Energy and Resources
Research Institute

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Combustion of Coal with Waste

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Seminar on ‘Co-firing and Fuel Characterisation’

At the Joint Meeting of the Coal Research Forum, Environment Division and the Royal Society of Chemistry, Energy Section

Tuesday,15th September, 2009

University of Nottingham

Co-Investigators

- Prof. Bernard Gibbs
- Prof. Paul Williams

Research students

- Tyre/Plastic co-firing - Dr. Surjit Singh
- Biomass co-firing - Mr. Shahid Munir
- Oxygen enrichment co-firing- Mr. Sheraz Daood

- **Introduction**
- Experimental facilities
- Results
- Conclusions

Pilot Scale Co-firing Studies at Leeds

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1. Waste tyres and coal – Co-combustion and "NOx reburning" (also waste plastics)

2. Biomass waste and coal - Co-combustion and "NOx Reburning" using shea meal and cotton stalk agricultural waste

3. O_2 enriched co-firing biomass waste/coal – Effect on NOx and C burnout

- Introduction
- **Experimental Facilities**
- Results
- Conclusions

NOx emission limits

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- **EC Large Combustion Plant Directive**

NOx Reduction - >500 MWEt plant – 500 mg/Nm3 (2008)

- 200 mg/Nm3 (2016)

- **Technologies – Low NOx burners**
  - **over-fire air**
  - **SNCR or SCR**
  - **Reburning (gas, coal, tyre/plastic waste)?**
  - **Co-firing waste biomass/tyre/plastic ?**

20 kW Down fired combustor

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- Overall height 3.5m
- 43 Utility ports
- Flexible to change the zone length, residence time and gas/Solid sampling
- Three different

Feeders

- A series of filters and dryers prior to online gas Analysers
- Analyzers and Thermocouples are linked with PC via a data logger

Combustion test facility (100kW+)

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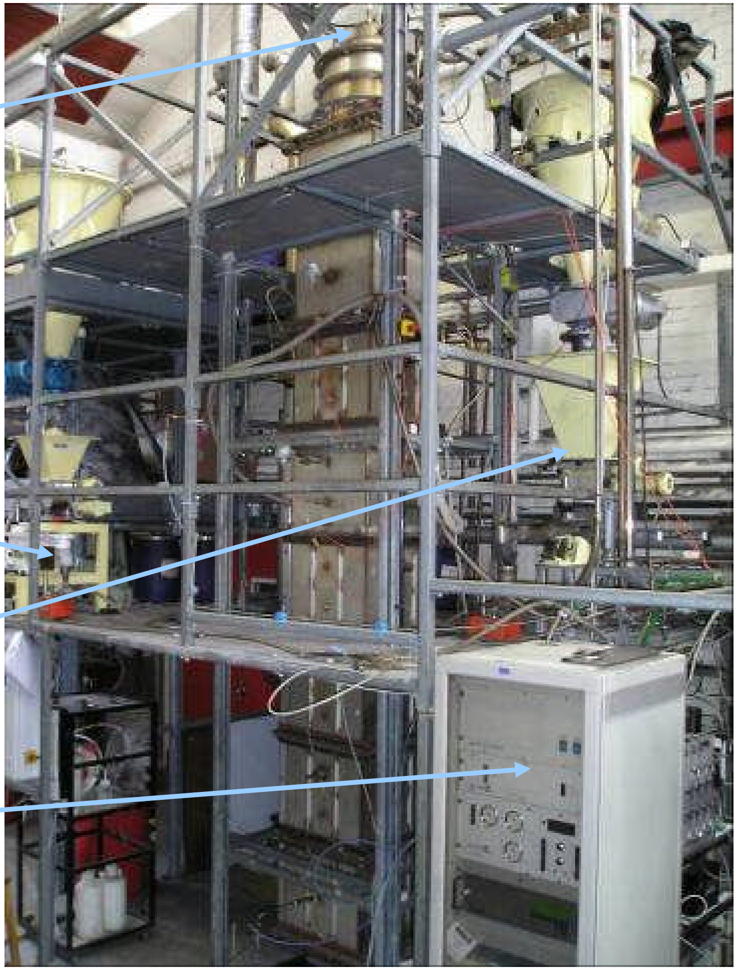

Refurbished Leeds CTF

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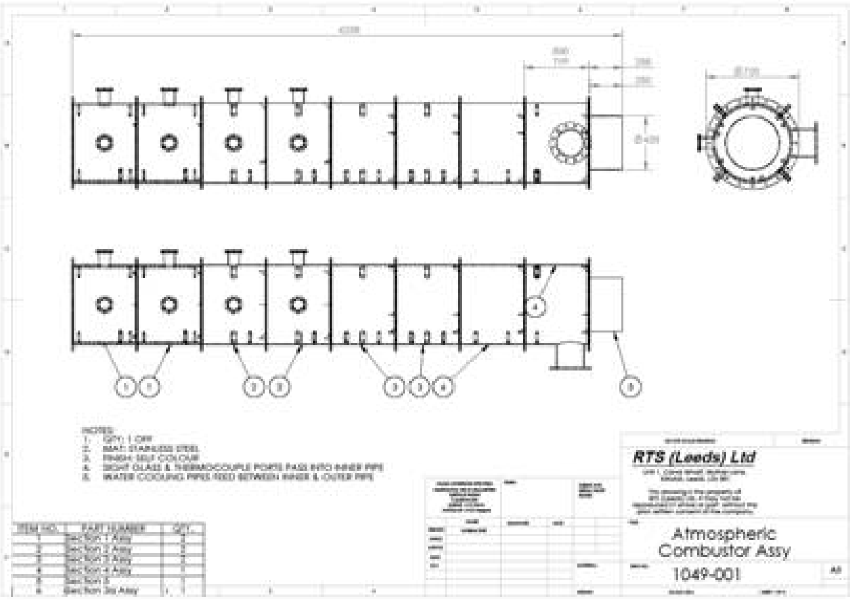

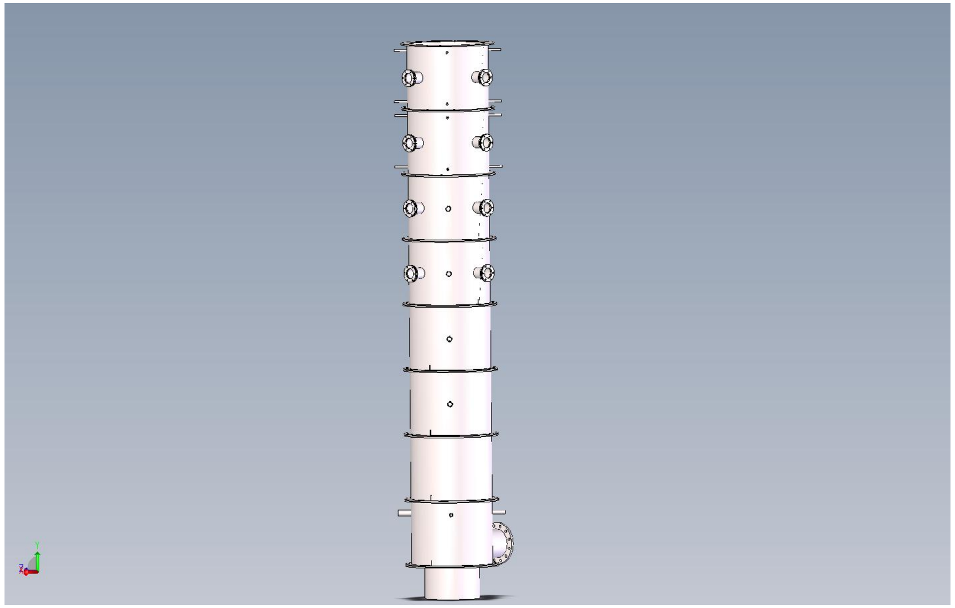

Co-firing fuel feeder configurations

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Co-firing –
coal with tyre

Biomass feeder

Co-firing –
coal with plastic

CTF – Schematic

NOx reduction

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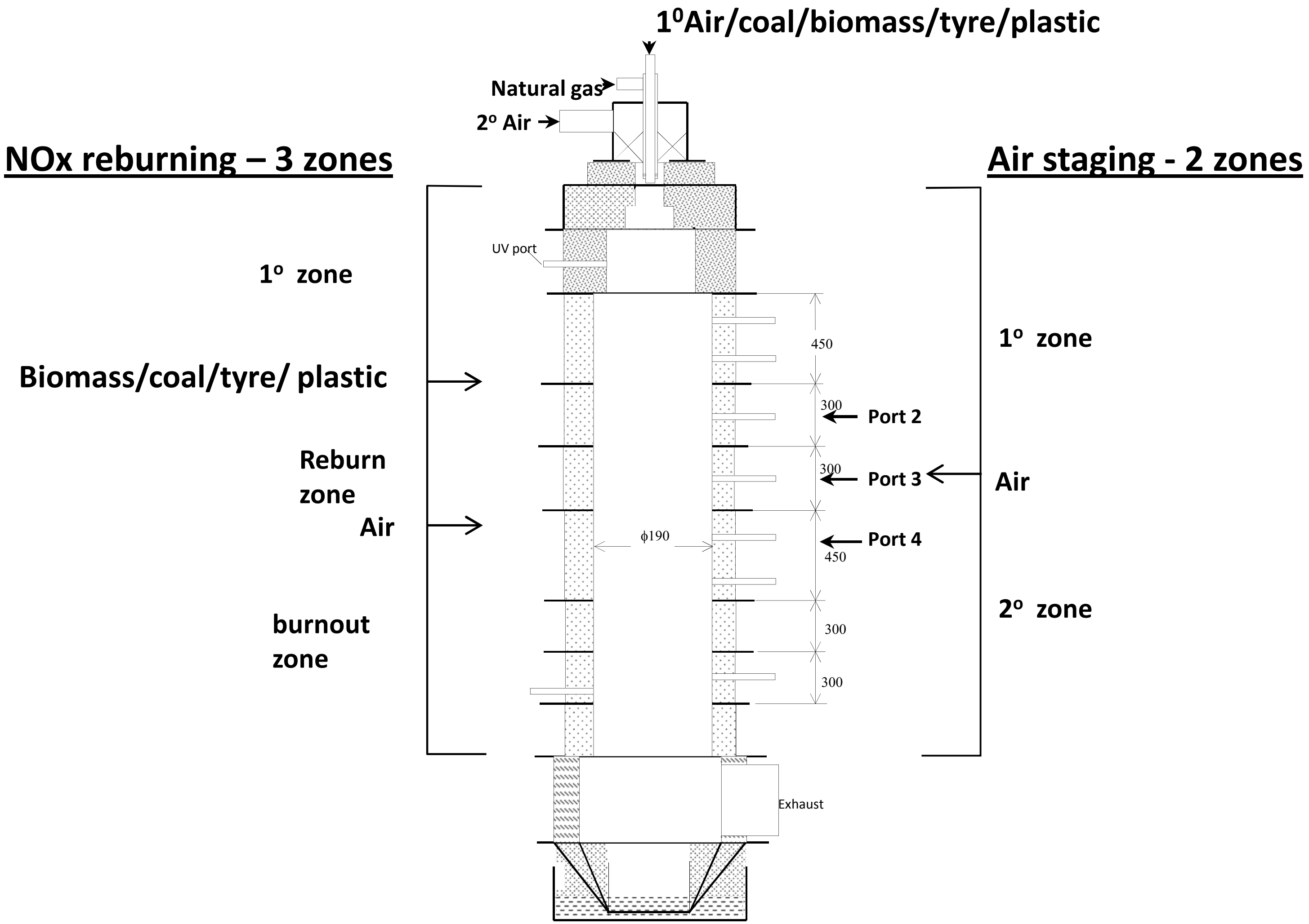

- Introduction
- Experimental
- **Results – waste tyre rubber/PC co-firing/reburning**
- Conclusions

Problem - Scrap Tyres

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Worldwide - 1000 million tyres (12 mt) / year

Management of Used Tyres in Western Europe and the USA

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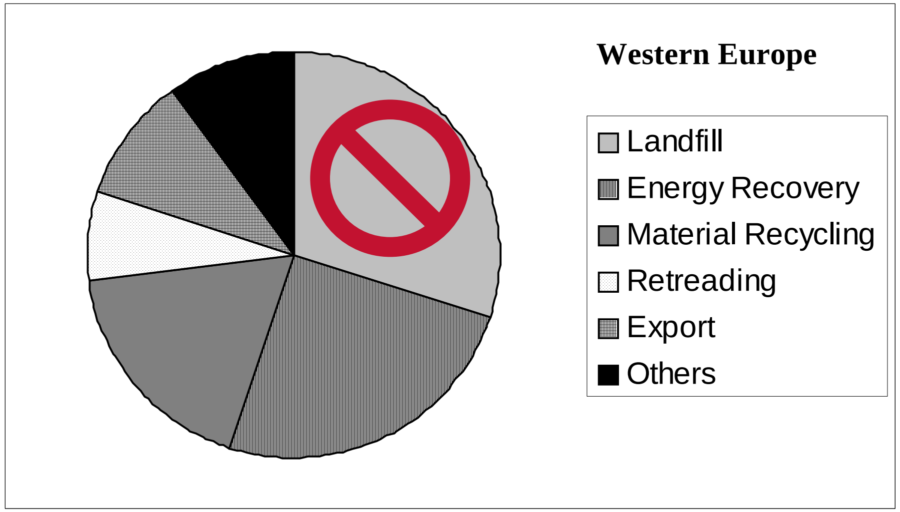
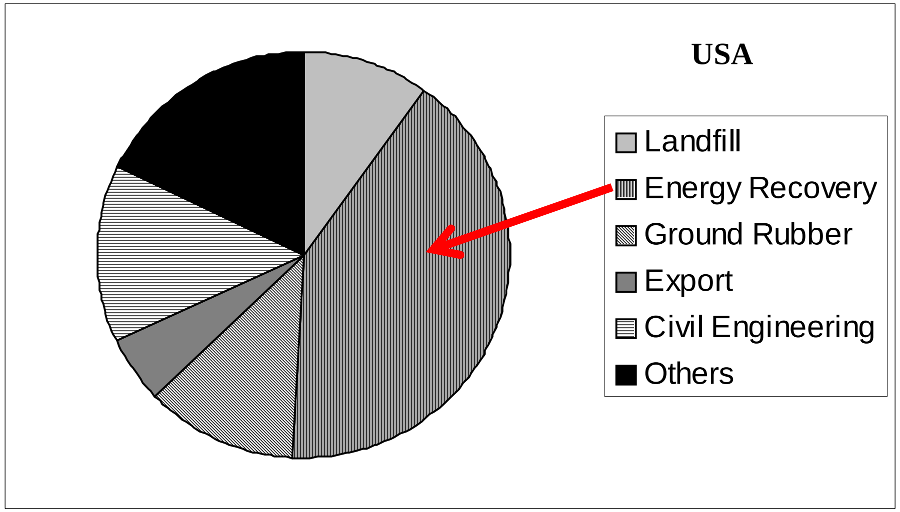
From July 2006 in Europe – landfill – NOT an option

– EU Landfill Directive





Western Europe (2004)

250 million tyres/yr

USA

280 million tyres/yr

Possible solution

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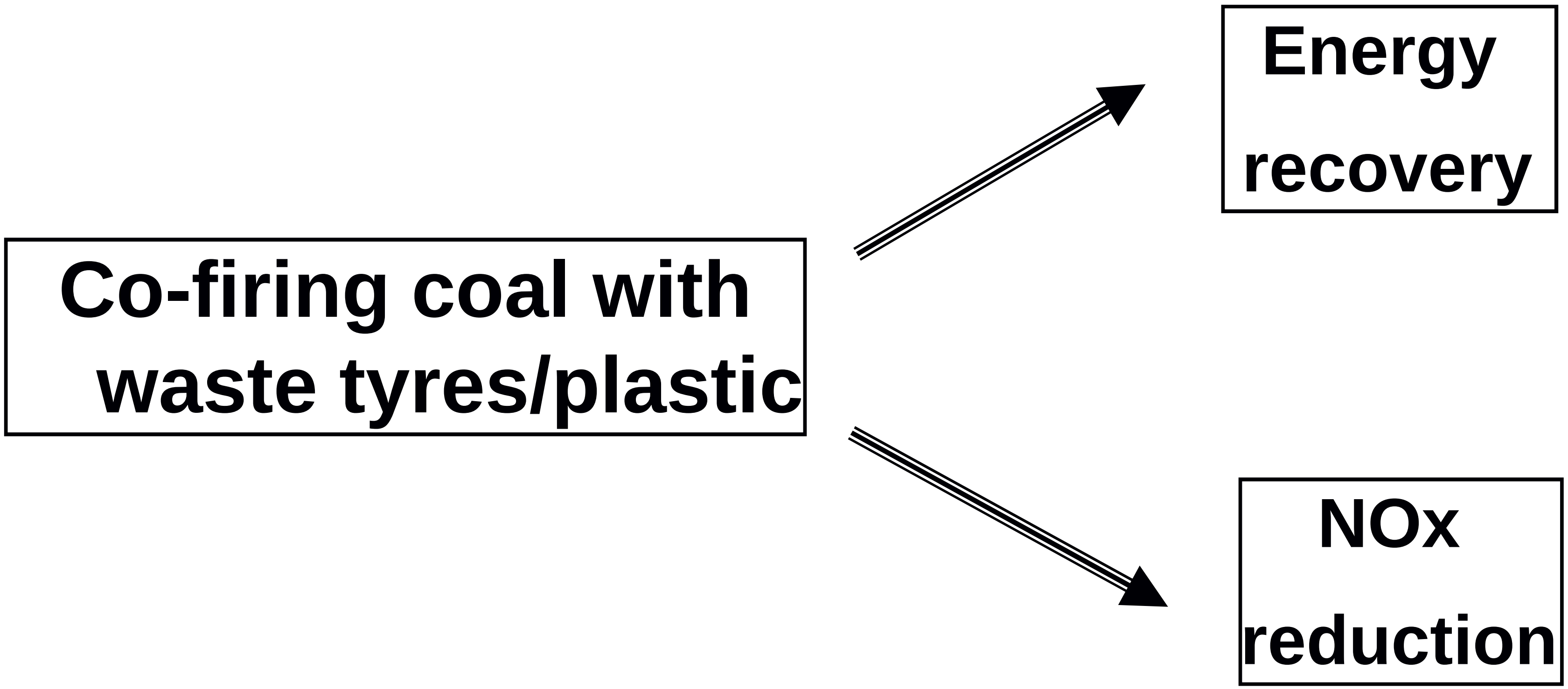

Scope of Study on Tyre Rubber Co-combustion

- **<u>Tyre Fuel characterisation</u> – TGA analysis, pyrolysis behaviour**
- **<u>Individual combustion tests</u> – tyre or coal alone as primary fuel**

  - effect of particle size on tyre combustion efficiency
- **<u>Co-firing</u> - Coal and tyre Fractions up to about 25%**
- **<u>NOx reburning</u> – NOx reduction by fuel-staging**
- **<u>Burnout analysis</u>**
- **<u>Ash composition</u>**

Pulverised tyre/plastic

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Pulverised waste tyres (<300μm)

plastics (<150μm)

Fuel characterisation
- size analysis

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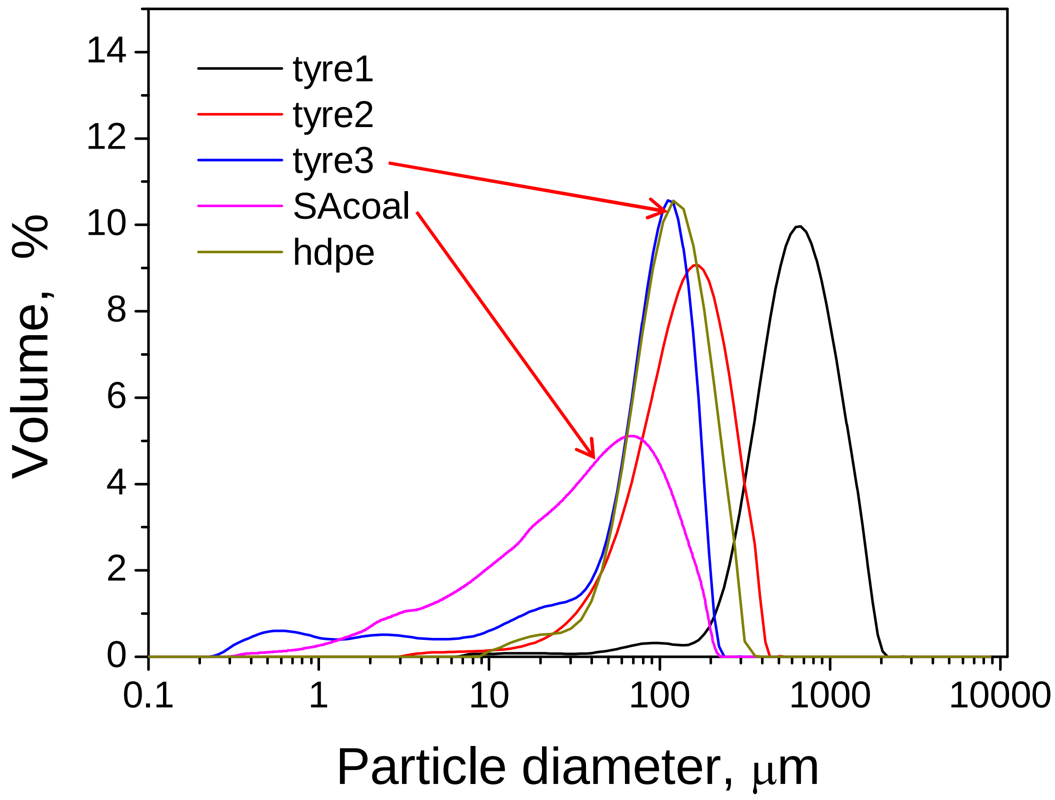
Fuel particle size distributions

Tyre 1	d(0.9) = 1200 μm
Tyre 2	d(0.9) = 290 μm
Tyre 3	d(0.9 = 180 μm
SA coal	d(0.9) = 130 μm
HDPE	d(0.9) = 200 μm



TGA volatiles release rates comparison

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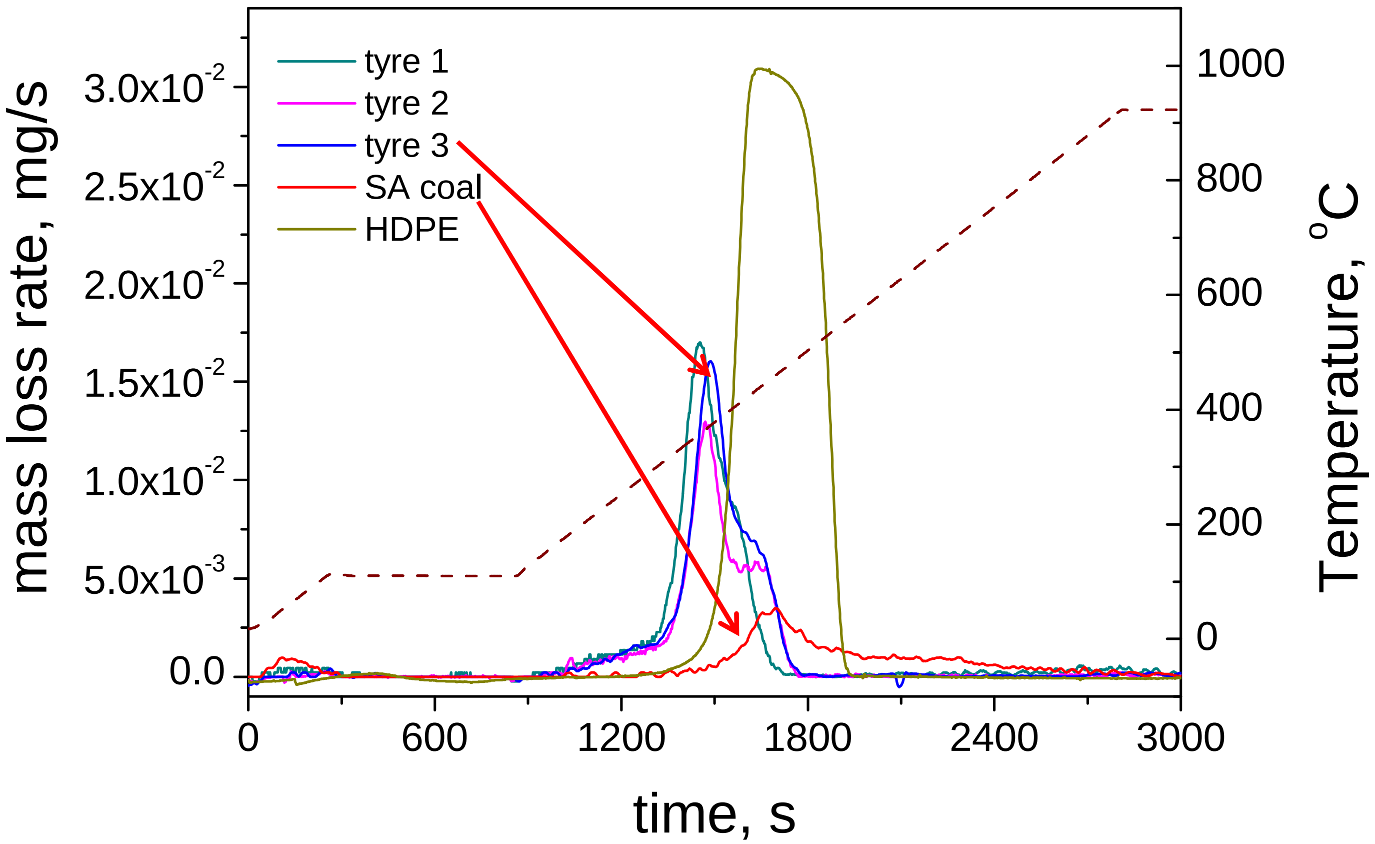

Significantly lower rates for coal

Co-firing tyre or HDPE with coal – Effect on NO emission

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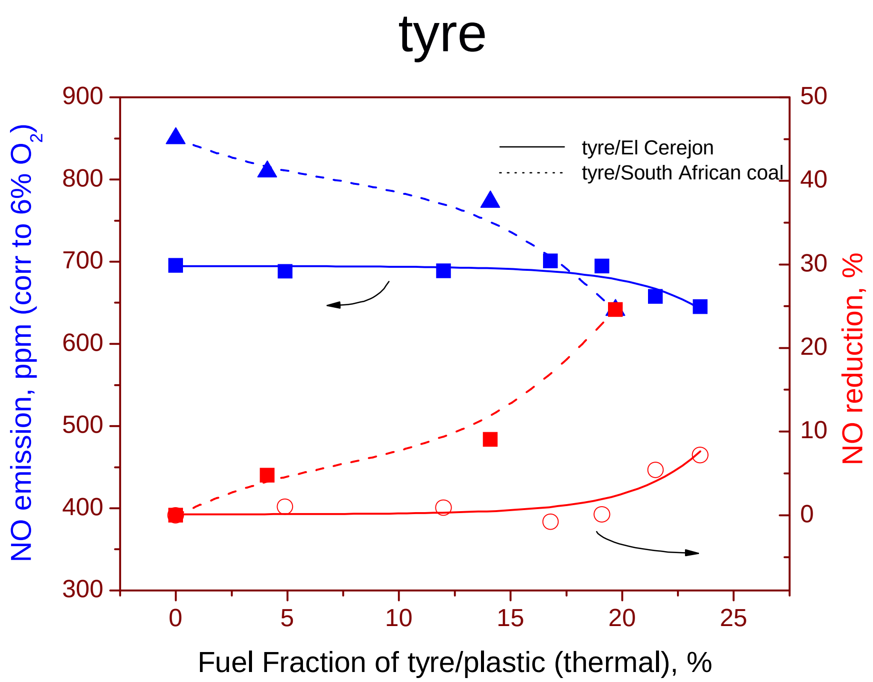

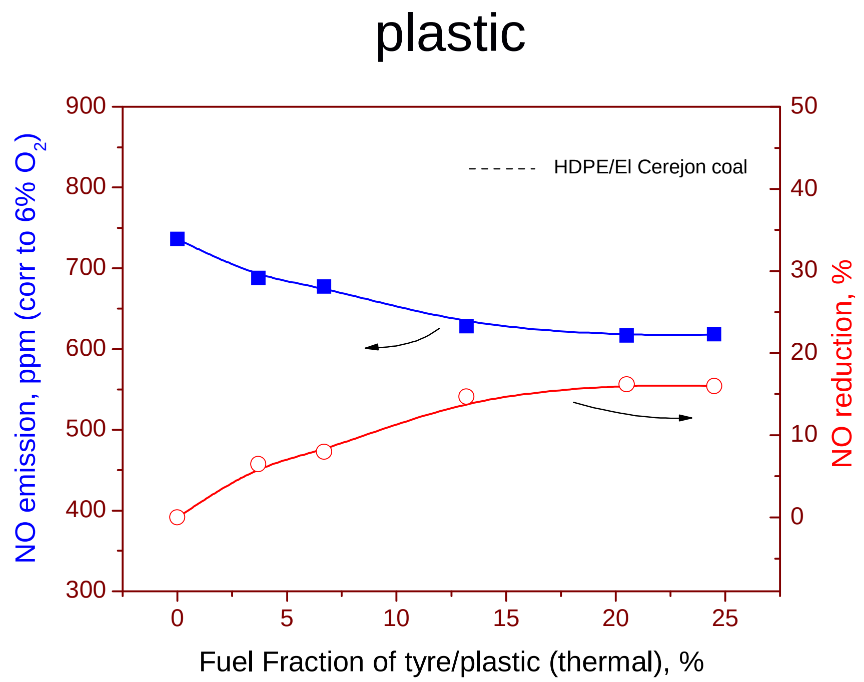

- **Effect on NO reductions with co-firing more pronounced with less reactive coal**

Co-firing tyre with S African and S American coals

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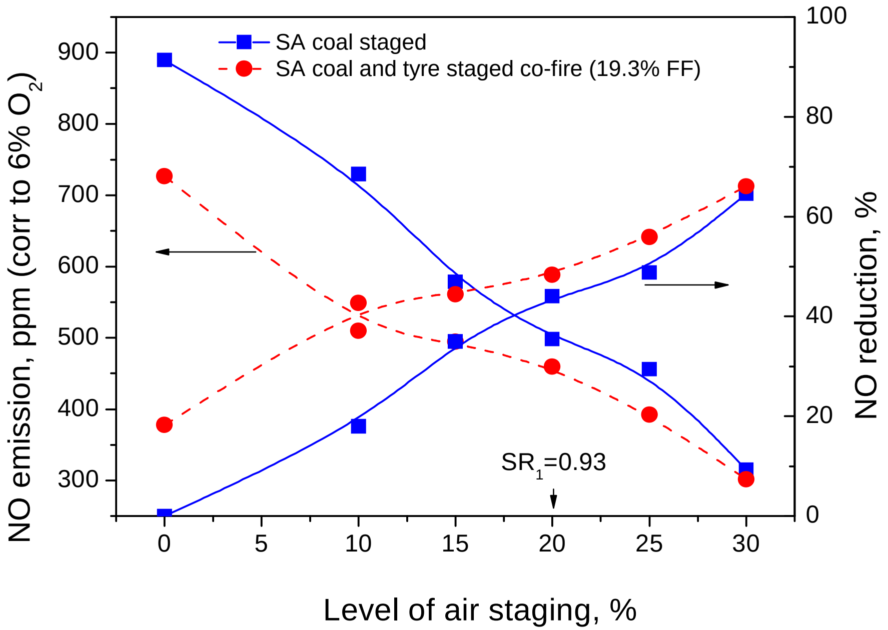

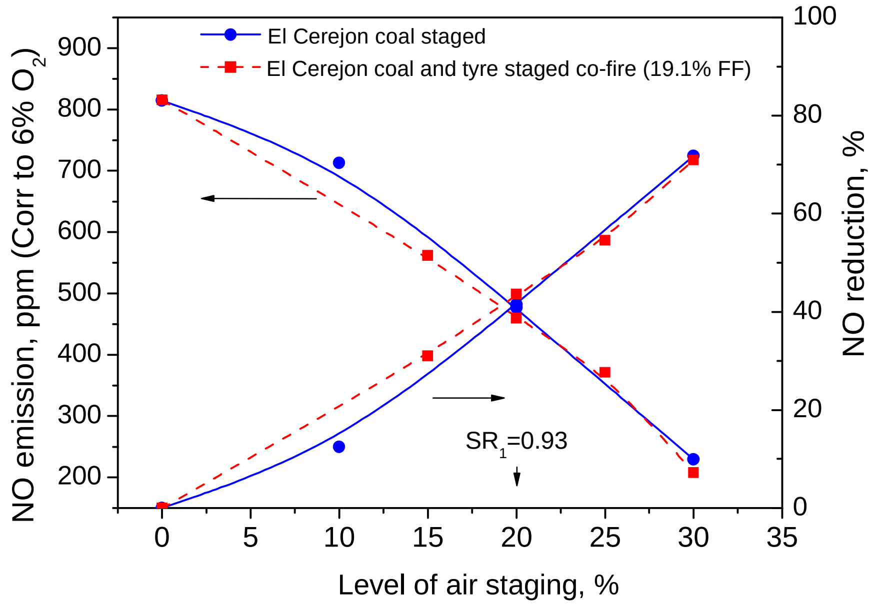

- **Effect of tyre on NO reduction diminishes with increasing levels of air staging**
- **Coal firing (solid lines) and co-firing (dashed lines).**

- **Co-firing tyre with El Cerrejón coal shows only slight differences in NO emission with increased levels of air staging.**

Combustion behaviour of co-fired tyre with S African coal

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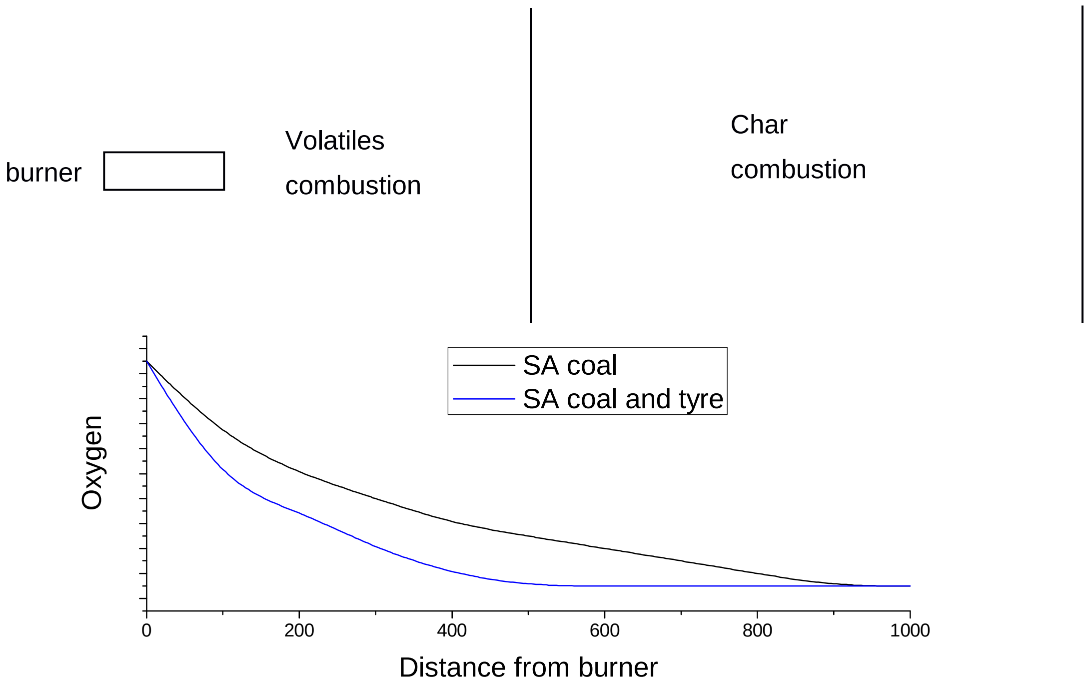
Schematic



- For less reactive coals, the tyre particles ignite earlier in the flame
- Some O_2 is consumed before volatile coal-N release, therefore lower conversion to NOx

Burnout – NOx reburning–
Effect of tyre particle size

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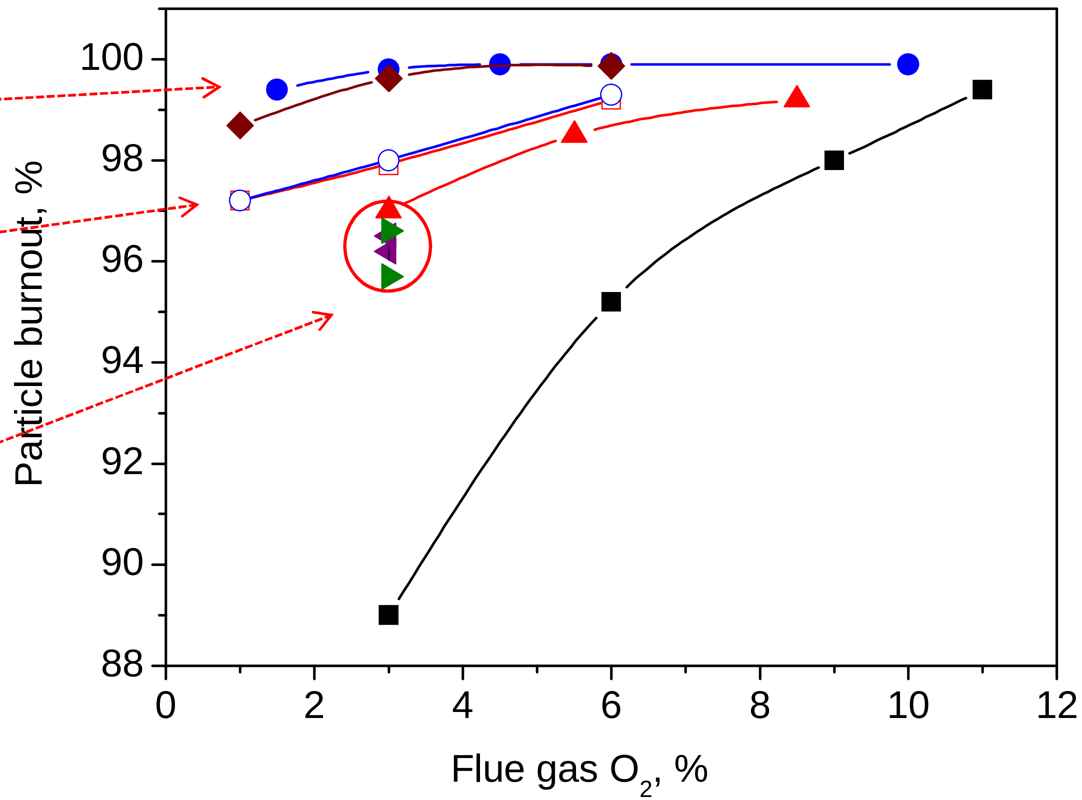
Primary combustion

Tyre 1 ■ (< 1.5 mm, d(0.9 = 1200 μm)

Tyre 2 ▲ (< 500 μm, d(0.9 = 290 μm)

Tyre 3 ● (< 300 μm, d(0.9 = 180 μm)

SA coal ◆ (d(0.9) = 130 μm)



Co-firing

Tyre Co-firing with South African coal (14.1 % FF) ○

Tyre Co-firing with South African coal (19.7 % FF) □

Reburning

tyre on coal reburn ◀ (*Rff*=5.1% and 19.1%)

coal on coal reburn ▶ (*Rff*=3.5% and 18%)

$$\text{Burnout} = (1-(ASH_{tyre}/ASH_{char}))/(1-ASH_{tyre})$$

Other effects of tyre co-firing

Potential advantages of tyre co-combustion

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Potential for small reduction of CO_2 emission

<u>Calorific value</u> in the region of 15-20% greater than coal – even though tyre can emit ~11% more CO_2/100kg fuel.

FF thermal	kW input coal	CO_2 kW input tyre	CO_2 from coal kmol/hr	CO_2 from tyre kmol/hr	CO_2 total kmol/hr	CO_2 reduction %	H/C Blend	O/C Blend
0	75.00	0.00	0.58	0.00	0.58	0	0.056	0.0867
2	73.50	1.50	0.57	0.01	0.57	0.4	0.057	0.0865
6	70.50	4.50	0.54	0.03	0.57	1.2	0.058	0.0861
8	69.00	6.00	0.53	0.04	0.57	1.6	0.059	0.0858
10	67.50	7.50	0.52	0.05	0.56	2.0	0.059	0.0856
12	66.00	9.00	0.51	0.06	0.56	2.4	0.060	0.0854
14	63.00	12.00	0.50	0.06	0.56	2.9	0.060	0.0852
16	63.00	12.00	0.48	0.07	0.56	3.3	0.061	0.0850
18	61.50	13.50	0.47	0.08	0.56	3.7	0.061	0.0847
20	60.00	15.00	0.46	0.09	0.55	4.1	0.062	0.0845
25	56.25	18.75	0.43	0.11	0.55	5.1	0.063	0.0839

Comparison with other potential fuels

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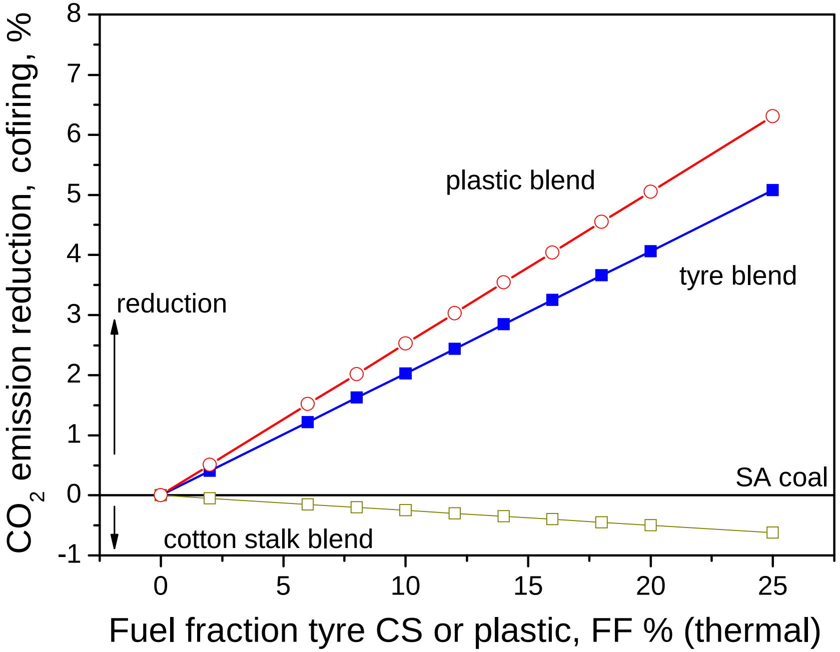
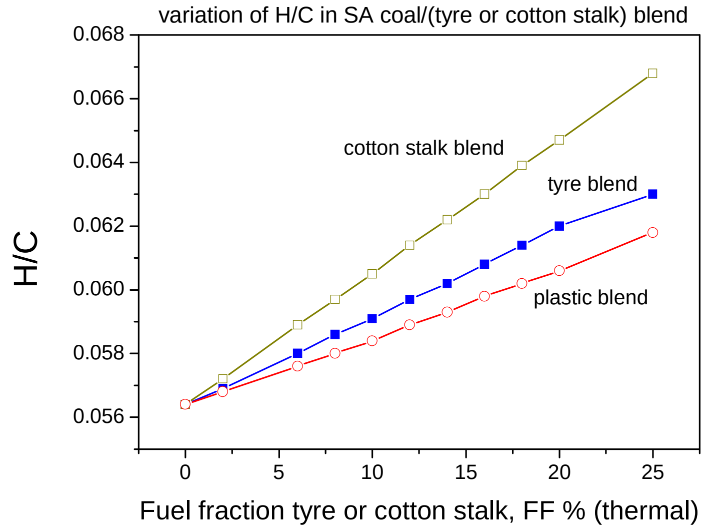
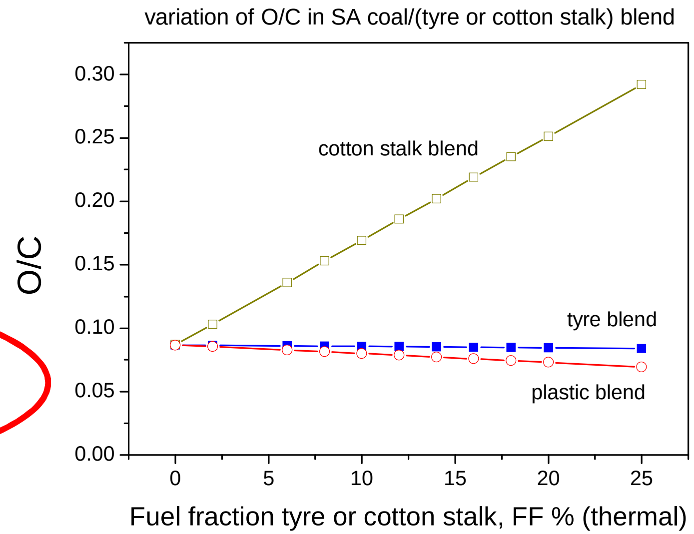
Calculated CO_2 reductions







Calculated Emission factors $kgCO_2$/ kWhr

Plastic(0.25) < Tyre (0.27) < coal (0.34) < biomass*(CS 0.35)

* Biomass EF officially rated 0 , C neutral

Co-firing tyre with S American coal impact on SO_2 Emissions

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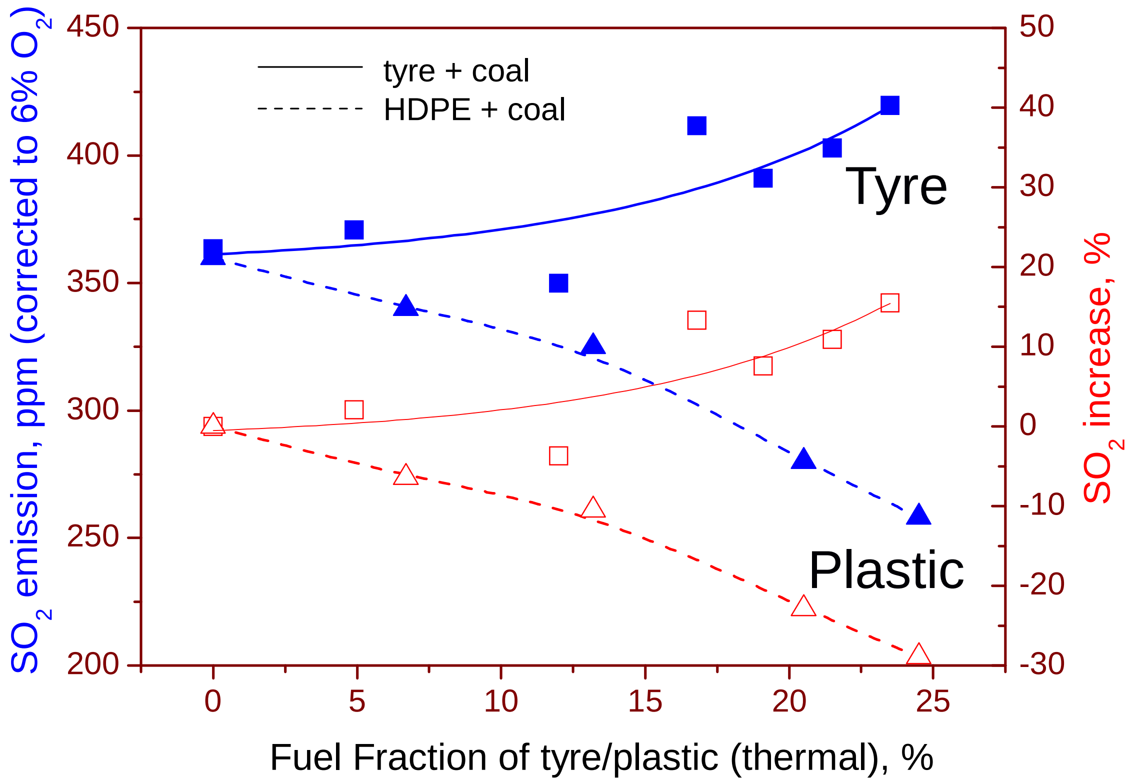

• **Tyre - <u>Increase</u> in SO_2 by 15% by replacement of coal at a fuel fraction of 25% (thermal).**

• **HDPE- <u>Reductions</u> in SO_2 by 30% by replacement of coal at a fuel fraction of 25% (thermal).**

Ash analysis

Tyre / Coal Co-Firing

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- Low levels of Zn in cyclone fly ash from tyre combustion

Sample	(08/0098) Sample A 60 mesh tyre (SRC) Raw	(08/0099) Sample D SA coal (SRC) Raw	(08/0100 Sample P El Cerrejon coal Raw	(08/0101) Sample H Ash 4.1% FF Co-fire	(08/0102) Sample I Ash 14.1% FF Co-fire	(08/0103) Sample J Ash 19.7% FF Co-fire	(08/0104) Sample N SA Coal Straight combusted ash	(08/0105) Sample O 60 mesh tyre (SRC) Straight combusted ash
Ash analysis (%, w/w)								
SiO_2	57.30	47.65	63.22	47.65	46.69	45.74	47.72	57.79
Al_2O_3	17.20	29.04	20.92	28.35	28.88	28.28	30.23	18.51
Fe_2O_3	2.31	4.33	7.70	3.74	4.03	3.95	3.48	3.21
CaO	1.31	7.75	1.93	7.40	7.75	7.90	7.85	2.80
MgO	0.78	1.34	2.26	1.27	1.32	1.31	1.30	1.39
TiO_2	0.82	1.73	0.97	1.62	1.76	1.69	1.90	0.89
Na_2O	0.75	0.11	0.82	0.12	0.16	0.16	0.15	0.79
K_2O	2.22	0.49	2.03	0.61	0.71	0.71	0.52	2.44
P_2O_5	0.56	1.85	0.20	1.40	1.74	1.88	1.71	0.53
SO_3	0.95	4.50	1.95	0.62	0.75	0.64	0.66	0.54
ZnO	19.59	0.07	0.02	0.25	0.59	0.65	0.22	0.64
C	-	-	-	8.63	3.23	3.14	1.31	8.04

Original tyre rubber

Combusted in CTF

What about the natural rubber content of tyres? Renewable??

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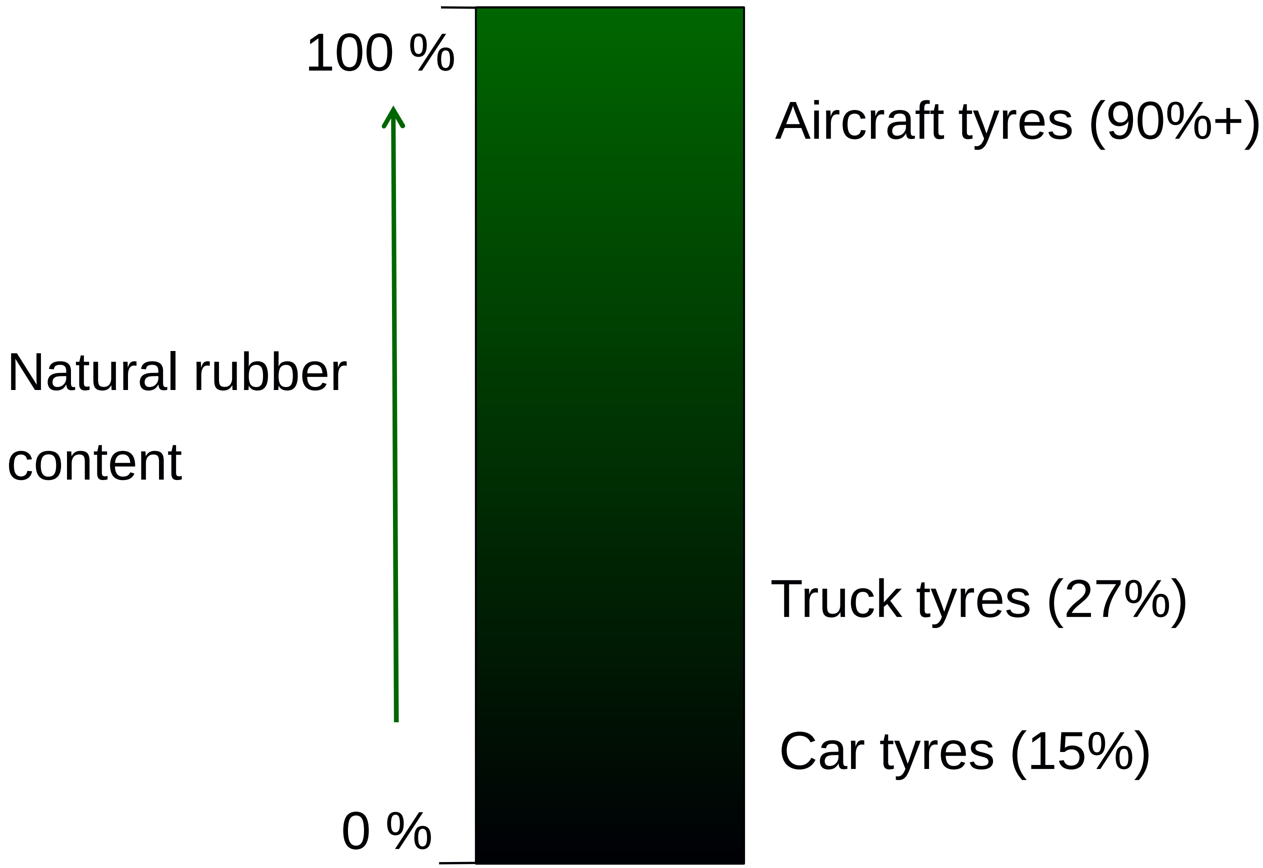

Effect of tyre costs on co-firing fuel cost

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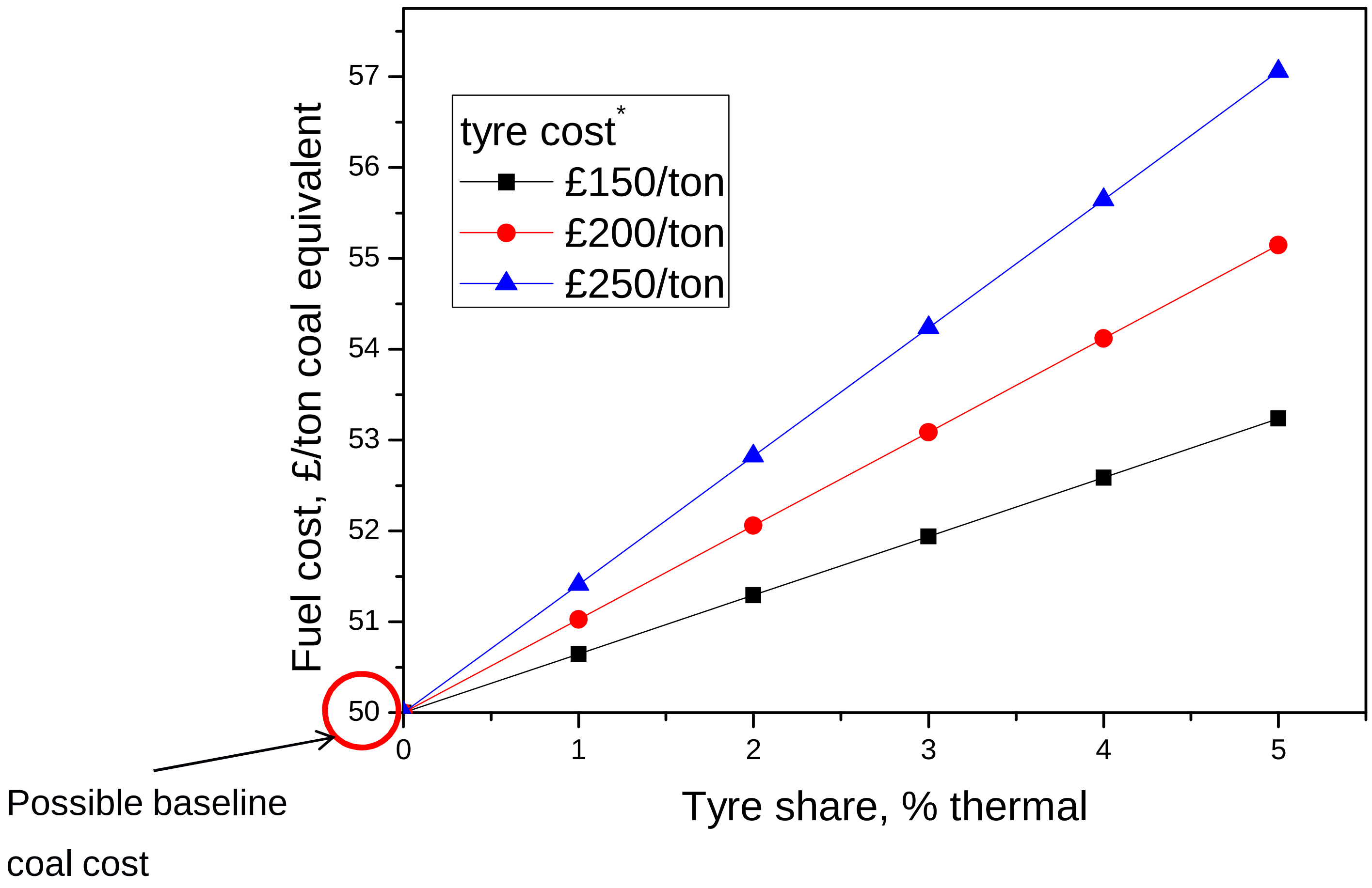


*Tyre cost includes preparation to 100µm mean particle size

- Introduction
- Experimental
- **Results – agricultural waste/PC co-firing**
- Conclusions

Problematic areas

- **Efficient management of waste yield from food crops in agricultural countries.**

- **These wastes are land filled and are a source of CH_4 release having 21 times higher global warming potential than CO_2 .**

- **Agricultural waste is largely not utilized in energy recovery schemes.**

Cotton stalk

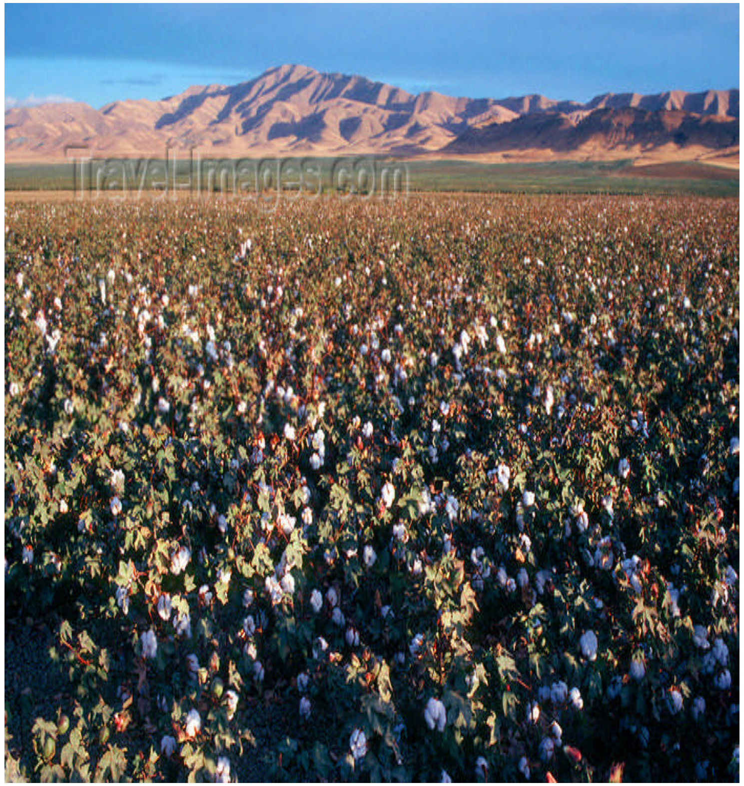
- **Cotton stalk (*Gossypium*) is the stem of cotton plant which is a leftover waste of the cotton crop.**

- **Often burned in the field as rotting vegetation may result in damage to future crops due to disease, infestation, etc.**

- **The annual amount of cotton stalk (residue) generated in Pakistan is 13.2 million tons.**

- **Cotton Stalk is considered a negative value biomass.**

- **A negative value biomass can become a positive value biomass by (a) solving a disposal problem and (b) producing high value fuels.**



Sheameal

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- **Shea meal (SM) is the <u>residue from the nut of the shea tree</u> (*Vitellaria paradoxa),* after the removal of fatty 'butter' which is used for cooking/cosmetics.**

- **This biomass material is <u>currently used as fuel in the UK power generating industry.</u>**

- **UK is <u>importing 5,420 tons of sheameal annually</u> from Africa for co-firing for electricity production.**

Fuel characterization

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Ultimate and proximate analysis and HHV of feedstock

Fuel	Ultimate Analysis[a]					Proximate Analysis[a]			Bulk density[c] (kg/m^3)	HHV (MJ/kg)
	C (%)	H (%)	O[b] (%)	N (%)	S (%)	Ash (%)	FC (%)	VM (%)		
SM	48.56	5.86	37.60	2.88	0.1	5.0	28.7	66.3	490	17.70
RC1	67.56	5.0	9.4	2.06	0.34	15.7	50.88	33.42	620	27.29
CS	47.07	4.58	42.10	1.1	--	5.1	18.8	76.1	310	17.7

[a] On dry basis except as denoted in table; [b] Calculated by difference; [c] Wet basis;

DTG Curves

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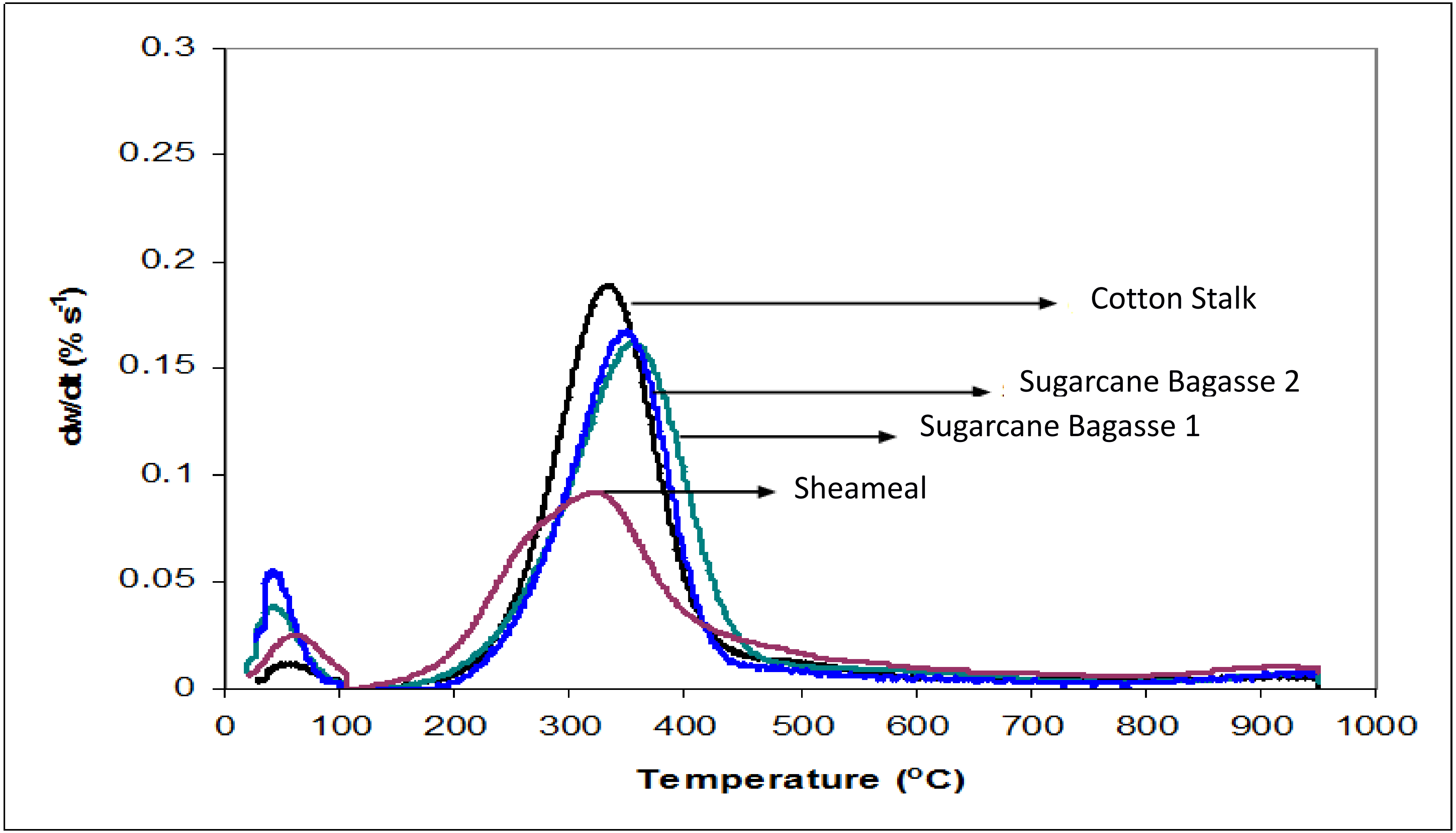

Source:Munir S etal,2009

Biomass/coal co-firing

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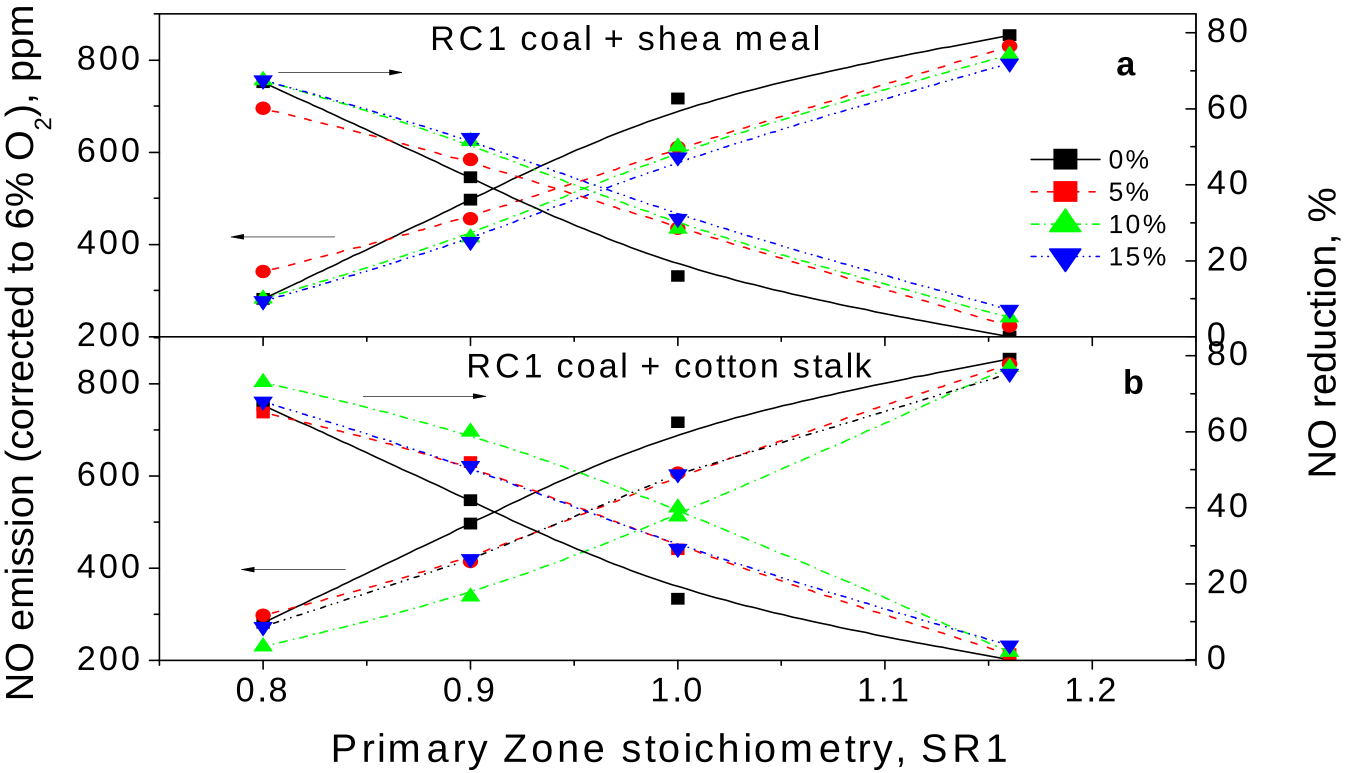
Un-staged and air-staged co-combustion

Greater NOx reductions with CS co-firing due to lower fuel N content



Burnout of coal-biomass blends

SR1=1.16

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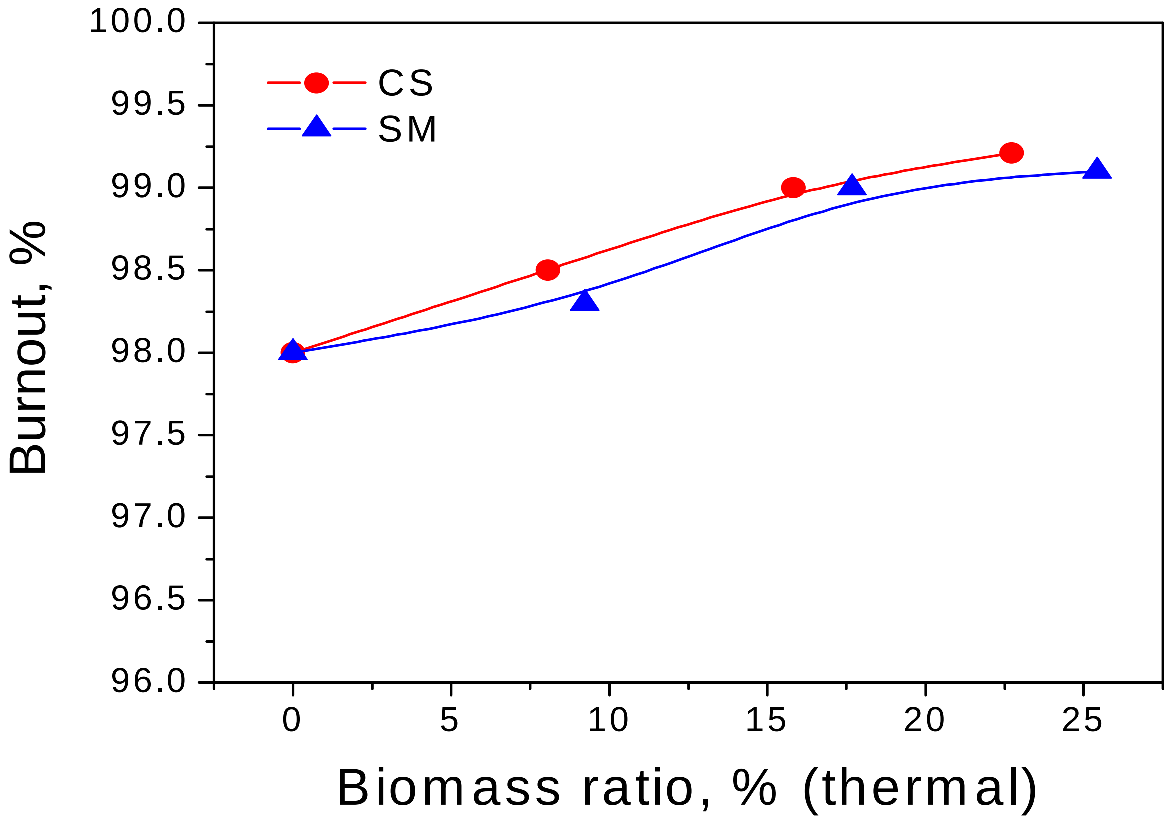
Improved burnout with increased biomass FF partly due to delayed ignition in flame – higher moisture content

Also, more reactive biomass char



Pure Biomass - NOx reburning

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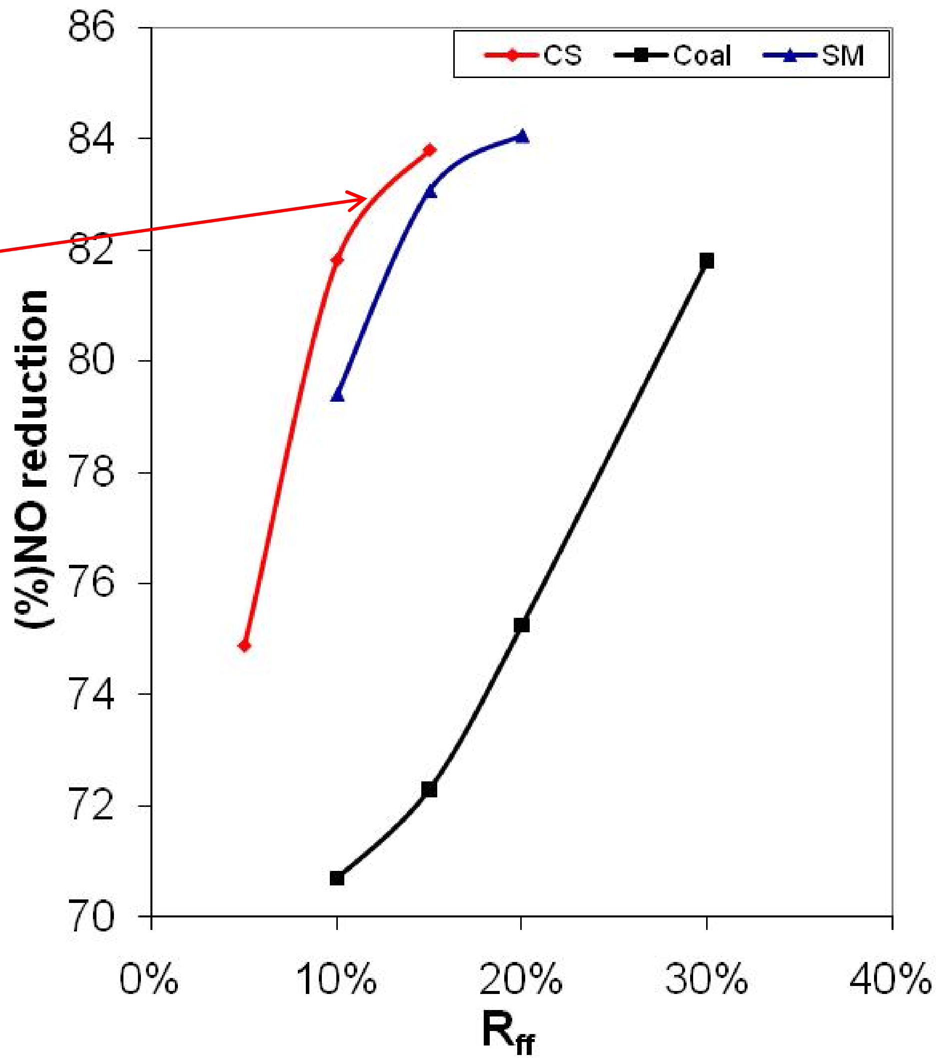
Reburning

High volatile CS

Better performer –

Higher NOx reductions

At lower fuel fractions



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O_2-enriched co-firing

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- Oxygen enriched air-staged co-combustion using different types of biomasses.

    - Russian coal – Shea Meal
    - Russian coal – Cotton Stalk

- Oxygen enrichment split factor in the burner and over fire air (OFA) for coal and coal-biomass combustion.

Overall oxygen levels in the combustion air - 2ry and OFA enrichment

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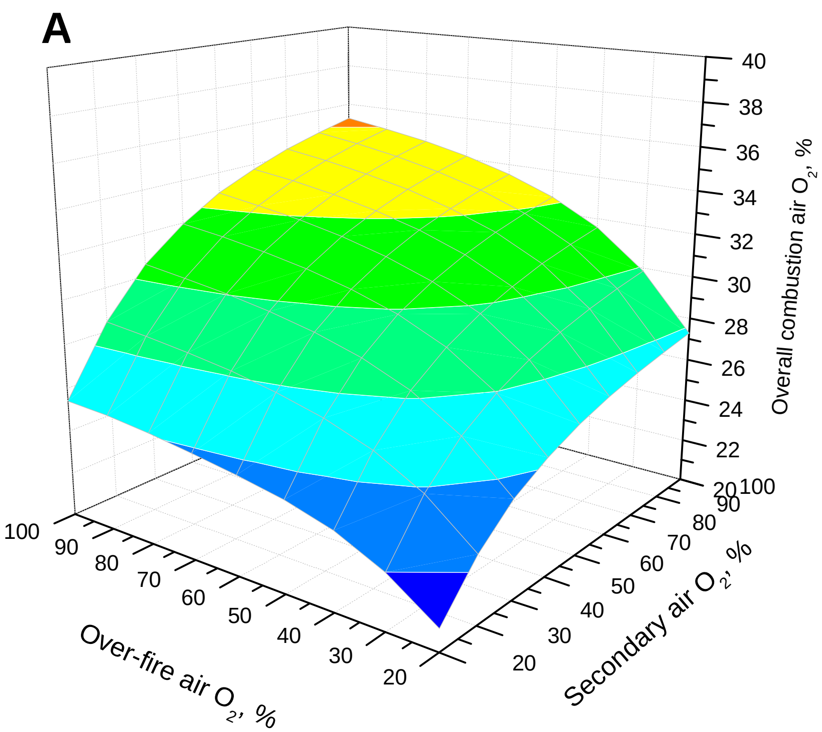
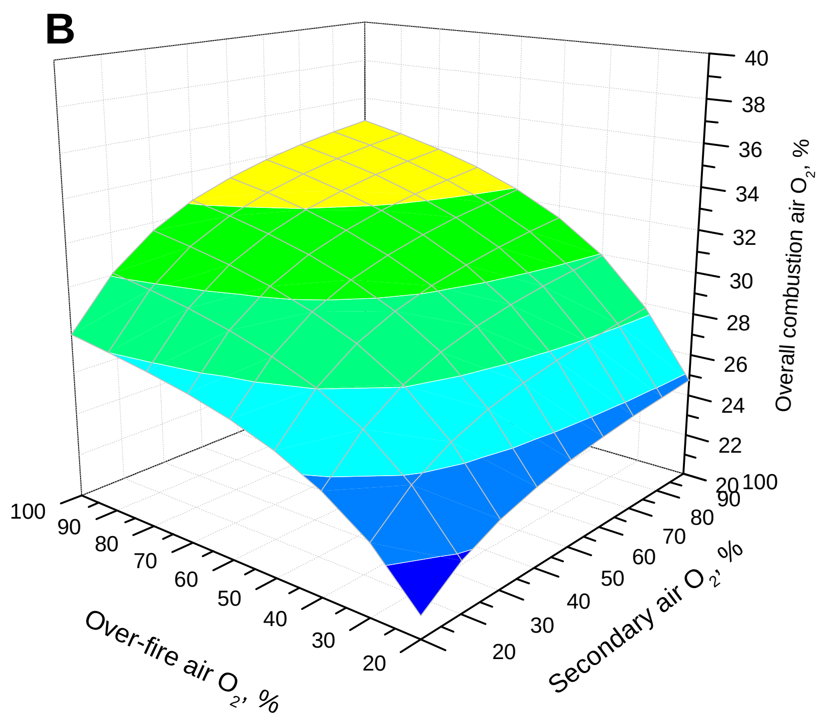
Calculated overall oxygen levels in the combustion air for over-fire and secondary combustion air enrichment

λ_1=0.9 (22% air staging)



λ_1=0.8 (31% air staging).



Dual O_2 enrichment of over-fire air and 2^{ry} air through burner

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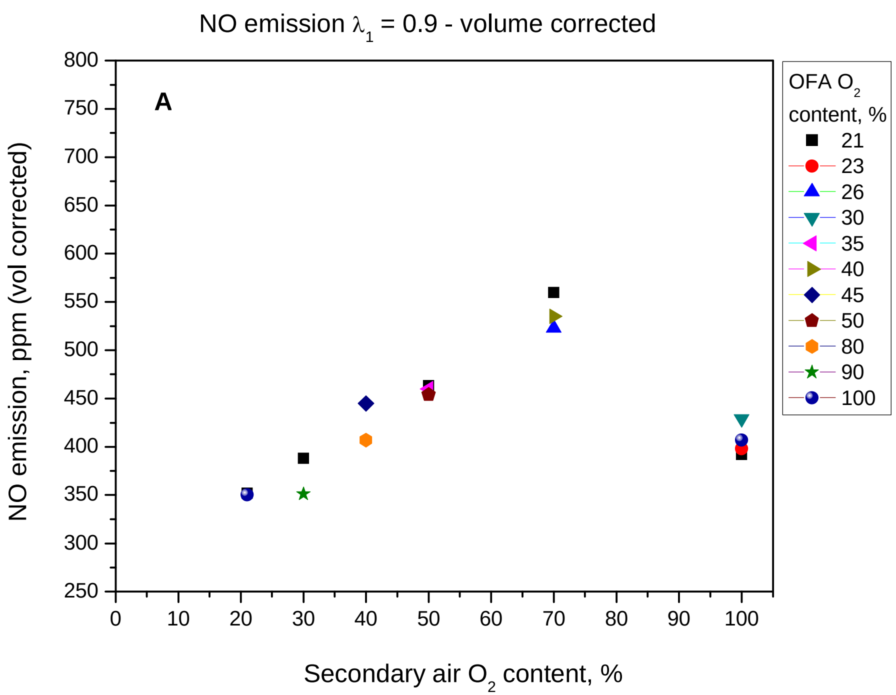
Coal only

λ_1=0.9 (22% air staging)



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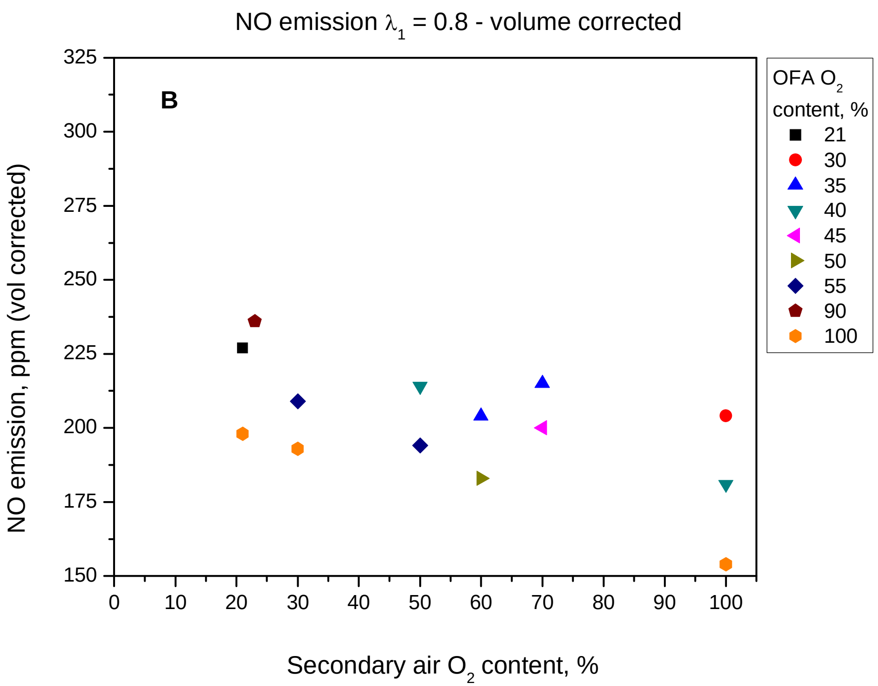

Dual O_2 enrichment of over-fire air and 2^{ry} air through burner

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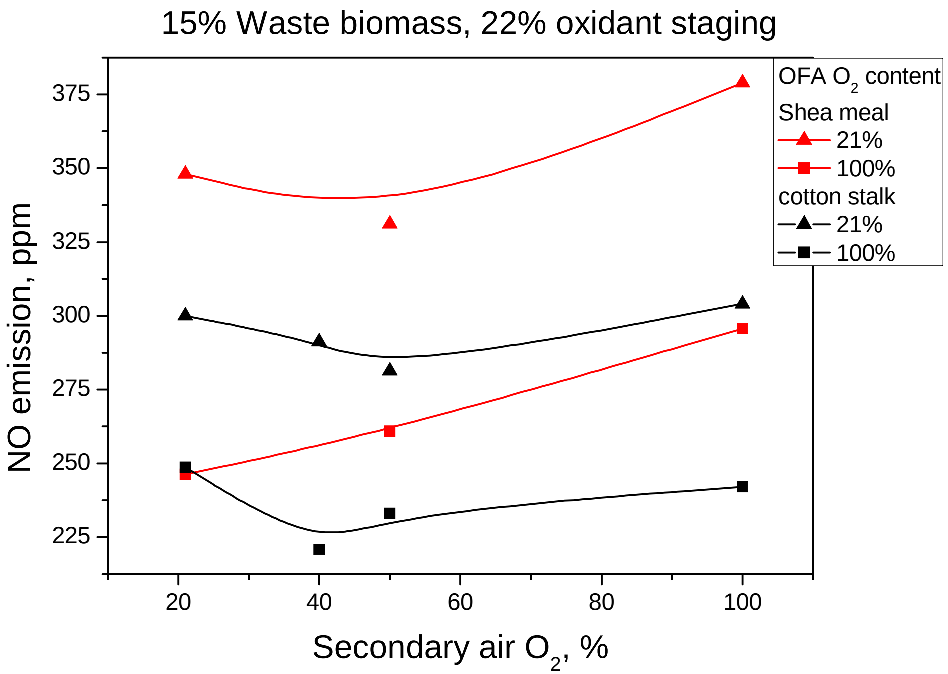
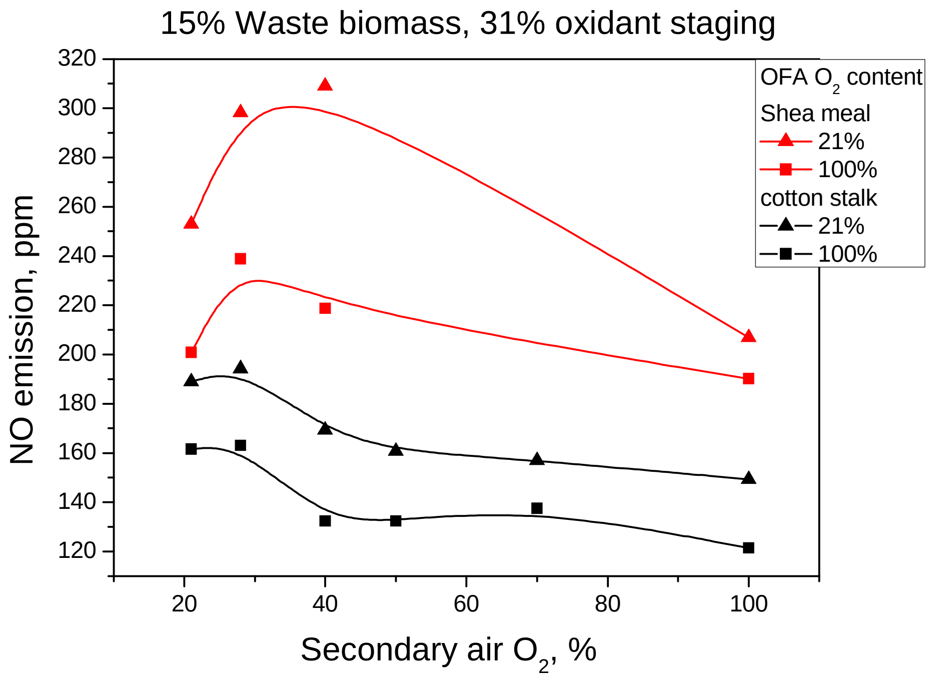
Co-firing shea meal and cotton stock and coal





Lower NOx levels for cotton stalk co-firing due to lower fuel-N than shea meal

Lower NOx levels at higher sec air enrichment for higher staging level

Burner air flow

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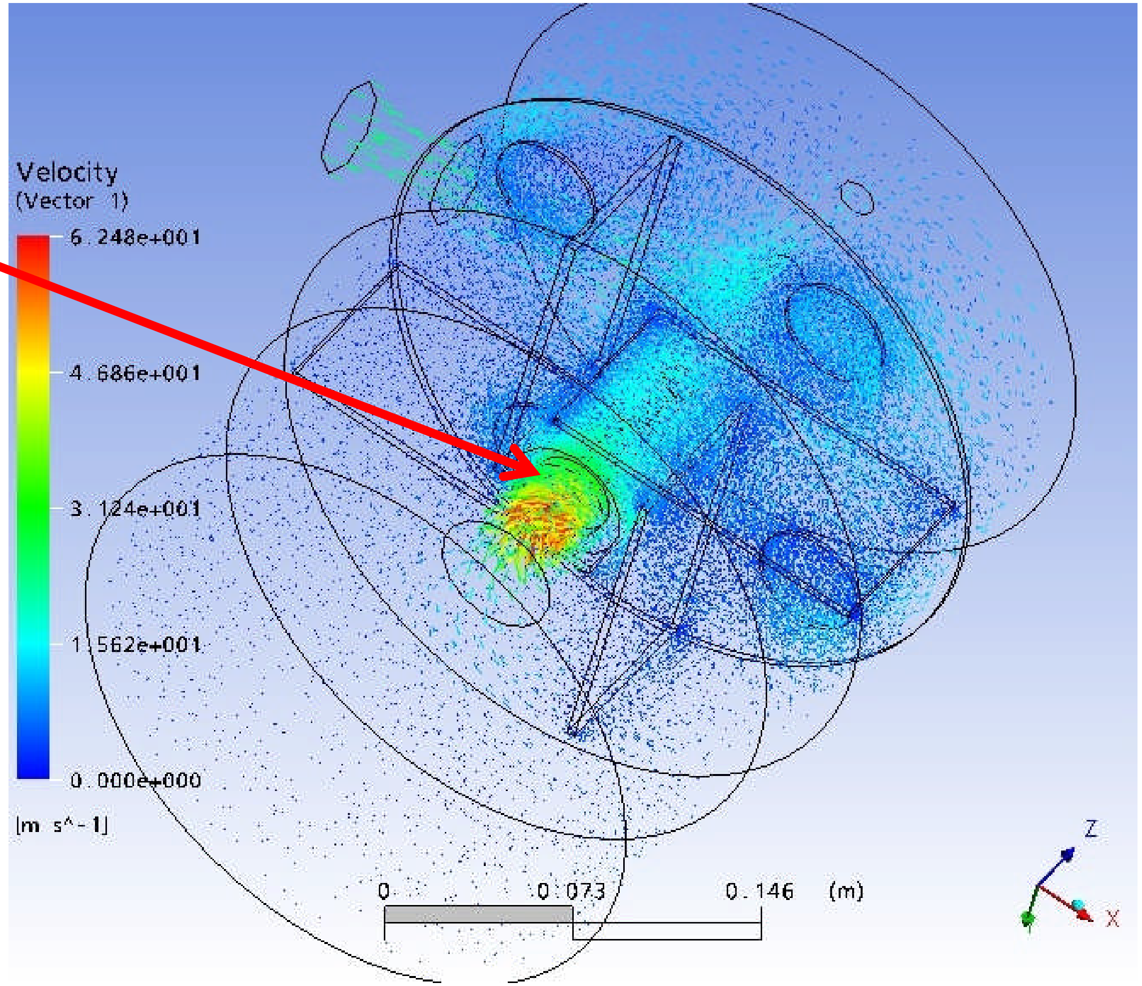
Swirling secondary air

– affected by O_2 enrichment levels

(0% - 79%,

21% – 100% O2)



Effect on NO emissions for OFA

O_2 enrichment

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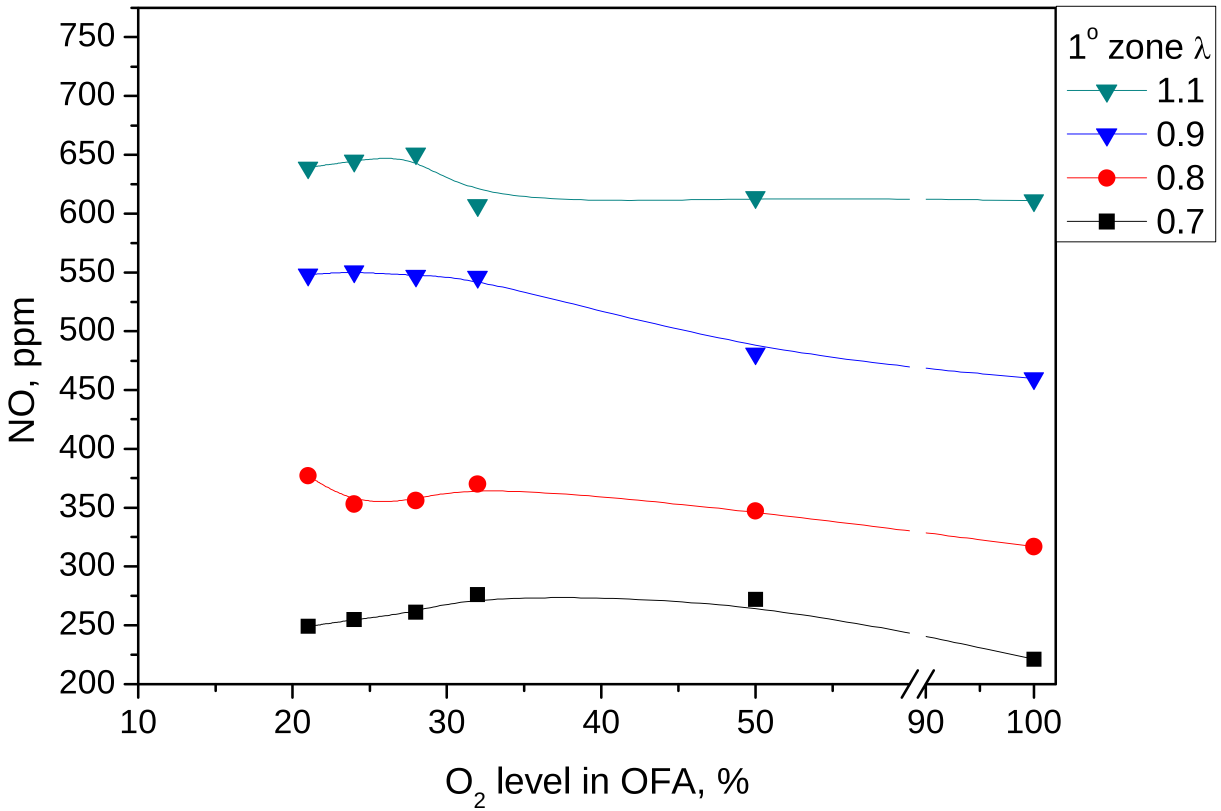
Slight reduction in NO emission with OFA enrichment –

Possibly mixing related due to reduced OFA flows



Effect on Carbon Burnout – Over-fire air enrichment

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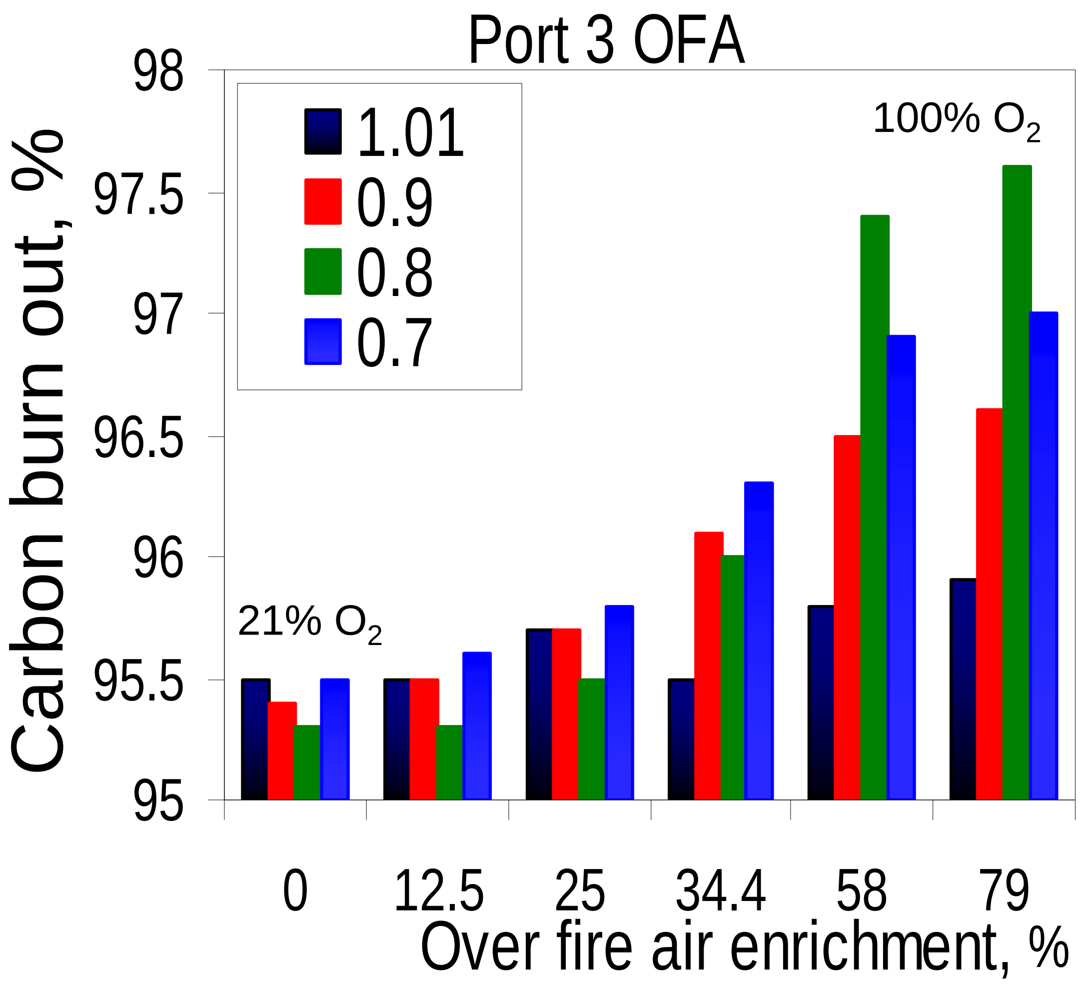
Higher levels of C burnout

At higher OFA enrichment



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Conclusions - Tyre co-firing

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Pros

- Technically feasible
- Can reduced NOx.
- CO_2 reduction a possibility.
- Renewable content (natural rubber).
- Performs better with lower quality fuels.
- Zn probably not a problem for slagging and fouling.

Cons

- High cost of tyre rubber production may be prohibitive.
- Waste classification.
- Co-firing may reduce burnout efficiency. (However, may be scope for better carbon burnout with O_2 enrichment).
- SO_2 production may increase depending on coal (may be handled by existing FGD systems).

Conclusions
HDPE Plastic co-firing

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Pros

- Reductions in NOx by co-firing plastic by reducing fuel-N in blend
- Potential for small reduction in CO_2 .
- Reductions in SO_2 of 30% by replacement of coal by at a fuel fraction of 25% (thermal).
- Low impact on ash.

Cons

- Waste classification
- Difficulty in producing pulverised plastic in quantity from mixed waste

Conclusions – Biomass waste/coal co-firing and O_2 enrichment

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- Lower levels of NO emission at higher levels of 2^o air enrichment - at higher oxidant staging levels
- Higher levels of C burnout for higher levels of biomass FF
- Higher levels of C burnout at higher OFA O_2 enrichment
- OFA O_2 enrichment may be used to improve carbon burnout for difficult coal combustion configurations such as "NOx reburning" (future project?)

Thank you for listening

and any questions?