Conference or Workshop Item:

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Particulate Emissions from a 350 kw Wood Pellet Heater

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Introduction - 1

In spite of the demonstrated advantages of biomass combustion for CO_2 reduction there are many reports of concern for the environment, especially in regards to particulate emissions.

Particulate emissions are a health hazard primarily due to the impact of ultrafine (<50nm) particles on lung function and heart related disease, due to the reduced oxygen absorbed into the blood with inflamed alveolar regions in the lungs.

There has been relatively little published work on ultra-fine particulate emissions from biomass combustion and this is a key theme of this work.

Two air 350 kW heaters for use in industrial process heating were compared using an oil fired burner in one heater and a biomass pellet fired heater in a similar air heater.

The EU (2013) criteria for small heaters and boilers is a solid PM maximum of PM 30g/GJ net heat input and 150 g/GJ NOx (as NO_2).

The GJ is the thermal energy input in the fuel NOT the energy output.

For a CV of 18 MJ/kg of fuel on a dry ash fry bases (daf) the above convert to

PM 0.54 g/kg of daf fuel (BUT – only Carbon and ash is included)

This is higher than is allowed for diesel engines where the current legislation requires <0.1 g/kg (based on a conversion from legislated emissions in g/km using the fuel consumption of a vehicle). Diesel carbon is about half the PM and hence diesel carbon is ~1/10 that of these regulations for small heaters and boilers. This is LAX regulation and is not technology forcing in biomass boiler design.

150 g/GJ NOx converts to 2.7 g/kg of daf fuel

Now this is ~ 27 ppm NOx at 15% oxygen (Ind. GT <25 ppm)
~ 7.7 ppm at 0% oxygen - Achievable for NG heat
~ 9 ppm at 3% oxygen

These are very low NOx and are technology forcing.

It is surprising that only NOx and PM are regulated by the EU and CO and HC are not.

CO is a crucial measurement in boiler and heater performance as it relates to the excess air and combustion efficiency. Biomass boilers must be set up for the fuel they are burning by increasing the excess air until the CO is low enough.

What is low enough, this is normally set in the emissions regulations and hence it is surprising that this has not been done in the EU emissions regulations for small heaters and boilers.

This would allow a manufacturer to tune for low NOx with no concern for CO emissions. Usually NOx and CO are inversely related.

Hydrocarbon emissions contain species that are harmful such as aldehydes and PAH. No control on HC means that any level can be emitted.

It is the HC that people smell around biomass burners, so the lack of control is of concern. The lack of control of total PM means that PAH in the PM volatile fraction are also not controlled.

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The Application

This project was based in a local factory that manufactured paving and roadside drainage pipework. The concrete formers were placed in setting sheds, heated to about 60^{o}C using air heaters.

Each air heater had a 350kW maximum power and there were about 20 on site and around 10 other sites in the UK and many International operations. The intention was to replace the current use of fuel oil heaters with pellet heaters and hence reduce their carbon footprint.

If the trial was successful then all UK sites might transfer to biofuel heaters. This would be 80MW of renewable heat in their UK operations and approaching 1 GW if their international plants were converted.

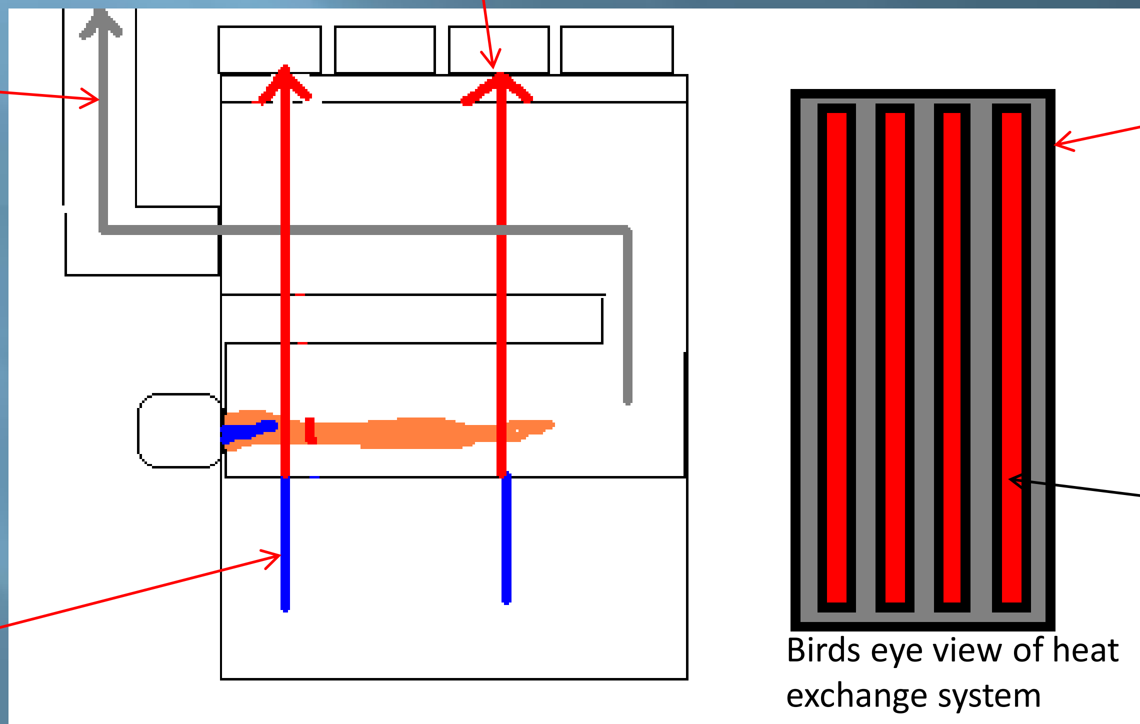
Internal Heat Exchanger Design

UNIVERSITY OF LEEDS

Heated air exit

Flue gas exit

Grey = path of flue gas

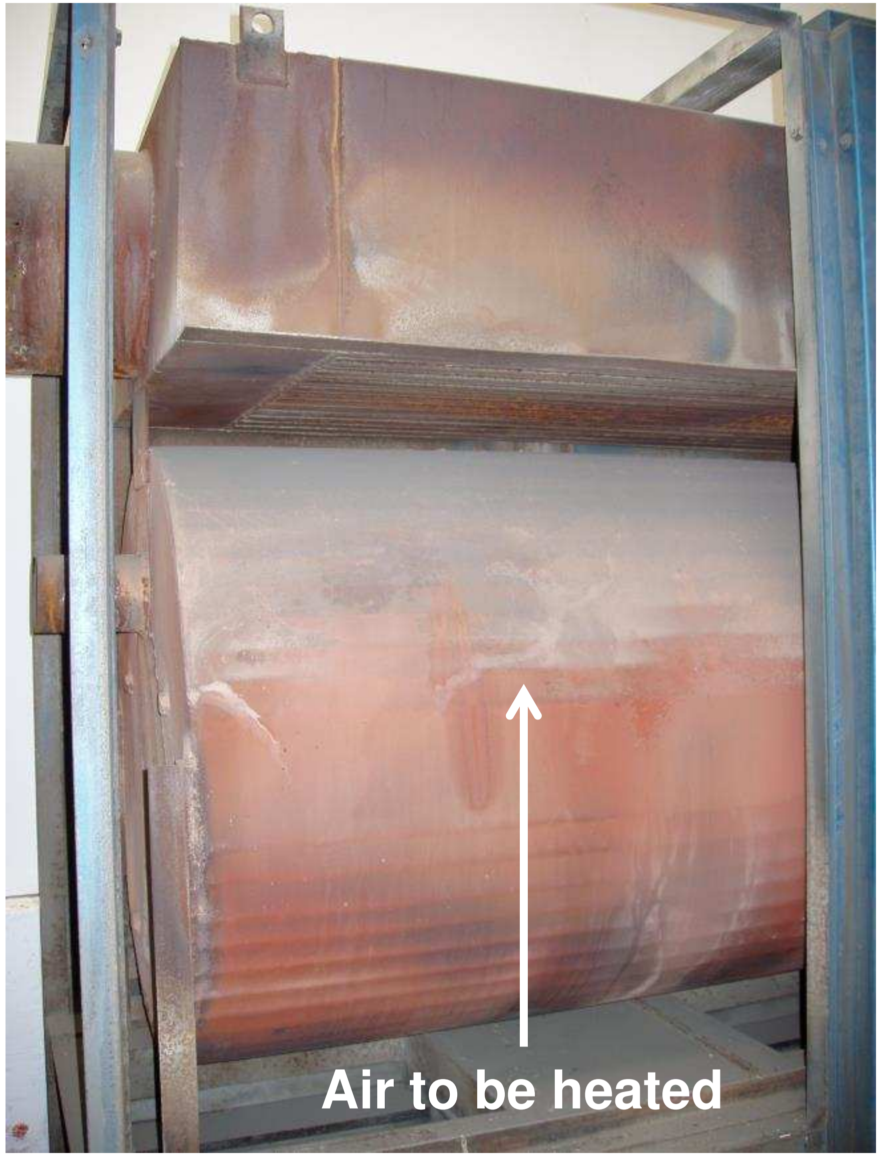


Red = Path of heated air to the room

Cold air into be heated

< Exhaust

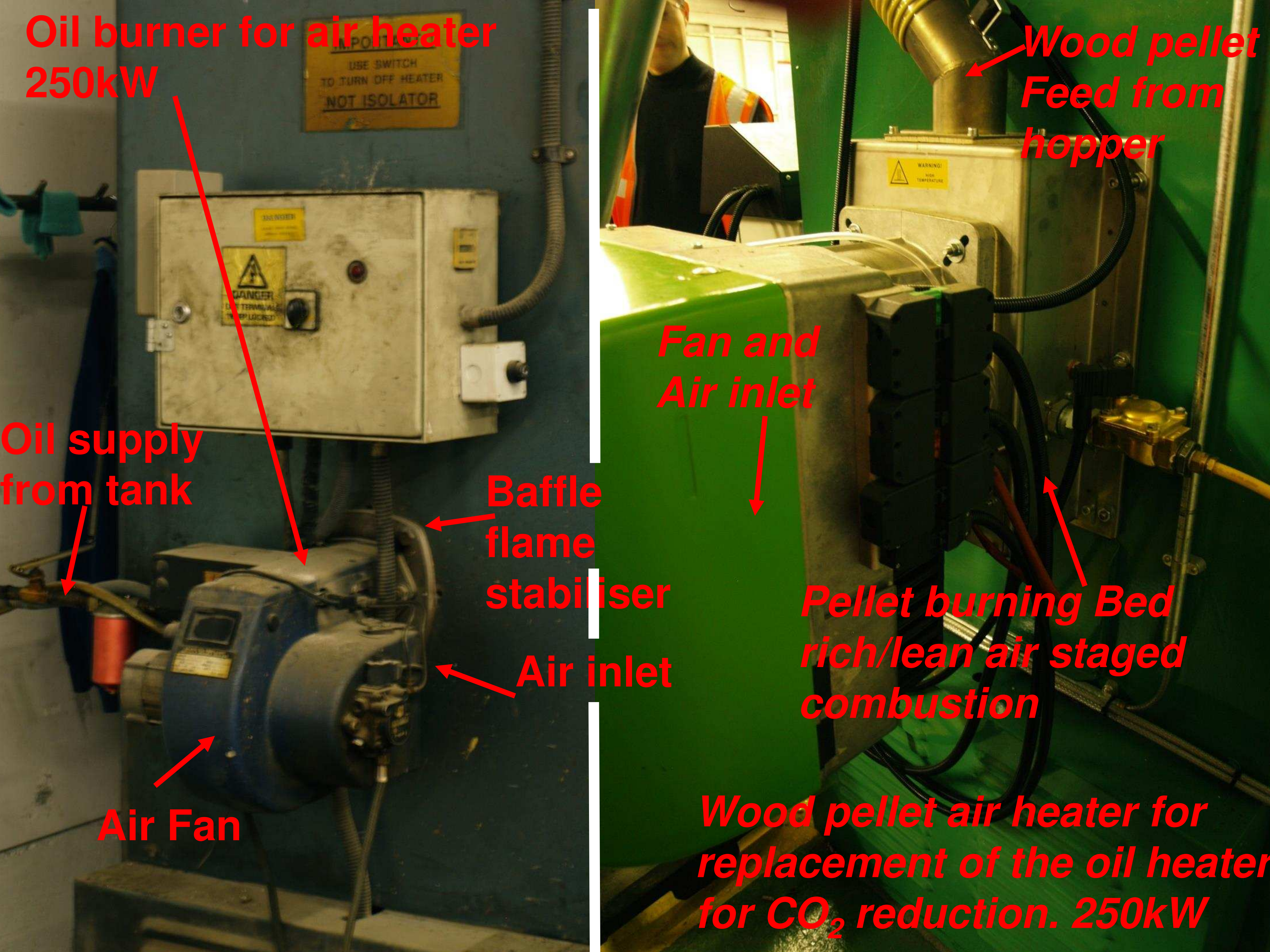
Burner >



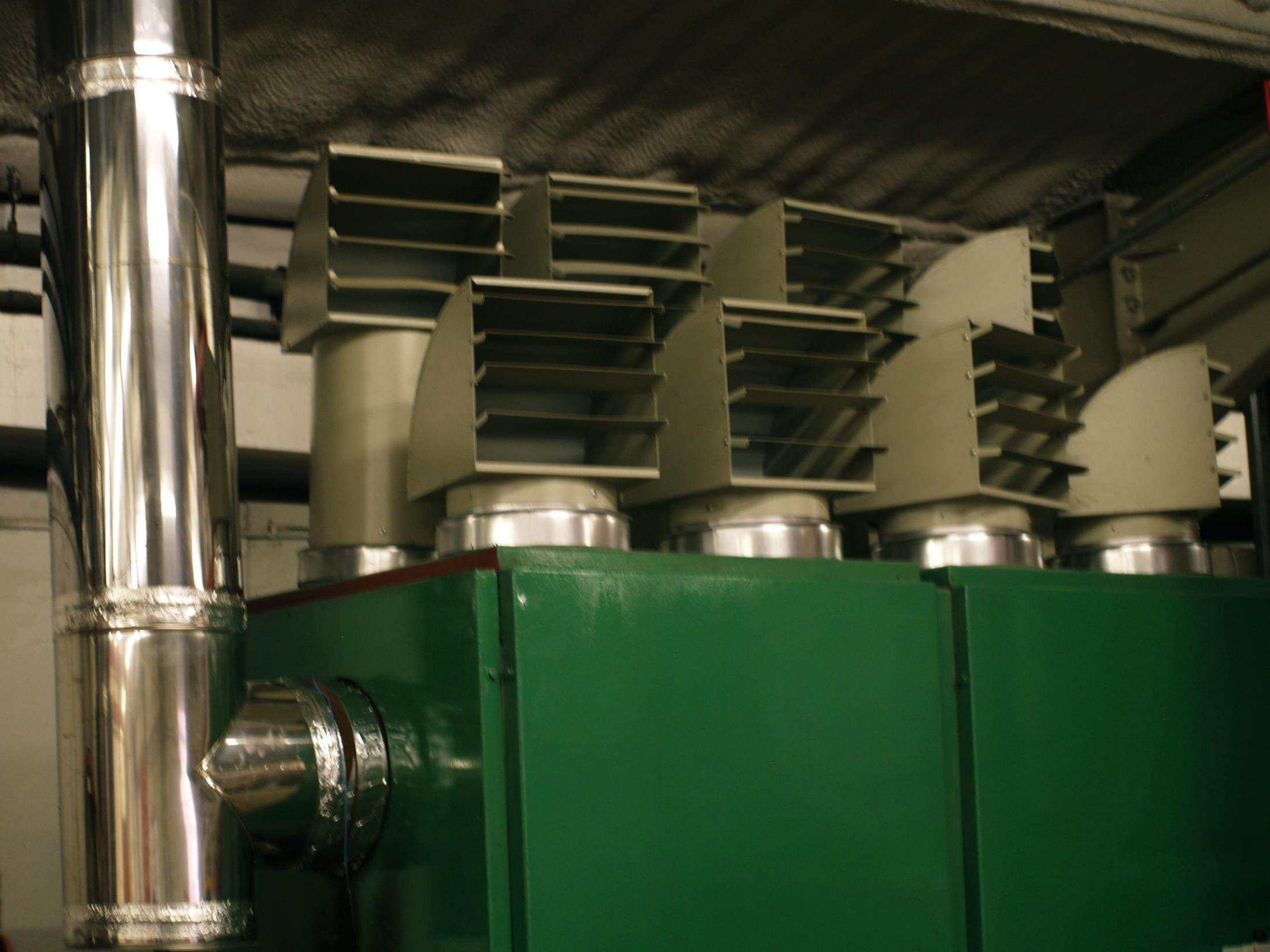
The reference fossil fuel burner was a 350kW gas-oil fired burner made by Nuway Ltd who specialise in burners for heating. The boiler currently being used is the Nuway NOL-13 light distillate oil (class D). The control on the burner was a high/low burner as continuous heating is required. The burner has two atomising nozzles. On low flame only one fires, on high flame both are fired. The air inlet flow rate is controlled by a butterfly valve actuated by a hydraulic ram which switches the air valve position between low fire (low air flow) and high fire (high air flow) [i].

[i] Nu-way. (1998). *Series NOL fully automatic oil burner models NOL13/NOL16.* Droitwich: Nu-way.

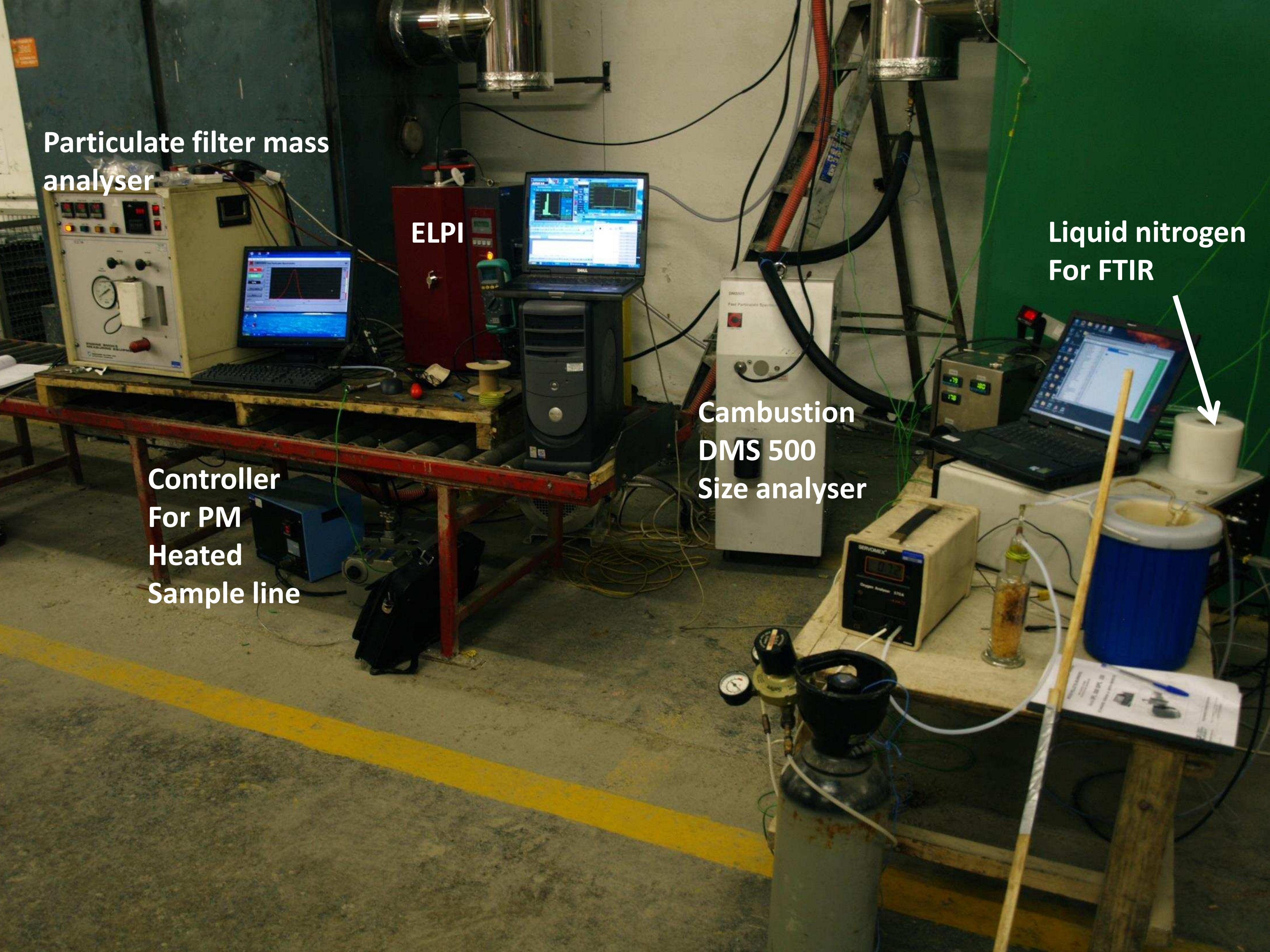
The wood pellet burner was a TermoCabi SPL 350 wood pellet burner (Italian manufacturer).
It has a variable power supply between 150-350kW and is fully automatic.
The burner consists of a 370W fan, 800W electrical glow plug igniter, and an 180W feed screw.
The burner creates a horizontal flame in the burner, and the pellets are dropped in from the top of the burner (an over-fed burner).
The fan speed and therefore air flow is controlled by the desired burner power output.
There was no oxygen feedback control fitted.

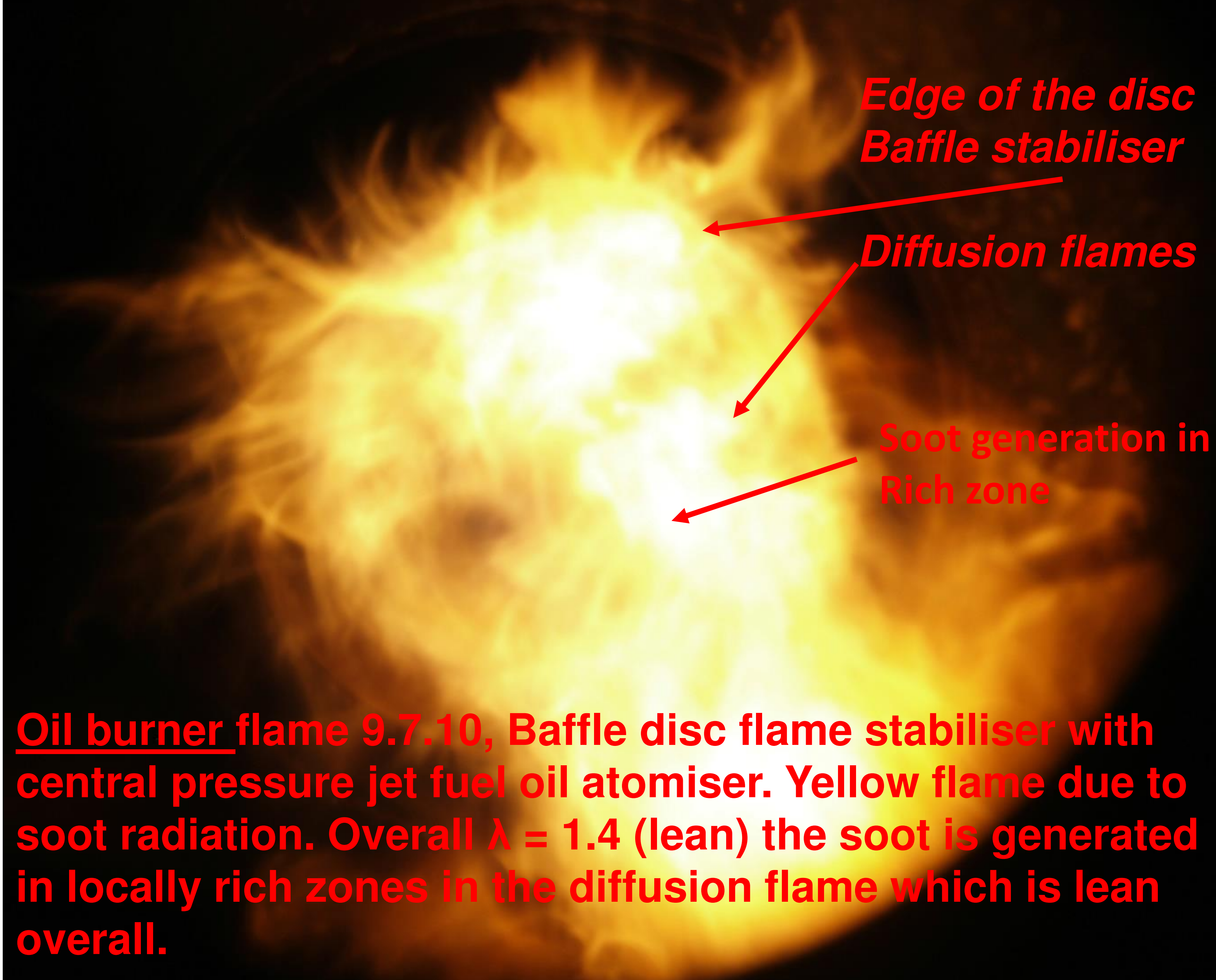

Oil burner for air heater 250kW
USE SWITCH
TO TURN OFF HEATER
NOT ISOLATOR
Oil supply from tank
Baffle flame stabiliser
Air inlet
Air Fan
Wood pellet Feed from hopper
Fan and Air inlet
Pellet burning Bed rich/lean air staged combustion
Wood pellet air heater for replacement of the oil heater for CO_2 reduction. 250kW


Bayferrox®



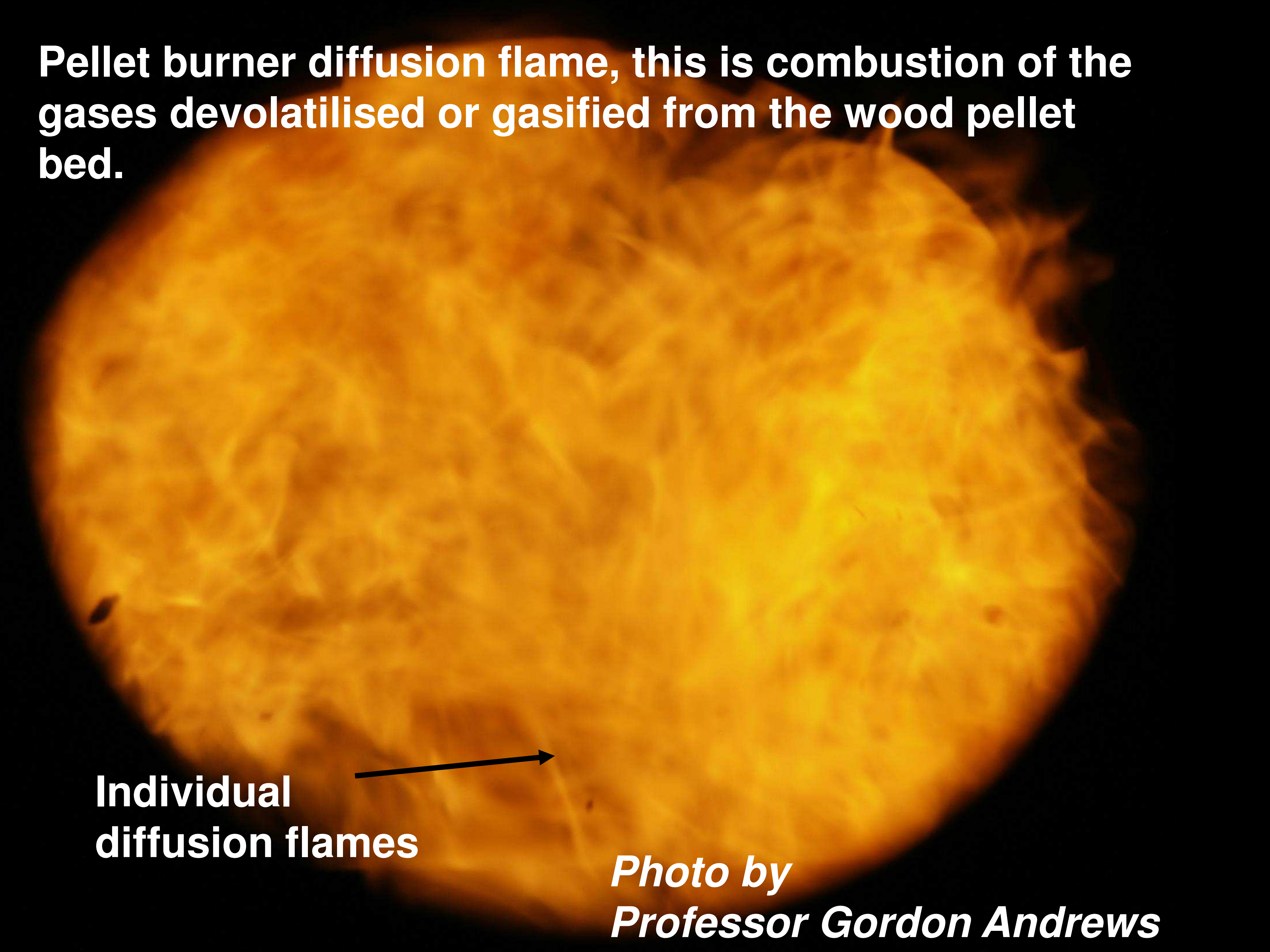

Heated
Sample
line
Sample line
Heater controller
ELPI
FTIR
Oxygn analyser


Particulate filter mass analyser
ELPI
Liquid nitrogen For FTIR
Cambustion DMS 500 Size analyser
Controller For PM Heated Sample line



Oil burner flame 9.7.10, Baffle disc flame stabiliser with central pressure jet fuel oil atomiser. Yellow flame due to soot radiation. Overall λ = 1.4 (lean) the soot is generated in locally rich zones in the diffusion flame which is lean overall.

Pellet burner diffusion flame, this is combustion of the gases devolatilised or gasified from the wood pellet bed.



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Wood Pellet Types

Five different UK (Yorkshire) wood pellets were compared.

Pellets A were produced from 100% sustainable forest wood and were manufactured at the forest site. This was high in FBN.

Pellets B were manufactured from virgin timber processing waste and wood residues from a furniture manufacturer. This was also high in FBN.

Pellets C and D were manufactured from construction wood waste sourced from municipal landfill sorting sites. The samples had large particles visible in the pellets and had an uneven colour and broke up easily. These samples were low in FBN.

Pellets E were manufactured from the stone seed waste from the olive oil industry. This sample had the highest FBN at 5%.

Pellet Proximate Analysis by TGA

Pellet	A	B	C	D	E
Water %	4.64	5.95	4.91	6.72	6.92
Volatiles %	85.5	83. 1	73.8	85.5	79.3
Fixed Carbon %	6.7	6.5	8.3	5.4	6.0
Ash %	3.3	4.5	13.0	2.4	7.8
Water& Ash %	7.9	10.5	17.9	9.2	14.7

The pellets all met the < 10% water EU pellet standard
The volatiles were in the 74 – 86% range
Ash was very variable and highest for C and lowest for D which had the same waste wood source.
The water plus ash was significant and had an important influence on the actual stoichiometric A/F.

Pellet Elemental Composition

Pellet type	C	H	O	N	S	Water	Ash
A	47.9	5.75	37.0	1.42	0	4.64	3.26
B	48.6	5.83	33.87	1.23	0	5.94	4.52
C	46.4	4.94	30.23	0.52	0	4.91	13.00
D	46.1	4.35	39.90	0.38	0.15	6.72	2.43
E	46. 7	6.16	34.81	5.36	0.03	6.92	7.79

Pellet Elemental Composition % on a Dry Ash Free Basis (daf) plus the Water and Ash by TGA
The elemental analysis is the basis of the stoichiometric A/F.

Stoichiometric Air/Fuel Mass on a daf basis y = H/C, z = O/C, w = N/C
= {[(1 + y/4)–z/2 –w/4] 137.94} / (12 + y + 16z + 14w)

Pellet	A/F daf	A/F actual including water and ash	% difference in actual A/F
A	5.52	5.08	8.0
B	5.66	5.06	10.6
C	4.95	3.67	25.9
D	4.68	4.25	9.2
E	5.56	4.74	14.7

A/F actual = (A/F)daf [1 – (w + a)] w = water and a = ash fractions
Oxygen feedback control is essential for biomass boilers as biomass Has variable composition and variable stoichiometric A/F_{actual}.

In the present work there was no oxygen feedback control and the optimum burner fan and fuelling settings were determined for the A pellets.

This fuelling and air was left constant and the other pellets tested. This kept the A/F constant, which would not keep the excess air constant due to the variability in pellet composition.

There was a significant variation in the resultant excess air (derived from the measured excess oxygen).

The optimum for A pellets was 42% excess air, but at the same burner settings the C pellets operated at 29% excess air and B operated at 57% excess air.

The present results show that oxygen feedback control is essential for adequate performance and emissions control in small biomass heaters – most boilers do have this.

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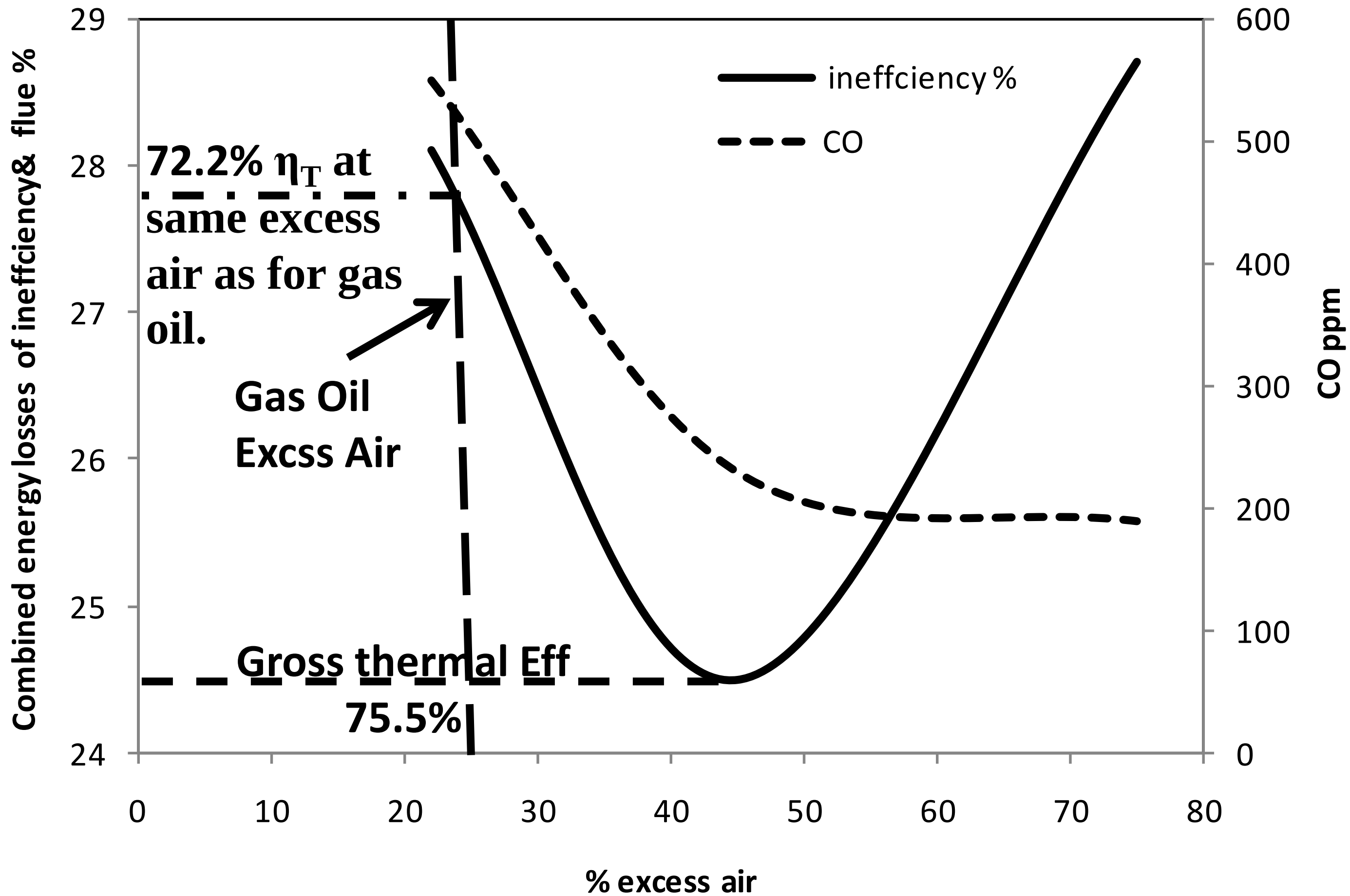

Variation of gross (HHV) thermal inefficiency and CO with excess air derived from the oxygen analysis for Pellets A. Optimum excess air 42% close to min. CO. Carbon in ash is not included here – only CO and HC.

Carbon in ash loss needs to be evaluated in biomass boilers.

In the present work the carbon in ash thermal efficiency loss was 1.4% for pellet A.

There was also significant unburnt solid char in the ash (25%), which should also be added to the thermal inefficiency.

There is very little data in the literature on biomass ash composition for carbon and unburnt fuel and more work is required.

A detailed thermal efficiency study on a 35 MW straw power station (DTI contract report 2003) included carbon in ash data.

The overall combustion inefficiency (CO and carbon in ash) was 0.51% for straw, 1.15% for OSR and 0.57% for 'Whole Crop'.

The carbon in ash dominated this loss and the CO loss was minor and its highest value was 13% of the total combustion inefficiency.

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Particulate Emissions from a 350 kw Wood Pellet Heater

Prof. Gordon E. Andrews, School of Chemical and Process Eng., U. Leeds, UK

Pellet	Excess Air %	Net Thermal Eff. %	Fuel N %	CO ppm	HC ppm	NOx ppm	NOx mg/Nm^3	NOx g/kg	NOx g/GJ
A	24	76.5	1.42	1079	220				
A	42	80.4	1.42	163	45	106	219	1.5	77
A	75	76.0	1.42	108	50	267	385	4.1	228
B	57	79.5	1.23	53	41	214	445	3.4	176
C	29		0.52	260	56	110	228	1.3	71
E	39		5.36	114	32	116	253	1.6	76
Greg Forbes This Conf	?								95-191
Gas Oil	23	82.0	0.01	14	67	81	170	2.5	55

NOx is strongly influenced by FBN and excess air

However, Pellets E with 5% FBN did not have a NOx issue!

Note that NOx is > EU Std of 150 g/GJ for Pellet A when operated lean at 75% excess air but at 42% excess air it is half the standard. Pellet B operates at 57% excess air at the same settings that Pellet A operated at 42% excess air and NOx was > std. This is classic rich/lean characteristics with high FBN.

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Under the clean air act the flue discharge has to be free of visible soot and this was observed and photographic records taken to show this, as shown here. All the pellet burner flue discharges were as clean as this.

Photo by Prof. G.E. Andrews

Particulate Emissions from a 350 kw Wood Pellet Heater

Prof. Gordon E. Andrews, School of Chemical and Process Eng., U. Leeds, UK

Fuel	PM mg/m^3	A/F Stoich.	Excess air %	Actual A/F	PM g/Kg fuel	PM g/GJ
Oil	12	14.3	23	17.45	0.19	4.2
Oil	400*	14.3	23	17.45	6.3	139
A	85	5.52	24	6.79	0.41	21.0
A	40	5.52	42	7.84	0.30	15.4
C	23	4.68	29	6.04	0.14	7.7
B	23.5	6.29	52	9.56	0.21	10.7
E	29	5.56	30	7.65	0.21	10.1
			New Zealand PM Regulations		1.50	

Particulate filter paper mass measurement at 50°C filter temp.

Note the unexpectedly low PM for Pellet C for 29% excess air which had the highest water plus ash content which would lower the flame temp.

Note that the EU regulation is 30 g/GJ and all the PM for biomass pellets were below this. However, the EU regulations are for only the carbon fraction and this is about 1.5%% of the PM mass for biomass. So the carbon emissions of a well optimised pellet heater are all about 1/10 of the regulation.

* Initial oil fired tests had very bad emissions due to deposits on fuel injector.

Particulate Composition Analysis by TGA

Fuel type	Excess air %	Volatiles %	Soot %	Ash %	Soot mg/m^3	Soot g/GJ
Oil	22	20	80	0	9.6	3
A	24	20	80	0	68	17
A	42	20.3	1.5	78.2	0.6	0.2
EU Regulation						30

For Pellet A the consequence of operating with inadequate excess air is very high soot emissions, but with optimised excess air the soot is negligible. Excess air could be controlled using CO emissions but these are not required to be measured under the EU regulations, which also do not control the thermal efficiency.

It would be preferable if the EU regulated total PM mass.

Author(s)	Excess Air %	mg/m^3	g/kg_{fuel}	g/GJ
Present PM	29 - 52	23 - 40	0.14 – 0.3	8 – 15
Kelk et al.	66		0.11	6.1
Nussbaumer & Lauber	?	30		
Michel et al.	?	120 - 180		
Linda and Johansson	?	62 - 180		
Greg Forbes This Conf.	?			65 - 390

Present results are in agreement with those in the literature for biomass PM – very few carbon only available.

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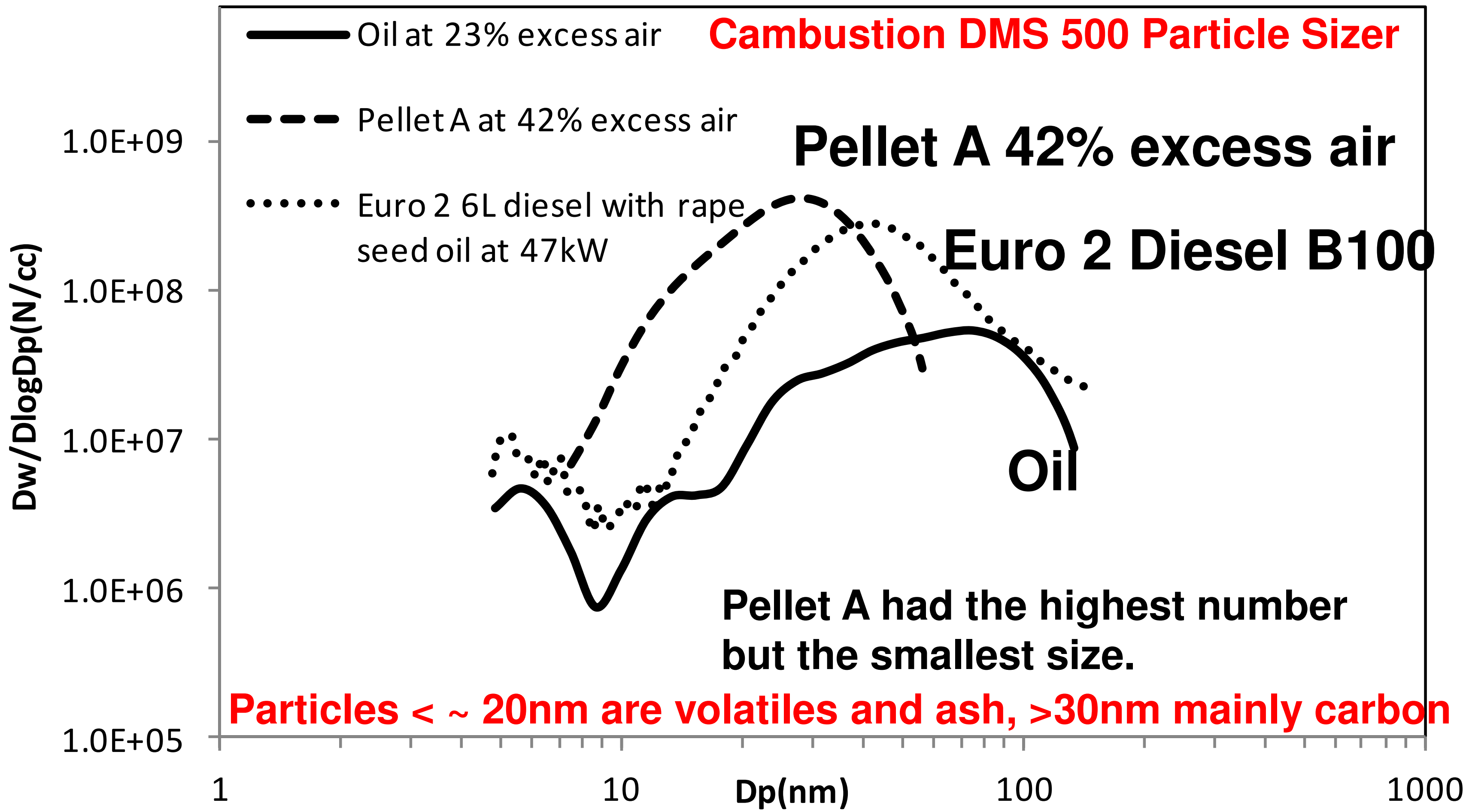
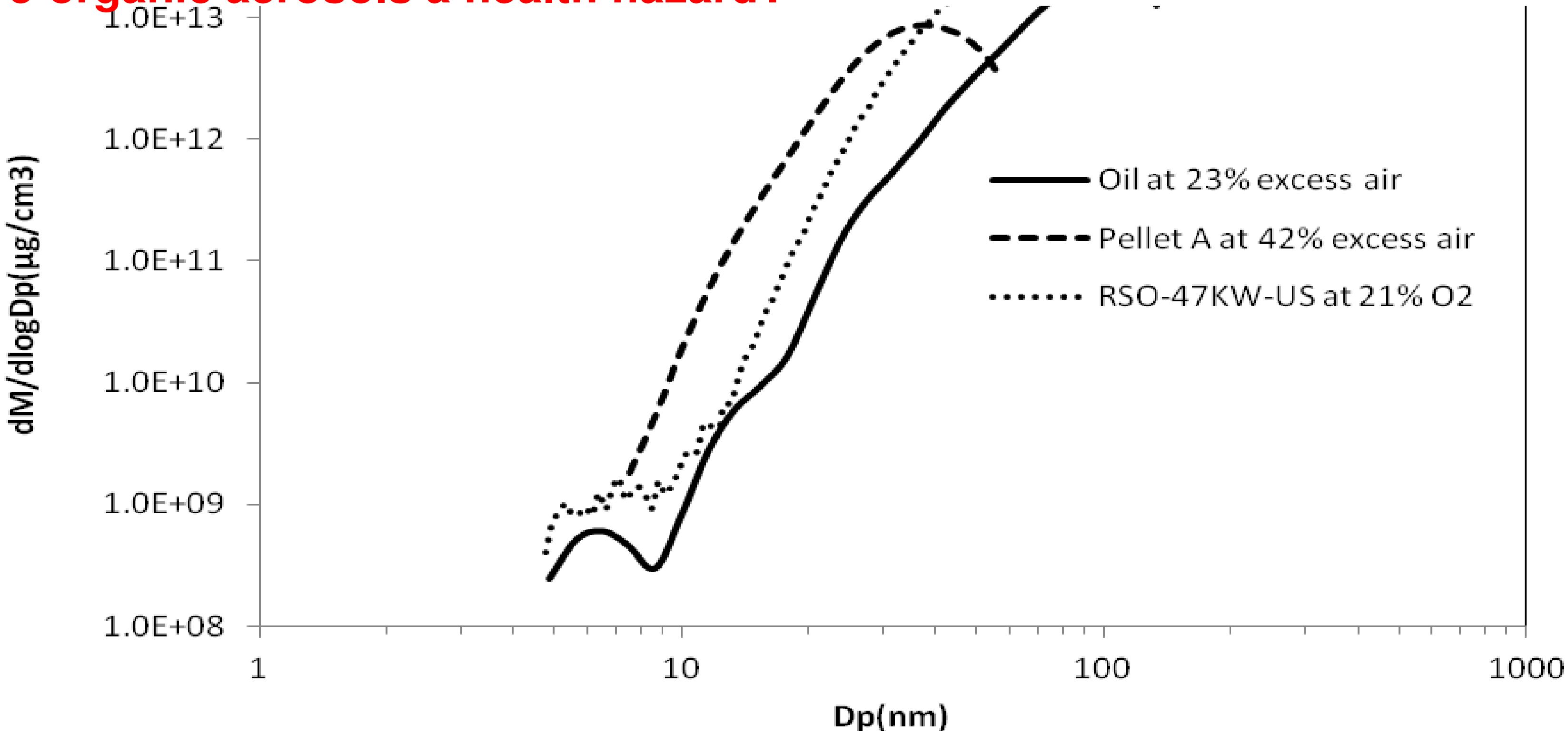
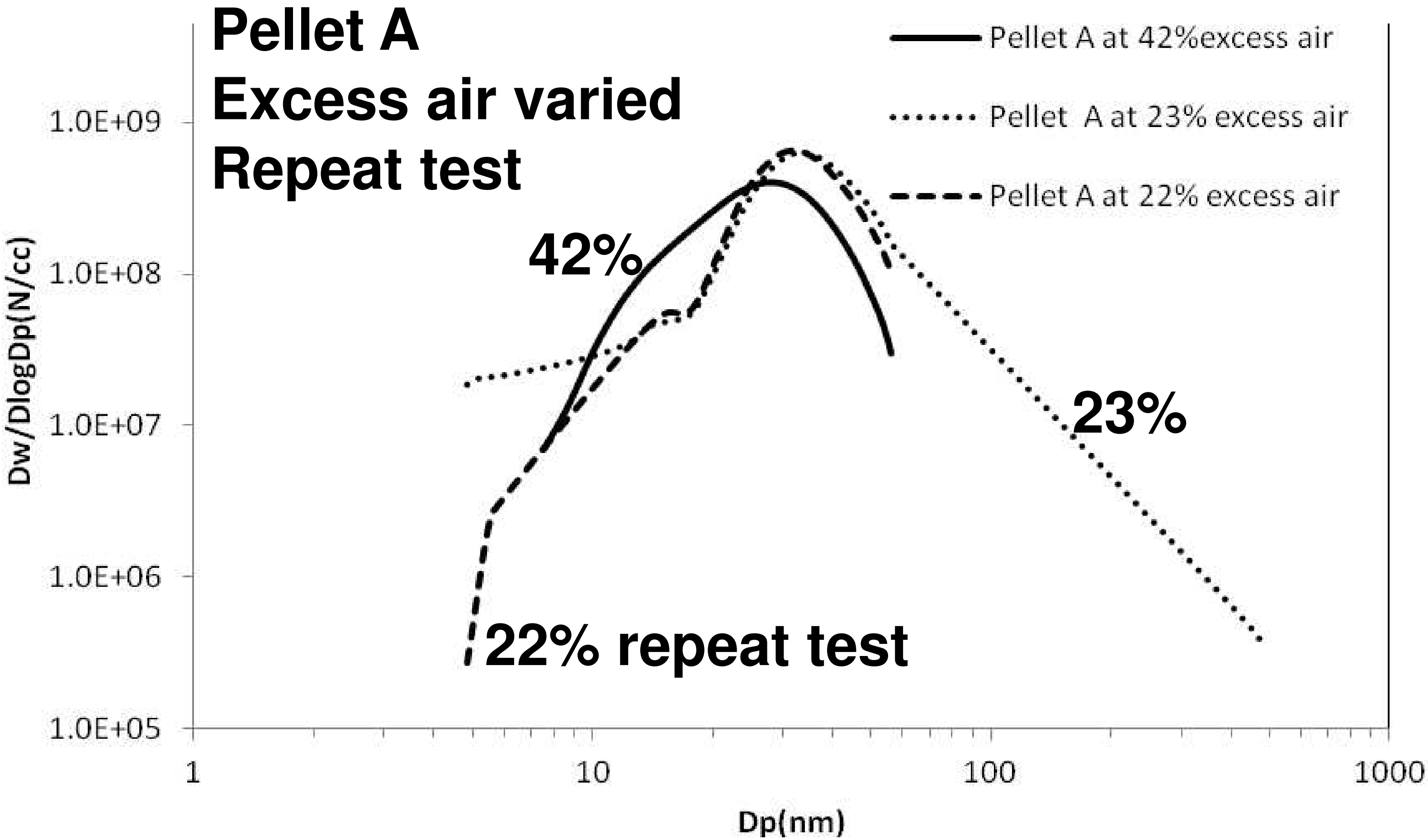


Particle number distribution as a function of size for pellets A and fuel oil with a comparison with a Euro 2 diesel on B100.

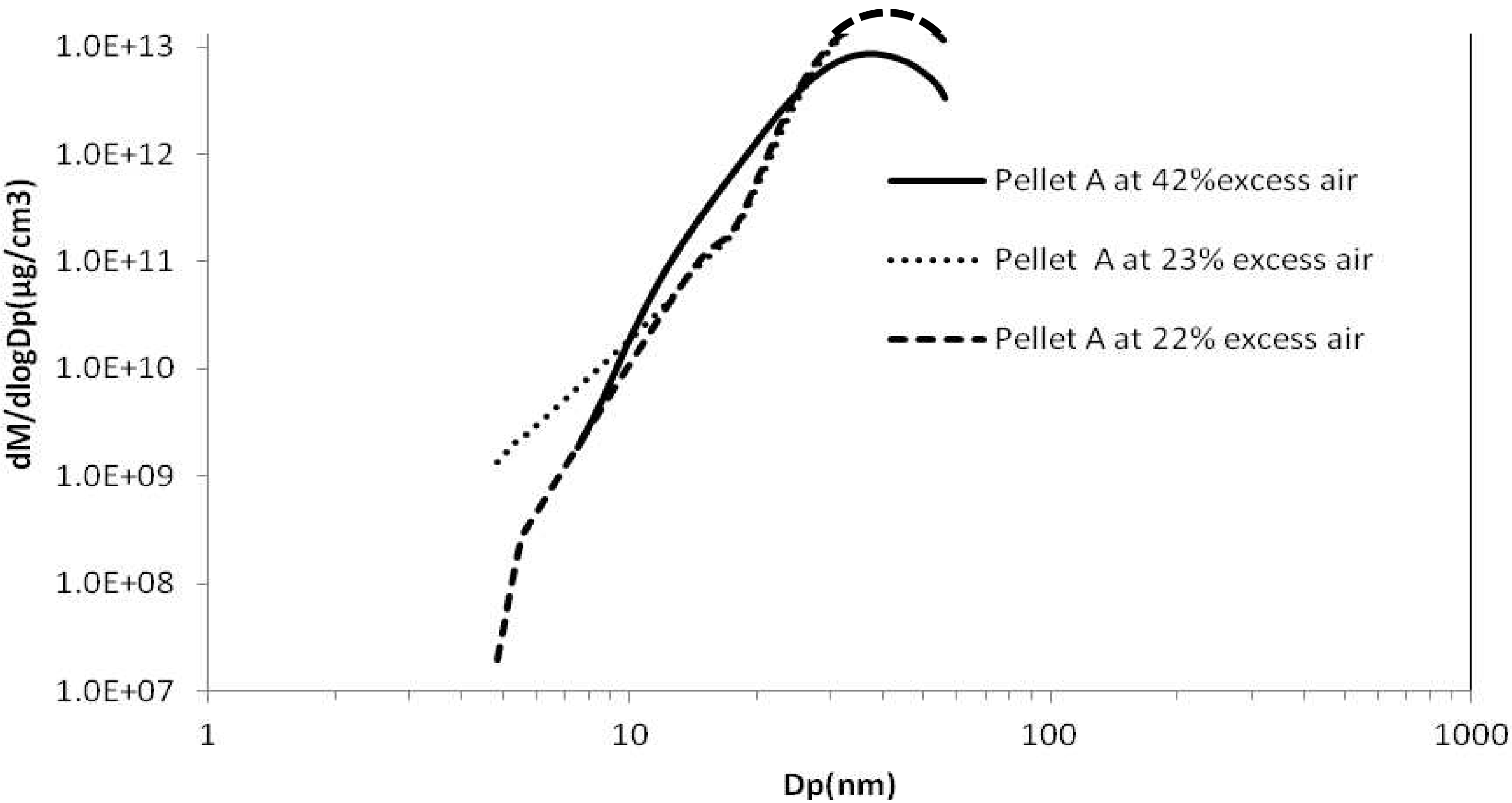
The problem with PM legislation by mass is that the health hazards are associated with PM <~30nm where there is little mass and little carbon. Are organic aerosols a health hazard?



Particle mass distribution as a function of size of particle for pellets A and fuel oil with a comparison with a Euro 2 diesel operated on rape seed oil.

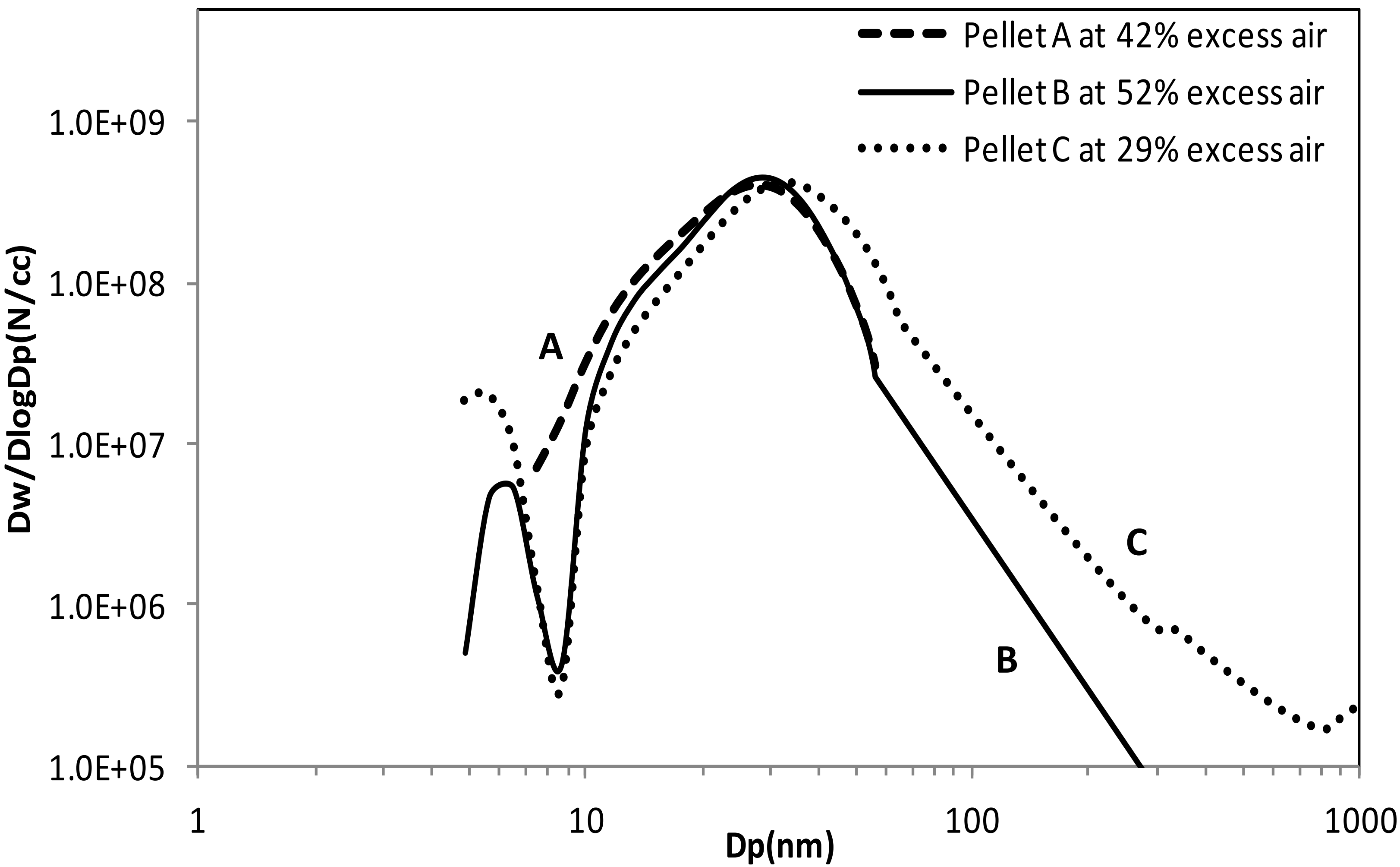


Influence of excess air on particle number size distribution for Pellets A. Mean size and number increases as excess air is reduced.

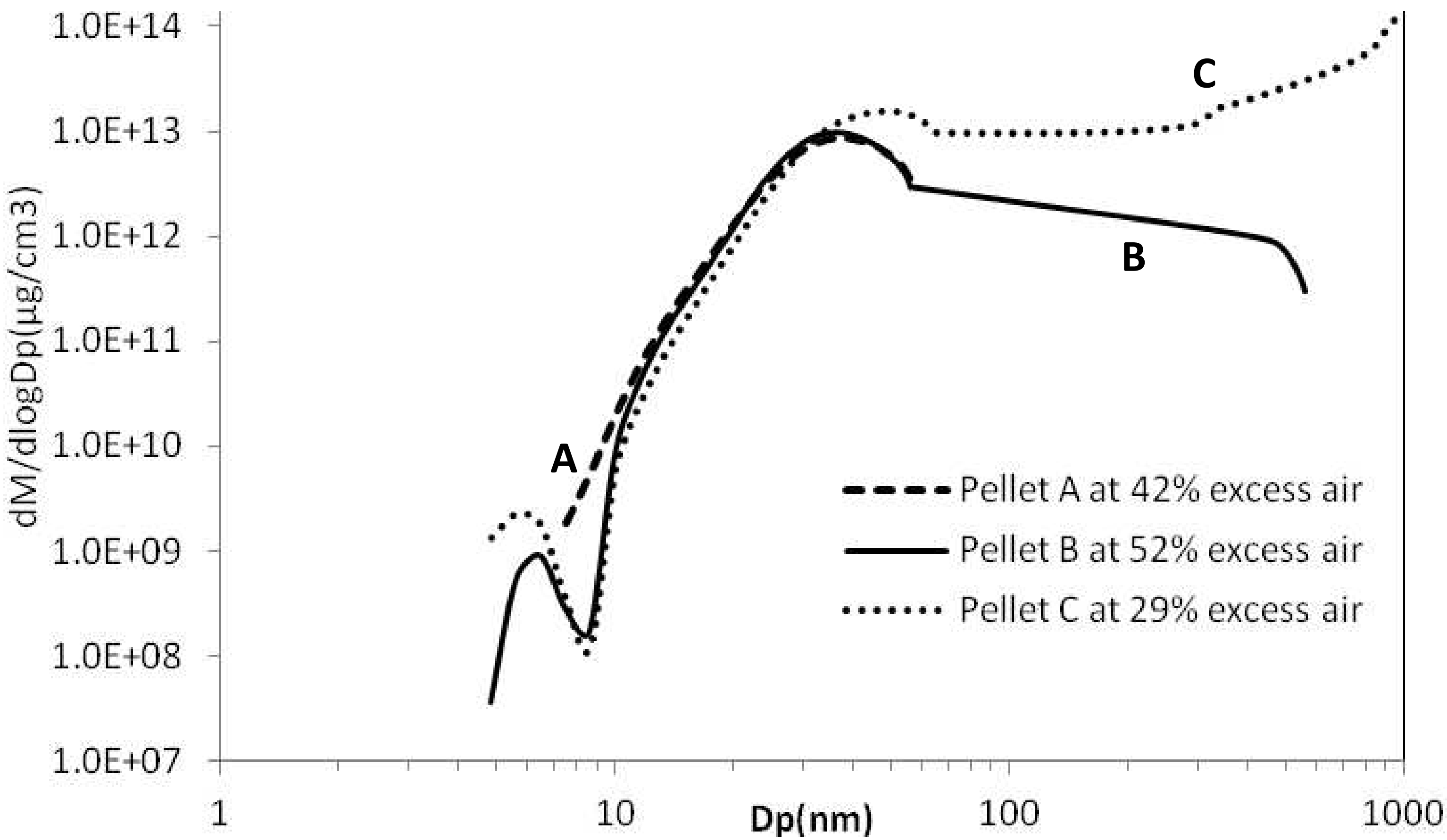


Influence of excess air on particle mass size distribution for Pellets A for two excess airs and a repeat test which shows good repeatability.

Size number distribution for three pellets at the same air flow



Size mass distribution for three pellets at the same air flow



Comparison of the present work with literature particle size

Author(s)	Biomass Boiler Size kW	Size for peak number	Peak number /cm^3
Nussbaumer & Lauber		160 nm	8×10^7
Migliavacci et al.		150 nm	1.55×10^7
Bologna et al.		60 nm	5×10^7
Michel et al.	50 kW Water	65 nm raw biomass 55nm torrefied	$3.1 – 3.7 \times 10^8$ $3.2 – 4.4 \times 10^8$
Present work	250 kW Air	30nm	5×10^8

The present results were for a larger heater than in the other work and was for an air heater whereas the others were water heaters, with a lower flue gas temperature than the 350°C of the present work.
The present work had the smallest particle size and the lower number In the other work was due to their higher size range but higher mass.

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Conclusions

1. The composition of biomass wood pellets is extremely variable and this leads to variability in the stoichiometric A/F ratio.
2. The biomass heater was optimised for excess air on pellet A at 42% excess air and at this air flow and pellet feed rate the excess air varied between 29 and 57% for other pellet compositions. This had a strong influence on emissions, particularly NOx and PM.
3. The 250 kW pellet burner had high CO, PM and C emissions with 24% excess air compared with much lower values at the optimum thermal efficiency and low CO 42% excess air.
4. The gaseous emissions were strongly dependent on the excess air and NOx emissions were strongly influenced by the pellet N composition. The EU regs. were easily met with the correct excess air.
5. With adequate levels of excess air the particulate mass emissions for three pellets ranged from 23 – 40 mg/m^3, or 8 – 15 g/GJ which were similar to published measurements from modern pellet water heaters and well below the 30 g.GJ EU regulation for small heating equipment.
6. The particle size distribution on a number basis showed the peak number occurred in the nano-particle size range at 30nm. This is significantly smaller than the 60 – 160 nm range reported for pellet fired water heaters. As a consequence the peak number was higher in the present work at 5 x 10^8 /cm^3 compared with 0.5 – 1.5 x 10^8/cm^3 found for pellet water heaters.
7. The gas oil heater could be replaced with the biomass heater with no adverse environmental concerns, provided oxygen feedback control was used to keep the excess air at the optimum level of 40-45%.