale reactors suitable for fundamental studies of the gasification [and combustion] of biomass [and coal, petroleum residues and waste fuels] over a wide range of operating conditions of temperature, pressure, gasification medium, fuel blend. Calcium looping studies also.
- Wire-mesh and “hot rod” fixed bed reactors. Pressures up to 100 bar, temperature to 2000C [for WMR]. Highly controlled reaction conditions – design data, modelling input, etc.
- Pressurised fluidised bed reactor that can be operated in spouted or fluidised bed mode and can run either as a batch reactor or continuously fed. Air/steam or CO₂/steam/oxygen gasification.
- Measure tar yield and quality – whole range of advanced analytical techniques for tar characterisation work.
- Capability for studying the partitioning of N,S, Cl etc. and trace elements between char/ash and liquid/gaseous products in combustion and gasification, e.g. potential Hg to the environment. Use of ICP-MS and dedicated Hg analyser.

Hot-Rod reactor

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“Tar Formation and Destruction in a Fixed Bed Reactor Simulating Downdraft Gasification: Optimization of Conditions”, *Energy & Fuels* 2008, 22 (3), 1955-1964.

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Wire-mesh reactor

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Wire-mesh reactor

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Fluidised bed reactor

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Cousins, A., Zhuo, Y., George, A., Paterson, N., Dugwell, D. and Kandiyoti, R., “Development of a Bench-Scale High-Pressure Fluidised Bed Reactor and Its Sequential Modification for Studying Diverse Aspects of Pyrolysis and Gasification of Coal and Biomass”.
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Spiegel, N., Sivena, A., Lorente, E., Paterson, N. and Millan, M., “Investigation of the oxy-fuel gasification of coal in a laboratory-scale spouted-bed reactor: Reactor modifications and initial results”,
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