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PARTICULATE EMISSIONS FROM A 350 kW WOOD PELLET HEATER.

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ABSTRACT

The particulate mass and size distribution was investigated for a biomass wood-pellet air heater with a direct comparison with an equivalent oil-fired burner using the same cross-flow air heater system. Five wood pellet fuels were investigated from different sources and the influence on particle mass and size distribution was determined. The influence of burner excess air on gaseous and particulate emissions was determined. The optimum excess air for minimum emissions and maximum thermal efficiency for the pellet burner was higher at 42% than for the oil burner at 23%. The thermal efficiency of the pellet heater was determined to be slightly less than that of the oil heater. The main reason for this was operation of the heater at higher excess air levels with pellets. The hydrocarbon and particulate carbon fraction emissions were lower for the pellet burner but the CO and NOx emissions were higher. Composition differences between different pellet manufacturers, due to the use of different wood sources, were significant and this produced significant variation in the stoichiometric A/F, which without oxygen feedback control, resulted in different excess air levels for the same pellet feed rate. This resulted in a significant influence of pellet composition on emissions due to excess air variations. Particulate mass and number emissions were low for the biomass pellet burner and similar to the oil burner, provided both burners were at their optimum excess air operational condition. Particulate emissions increased dramatically if the excess air was reduced to 23%.

1. INTRODUCTION

Biomass is an important source of renewable energy both in terms of renewable electricity and renewable heat. This work is concerned with renewable heat applications of biomass [1] as this is the most effective use of biomass with thermal efficiencies >75% available, which cannot be achieved in transport or electricity production at present. In the UK heat is 42% of final energy demand. Direct combustion of biomass for heat offers the least upstream CO_2 emissions with minimal processing costs and similar transport costs as other biofuels. This is because there is no chemical transformation of the biofuel involved. The present work involves the use of biomass wood pellets, formed by drying the pulverised wood and then compressing it to form pellets. It is the most common form of biomass used for renewable heat. All the pellets used were manufactured in the Yorkshire area of the UK.

Most biomass fuels contain very low levels of sulphur and produce significantly lower NOx than coal, thus reducing harmful acidic pollutants and also reducing corrosion and fouling within heat exchangers [1-3]. Biomass fuels emit significantly lower amounts of soot and PAH (polyaromatic hydrocarbons) than most fossil fuels [4]. PAH can be created naturally but they are also produced in-situ during combustion [5, 6]. In spite of these demonstrated advantages of biomass combustion there are many reports [4-8] of concern for the environmental impacts of biomass combustion, especially in regards to particulate emissions. Particulate emissions are a health hazard primarily due to the impact of ultrafine (<100nm) particles on lung function and heart related diseases, due to the reduced oxygen absorbed into the blood with inflamed alveolar regions in the lungs [9]. There are 1% of extra deaths for each $10\mu g/m^3$ increase in PM_{10} emissions in the atmosphere [9] There has been relatively little published work on ultra-fine particulate emissions from biomass combustion for heat applilcations and this is the main theme of this work. Two identical air heaters, in terms of their thermal power, for use in industrial process heating were compared using the original oil fired burner in one heater and a new pellet fired heater in an identical air heater.

2. EXPERIMENTAL METHODS

2.1 Air Heater Burners

The wood-pellet heater and its oil equivalent used the same design of cross-fired air heaters. The oil heater used Nuway NOL-13 burners for light distillate oil (Class D) rated at 350KW full power, with lower powers achieved by reducing the fuel flow rate. The wood pellet burner was a TermoCabi SPL, rated at 150 to 350kW with a 304mm diameter hot gas outlet on the centre line of the heater. The distance from the bottom of the pellet bed to the centreline of the 204mm outlet was 286mm, giving a maximum pellet bed depth of 52mm. The air supply to the pellet bed was split into two with the primary air producing gasification of the pellets and the secondary or overfire air completing the combustion inside the air heater combustor. The pellets were screw fed from a hopper and dropped from the top of the burner (over-fed burner) through the combustion gases into the combustion bed. Both burners had an exit on the centreline of a cylindrical combustor of 0.5m diameter which exited through a 180° bend into a tubular heat exchanger and then into a flue where the emissions were sampled. The air flow to be heated flowed over the external skin of the 0.5m combustor and through the tubular heat exchanger and then emerged as process heat, which was used for accelerated concreate setting in moulds for the production of roadside drainage pipes and related inlets and gulleys. This was one of 20 units at that site and the company had 8 other sites in the UK and also operated worldwide. The pellet burner did not have oxygen feedback control to keep the excess air constant irrespective of the pellet fuel composition, nor did the oil fired heater. This will be shown later to be a problem in the operation of the pellet burner.

The oil burner was a conventional circular baffle burner with a central pressure jet swirl atomiser which produced a fan shaped spray that was injected into the recirculating air flow around the baffle. The flame could be visually observed from a window on the centreline of the burner and was yellow, indicating mixing controlled combustion with soot formation in the locally rich regions of the flame. The pellet burner flame was also yellow indicating soot formation was occurring. The oil and biomass burners were compared at the same thermal input of 250 kW.

2.2 Wood Pellet Types

Five different sources of wood pellets were compared, which were representative of those in the UK market. Pellets A were produced from 100% sustainable forest wood and were manufactured at the forest site and had little upstream transport CO_2. The pellets had good binding properties and did not break up easily and they had a uniform light golden colour. Pellets type B were manufactured from virgin timber processing waste and wood residues from a furniture manufacturer. These pellets like pellet sample A were well bound and did not break up easily, they also had a uniform light golden colour. Pellet samples 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. The second sample was taken from a different manufacturing feed and looked different from the first and was much less friable and had an even colour. Finally Pellet sample E was manufactured from the stone seed waste from the olive oil industry. Not all the different wood pellets were used on the pellet heater, but the composition analysis is included to show the significant variability in pellet composition.

2.3 Thermal Efficiency
Thermal efficiency was determined by measuring the energy rejected in the flue gases as a ratio of the energy in the fuel. The rejected flue gas energy included the chemical energy of CO and HC emissions. The thermal loss requires the measurement of the mean exhaust temperature together with the exhaust mass flow rate. The exhaust flow rate could not be determined from the flue gas flow measurements as the pitot tube pressure was too low to measure accurately. Instead the air/fuel ratio was determined by carbon balance from the exhaust gas composition. The fuel mass feed rate was calibrated as a function of the rotary feeder speed. The A/F and fuel mass flow determination enabled the air flow to be computed and the sum of the fuel and air feed rates gave the exhaust mass flow rate.

The mass flow rate for the combusting biomass fuel was measured by the weight of pellets delivered over a 2 minute period at a given power setting, while the burner was at steady state. The flow rate for the oil burner was recorded by a turbine total flow meter calibrated using the time to pass one litre of fuel into a measuring container. All the tests used the same batch of fuel oil.

The pellet elemental composition was determined and the HCO composition of the fuel was expressed as CH_yO_z where y is the H/C ratio and z the O/C ratio. The CH_yO_z composition was used to determine the stoichiometric

A/F by mass. Comparison with the A/F computed from a carbon balance on the exhaust gas composition enabled the equivalence ratio, Ø to be determined and this was checked against the measured excess oxygen. A Parr bomb calorimeter was used for the determination of pellet Calorific value (CV).

2.4 Elemental analysis

The elemental analysis was carried out in a Flash 1112 series Thermo-quest analyser. The method first reduces the size of the particles in the sample by milling. This has to be done as only approximately 3g are required for the method and this must be representative of the mean particle composition. The elemental analysis was carried out on a dry basis with the milled sample put into an oven for 2 hours at $150^{o}C$ prior to the analysis.

2.5 Thermal Gravimetric Analysis(TGA) analysis

The proximate analysis of the samples determines the water content, volatile matter, fixed carbon (non-volatile carbon) and ash content. The analyser used was a TGA-50 Shimadzu thermo gravimetric analyser with a TA60WS processor. The main process for the analysis is the heating of water at $100^{o}C$ in an inert atmosphere of nitrogen for 10 minutes. Then the temperature is increased to $900^{o}C$ at a uniform heating rate of $25^{o}C/min$ to volatilise any organic compounds. The nitrogen was then switched to oxygen and the fixed carbon content was oxidised and the remaining weight was ash. The same procedure was also used for analysing the composition of the particulate matter collected on the filter paper from the flue gases. This enabled the carbon, volatile and ash particulate emissions to be determined.

2.6 Flue gas analysis

A Temet Gasmet CR-2000 Fourier Transform Infrared (FTIR), an MCERTs UK approved emissions measurement instrument, was used to measure the emissions [10]. In this work, the FTIR was used to measure the CO as part of the determination of the optimum excess air. The speciation the emissions will be reported separately. The outlet from the analyser was passed through a water condenser to a Servomex paramagnetic oxygen analyser, from which the excess air of the combustion process was calculated.

2.7 Determination of the Particulate Mass

The particle mass was determined from a direct flue gas sample with the sample passed through heated lines at $180^{o}C$ into an SAE smoke meter. The hot sample was cooled in an oven to $50^{o}C$, which is sufficient to prevent water condensation but allows hydrocarbon vapour condensation onto the particle mass. The filter paper holder was also heated to $50^{o}C$ with separate temperature control to that of the oven. The gas sample was then passed through a pre-weighed Whatmann GF/F glass fibre filter and the total flow was measured using a certified positive displacement gas meter. The increase in filter mass was measured and this was divided by the total sample volume to produce particulate mass emissions in g/m^{3}. The filters were weighed to $10\mu g$ accuracy before and after the tests and the particulate mass on the filter was always in the range 1-5mg so that the weighing accuracy was at least 2% for 1mg and 0.4% for 5mg. The sample volume varied between 50 and 200 litres and the sample flow rate was 5 L/min giving a sample time from 10 minutes to 40 minutes. The longer sample time was necessary for low particle mass emissions.

2.8 Determination of particulate size distribution.

The Cambustion DMS500 (Differential Mobility Spectrometer) [11] was used to measure the distribution of particle number from 10nm to 500nm. A heated sample line was used to connect the instrument to the flue with a separate sample point to that for gas analysis, which enabled simultaneous particle size and gas composition measurements to be taken. The sample inlet line of the instrument was heated to prevent condensation of HC and water. The sample was diluted with ambient air at Dilution ratio: 10:1, which prevents particle agglomeration in the sampling system and prevents water vapour condensation whilst ensuring condensation of high MW hydrocarbons.

3. RESULTS AND DISCUSSIONS

3.1 Pellet Properties

3.1.1 Elemental Analysis

The elemental analysis for the five pellet samples is shown in Table 1. The fuel compositions in terms of $CH_yO_zN_w$ are summarized in Table 2, where y, z and w are the molar ratios of H/C, O/C and N/C respectively.

The Stoichiometric A/F by mass derived from the $CH_yO_zN_w$ composition is shown in Table 3. The stoichiometric A/F on a dry ash free basis may be converted to a stoichiometric A/F on an actual fuel mass basis using the TGA analysis for water (w% by mass) and ash (a% by mass), the results are shown in Table 3. The results for the water, volatile, carbon and ash proximate analysis by TGA are shown in Table 4.

Table 1 Pellet Elemental Composition % on a Dry Ash Free Basis (daf) plus the Water and Ash by TGA

Pellet type	C	H	O	N	S	Water	Ash
A	47.91	5.75	37.0	1.42	0	4.64	3.26
B	48.61	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	46.07	4.35	39.90	0.38	0.15	6.72	2.43
E	46. 72	6.16	34.81	5.36	0.03	6.92	7.79

Table 2 Chemical formulae on the basis of $CH_yO_zN_w$ on a fly ash free basis (daf)

Element	A	B	C	D	E
Carbon c	1	1	1	1	1
Hydrogen y	1.44	1.45	1.28	1.13	1.58
Oxygen z	0.70	0.68	0.79	0.80	0.66
Nitrogen w	0.025	0.022	0.009	0.006	0.09
S				0.001	0.0002

Table 3 Stoichiometric A/F by mass on a dry ash free basis and on an actual fuel mass basis

Pellet	A/F daf	A/F actual including water and ash	% difference in 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

Table 4 Water, volatile and ash content of pellets by TGA

Pellet	A	B	C	D	E
Water%	4.64	5.95	4.91	6.72	6.92
VOC%	85.45	83. 08	73.84	85.49	79.26
Fixed Carbon%	6.65	6.46	8.26	5.36	6.02
Ash%	3.26	4.52	13.0	2.43	7.79
Water& Ash%	7.9	10.46	17.91	9.15	14.71

The differences of the actual A/F from the A/F_{daf} are large due to the difference in ash content between pellet sources. The differences due to pellet composition in stoichiometric A/F on a daf basis are also considerable as shown in Table 3, which has a 21% variation in stoichiometric A/F between the highest and lowest A/F, which increases to 38.4% when the variations in water and ash content are taken into account. This is a problem for the operation of combustion systems on solid biofuels, as the thermal efficiency and emissions are a strong function of the excess air. Without oxygen feedback control, adequate excess air control cannot be achieved, as it is impossible to analyse the biomass composition on line. In reality the situation could be worse as the range of composition of wood around the world gives a range of stoichiometric A/F daf from 3.8 to 8 [12]

In the present work there was no oxygen feedback control and the optimum burner fan and fuelling settings were determined for pellets A. Then this fuelling and air was left constant and the other pellets tested. There was a significant variation in the resultant excess air (derived from the measured excess oxygen). The optimum for pellets A was 44% excess air, but at the same burner settings the pellets C operated at 29% excess air

3.1.2   Calorific Value Results
The gross calorific values (HHV) for all the pellet samples are shown in Table 5, which shows that there were only small differences in the gross CV for the pellets tested. The ratio of the highest to lowest CV was 1.062. The latent heat of vaporisation of water produced in the products of combustion may be calculated from the elemental compositions in Table 2 and the results are shown in Table 5. The net CV (LHV) can then be

calculated from the Gross CV and this is shown in Table 5. This is the more commonly quoted value for the CV of wood fuels. The CV expressed as MJ per kg of stoichiometric air is also given in Table 5 and this illustrate why the heat output of the biomass heater can be controlled solely by the fan air flow, provided there are pellets in the base of the burner. The pellet burner is effectively a batch combustion system with the quantity of pellets topped up periodically by the screw feed. There is no attempt to continuously keep the air and fuel flow rates in proportion as in the oil burner. The result of this is a fluctuating CO output as pellets are added and then consumed at constant air flow.

Table 5 Gross Calorific Value in MJ/kg fuel

Fuel	Gross CV MJ/Kg $_{fuel}$	A/F daf	Gross CV MJ/Kg air	Latent heat MJ/Kg fuel	Net CV MJ/Kg fuel	Net CV MJ/Kg air
A	19.42	5.52	3.52	1.17	18.25	3.31
B	19.16	5.66	3.39	1.19	17.95	3.17
C	18.28	4.95	3.69	0.99	17.29	3.49
D	19.10	4.68	4.08	0.86	18.24	3.90
E	20.83	5.56	3.75	1.31	19.52	3.51
Oil	45.4	14.6	3.11	2.8	42.6	2.92

3.2 Excess Air Optimisation for Pellets A

The thermal efficiency of combustion heating equipment is strongly dependent on the excess air or equivalence ratio. Increasing excess air for the same thermal input increases the flue gas mass flow rate and this increases the flue gas thermal loss for the same flue gas temperature. However, the chemical losses in terms of the unreleased energy content of CO, HC and carbon emissions decrease as excess air is increased. Air fan pumping power losses also increases as excess air is increased. The net result is that the optimum thermal efficiency has to be determined experimentally. This was done for Type A Pellets, and took several days due to the time to establish steady state long enough to sample the particulates on a filter paper and to average the CO emissions. For this reason this exercise was carried out on only one pellet type and the other pellets were then tested at this air flow condition. This excess air optimisation was carried out at 270kW gross thermal input, which was held constant as the air flow was varied. This was 77% of the maximum thermal power of the oil and pellet heaters.

Figure 1 shows that the optimum thermal inefficiency was for 44% excess air which is 9% excess oxygen (λ=1.44 and $\varnothing$=0.69) for pellets A. The minimum thermal inefficiency in Fig. 1 coincided with the end of the reduction of CO as the excess air was increased. A CO of 200ppm is approximately 1% combustion and thermal inefficiency. This indicates that the optimum thermal efficiency excess air was controlled by the CO emissions. This was also found by Nussbaumer and Lauber [7] who on a CO basis only determined the optimum excess air for minimum CO (100ppm) to be 55% (λ=1.55) for a pellet water heater. Kelz et al. [6] investigated a modern pellet water heater that was set up to operate at 12.5% excess oxygen (60% excess air or λ=1.6), which is much leaner than the optimum found in the present work but similar to that used by Nussbaumer and Lauber [7]. Figure 1 shows a thermal efficiency penalty of 1.5% if operation at 60% excess air was used, with little CO benefit.

Fig. 1 shows that the optimum gross thermal efficiency at 44% excess air was 75.6%, which is reduced to 74.2% if the carbon in ash energy loss is taken into account. The thermal efficiency of pellet water heating boilers is more commonly expressed in terms of the net (LHV) thermal efficiency and on this basis the optimum thermal efficiency was 80.4% or 79.0% including the carbon in ash energy loss. Fantozzi et al. [13] have reported a measured thermal efficiency of a modern pellet 7.4kW water heater of 82.9% on a LHV basis. This is a little higher than in the present work for an air heater, due to better heat transfer in the flue gas/water heat exchanger which resulted in lower flue gas temperatures in the water heater tests of 169°C compared with 307°C for pellet A at 43% excess air.
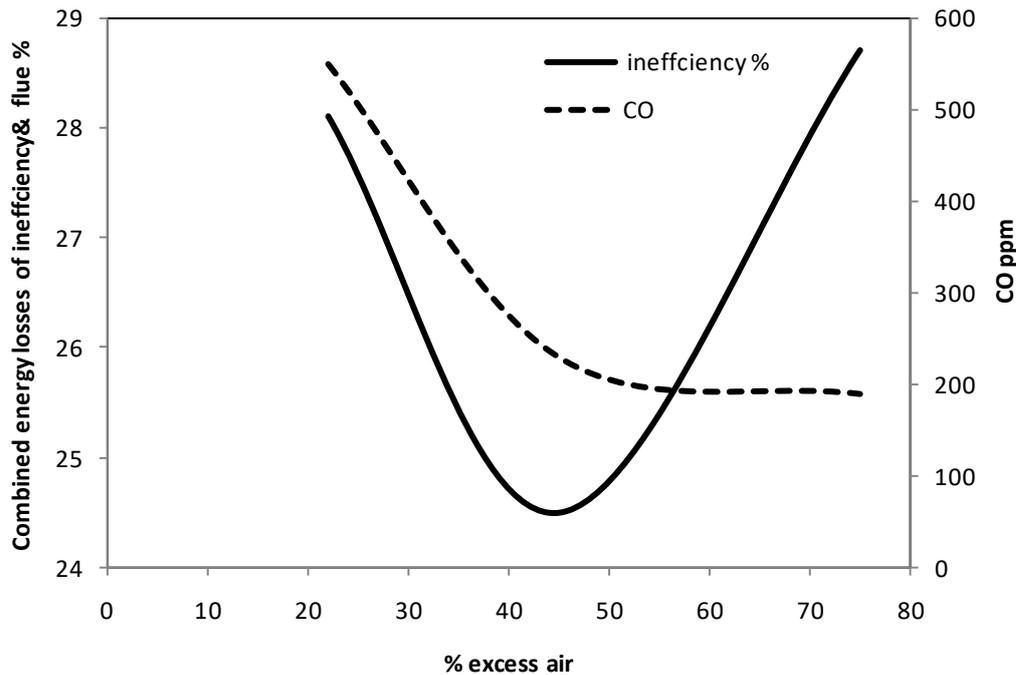
Figure 1. Variation of gross (HHV) thermal inefficiency and CO with excess air derived from the oxygen analysis for Pellets A.

3.3 Influence of Pellet Composition on Gaseous Emissions and Thermal Efficiency at Constant Air Flow

The optimum condition for Pellet A in Fig.1 was 42% excess air and at these optimum air and fuel flow rates the other pellets were tested. The results are summarised in Table 6 which also includes emissions data for three excess air levels for Pellets A. Table 6 shows that with the burner settings unaltered for 42% excess air on pellets A , pellets B operated at 57% excess air, but pellets C operated at 29% excess air and pellets E 39% excess air. Pellets C with much less excess air had higher CO and HC. Pellets B with 57% excess air operated with lower CO and HC.

Table 6 Gaseous Emissions and Thermal Efficiency and Excess Air for Different Pellets

Pellet	Excess Air %	Net Thermal Eff. %	Fuel N %	Stoich A.F daf	Actual A/F Stoich	CO ppm	HC ppm	NOx ppm	NOx mg/Nm^3	NOx g/kg	NOx g/GJ
A	24	76.5	1.42	5.52	5.08	1079	220				
A	42	80.4	1.42	5.52	5.08	163	45	106	219	1.5	77
A	75	76.0	1.42	5.52	5.08	108	50	267	385	4.1	228
B	57	79.5	1.23	5.66	5.06	53	41	214	445	3.4	176
C	29		0.52	4.95	3.67	260	56	110	228	1.3	71
E	39		0.36	5.56	4.74	114	32	116	253	1.6	76
Gas Oil	23	82.0	0.01	14.6	14.6	14	67	81	170	2.5	55

The NOx emissions for pellets A showed an increase in NOx as excess air was increased, which is a characteristic of the rich/lean operation of staged combustion in biomass burners. Linda and Johanssona [15] showed found that PM emisisons for a range of biomass boilers was 80 g/GJ for excess air from 70 to 400%. This is very similar to the present results in Table 6, which are all slightly lower particle matter. Michel et al. [16] also found that NOx increased with increase in secondary air for raw and torrefied wood pellets, both with low fuel bound nitrogen (FBN). The NOx levels for the highest secondary air were 113 mg/m^3 for the torrefied pellets and 252 mg/m^3 for the raw pellets. These are very similar values for raw biomass as in Table 6.

Also with a high fuel bound N content of 1.42% there was a high FBN generated NOx with the lean overall combustion. The NOx at the 75% excess air condition exceed the European standard for biomass thermal heat of 150 g/GJ, but easily met the standard at the optimum 42% excess air. Pellets B that operated with more excess air also had high NOx due to the high FBN and exceeded the NOx standard. Pellets C and E with lower excess

air and low FBN both had low NOx that easily met the NOx standard. However, the FBN content of the biofuels tested resulted in an increase in NOx relative to the gas oil burner. The only way that the emissions could be controlled for each pellet composition is to have oxygen feedback control so that the fuel feed rate is adjusted to give the same excess air. This will then control NOx and CO emissions.

4. **Particulate Emissions**

4.1 Filter Paper Particulate Mass

The filter paper gravimetric particulate mass (PM) emissions for the fuel oil and pellet fuels are presented in Table 7 in mg/m^3 and g/kg of fuel (EI) units. The emissions of PM were extremely high (400 mg/m^3) for the oil burner before the fuel injector was cleaned, due to bad fuel and air mixing in the spray from the effect of injector deposits on the spray. However, after the injector was cleaned the particulate mass was very low. Pellets A combustion flue gas was sampled at two excess air levels of 24% for direct comparison with the fuel oil PM and then at the optimum thermal efficiency condition of 42% excess air. Table 7 shows that the influence of excess air on PM for pellets A was high with a doubling of the PM mass emissions at 24% excess air. This filter paper was observed to be black compared with light brown at 42% excess air. At 42% excess air the PM mass was greater than the cleaned injector fuel oil PM by a factor of about 3. The European standard for PM mass emissions for biomass thermal heat applications is 30 g/GJ and all the present results are well below this standard, even for pellets A at 24% excess air. Pellets C operating with 29% excess air had very low particulate emissions. It will be shown below that ash was the dominant constituent of the PM for pellets and it is possible that the ash retention in the air heater was different between the pellets and this contributed to lower PM emissions.

Table 7 shows that if the PM emissions are converted into an emission index (EI), then the pellets B and E had very similar PM EI to fuel oil and only Pellet A had higher emissions than fuel oil (by only 50%). Pellet C had lower PM EI than for fuel oil. It should be recognised that all the PM emissions in Table 7 are very low, apart from the initial fuel oil results. For comparison a diesel engine that meets Euro 4 PM legislation has an EI of about <1 g/kg and Euro 6 legislation requires about <0.1 g/kg. Thus the emissions in Table 6 are equivalent to a modern clean diesel engine without the use of flue gas filtration that is used in diesel engines at Euro 6 PM levels.

Table 7 Particulate filter paper mass measurements

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

Table 8 Particulate Composition by TGA

Fuel type	Excess air %	HC volatiles %	Soot %	Ash %	Soot mg/m^3
Oil	22	20	80	0	9.6
A	24	20	80	0	68
A	42	20.3	1.5	78.2	0.6

Table 8 shows the TGA derived composition of the particulates for pellets A and gas oil. This shows that the composition of the black filter papers at an excess air of 24% was very different, consisting of 80% soot and the soot emissions were about 7 times those for fuel oil. At 42% excess air the filter paper was a light brown colour and the exhaust was visibly clear of black particles. The TGA analysis in Table 8 shows that the carbon was now only 1.5% of the PM mass with volatile HC comprising 20.3% of the mass with a very large ash contribution to the PM mass. The soot or carbon emissions were now only 6% of those for fuel oil. Thus the use of pellets with the correct excess air will produce a major reduction in soot emissions relative to those for fuel oil. All the other pellets filter papers had a similar light brown colour and a composition similar to that of Pellet A with 44% excess air. This shows the importance of controlling the excess air in pellet heaters using oxygen feedback to control the fuel flow rate. The bad reputation that pellets boilers have for emissions is likely to be

associated with the poor burner control of excess air for different pellet compositions. The EU PM regulations for thermal heat have a measurement method that uses a quartz filter in an oven at $190^{o}C$ compared with $50^{o}C$ in the present work. The effect of this is to only measure solid particulate emissions, whereas the present measurements are for total particulate emissions. The present work shows that the total PM emissions are lower than the EU standards and this means that the solid emissions are much lower and dominated by ash, as shown in Table 8.

The present pellet burner PM emissions of 23-40 mg/m^3 or $0.14 - 0.3$ g/kg_{fuel} or $7.7 - 15.4$ g/GJ compare well with measurements in the literature. Kelk et al. [6] reported a modern pellet boiler operated with 12.6% O_2 (66% excess air) had PM emissions of 6.1 g/GJ and if a typical CV for the pellets of 18 MJ/kg is used then this converts to an EI of 0.11 g/kg, which is slightly lower than the present lowest PM measurement. Nussbaumer and Lauber [7] for a pellet water heater with $\lambda=1.55$ found filter papers were light brown, as in the present work, and they measure PM mass emissions at 30 mg/m^3, which is in very good agreement with the present work. They also reported black filters for $\lambda=1.2$ with 50 mg/m^3. Michel et al. [16] found that for thermal powers 30 – 50 kW the PM emissions were between 180 and 120 mg/Nm^3 for raw biomass and between 100 and 40 mg/Nm^3 for torrefied biomass. The present results for a larger biomass burner are less than these measurements and much lower for the raw biomass. It may be concluded that the present PM mass emissions are typical of those from modern pellet burners. Linda and Johansson [15] surveyed a range of biomass combustion equipment and reported PM emissions for pellet burners from $62 - 180$ mg/m^3 and the present measurements are well below this range, representing combustion advances since their survey in about 2003. However, they did show that older biomass combustion system were much worse for PM emissions. For modern biomass burners, whether pellet, chip or log, the PM emissions were all within the above range.

4.2 Particle number and mass Size Distribution

The particle number size distribution for Pellets A with 44% excess air is shown in Fig. 2 where it is compared with the equivalent number size distribution for the fuel oil fired heater and for a Euro 2 6 cylinder 6L TCIC diesel engine that was operated on 100% rape seed oil [14]. The peak of the number distribution occurred at 25nm size for the pellets A and this was not strongly influenced by the excess air. The peak number was 5 x 10^8 and this was higher than for the fuel oil burner, but this had a peak number at 100nm, indicating more particle coagulation. The diesel engine had a typical diesel size distribution with a peak number at 50nm. The equivalent mass distribution, assuming spherical particles of density 1200 kg/m^3 is shown in Fig. 3. This shows that there is very little mass in the ultra fine particle region. Also the particle size with the largest mass is at a higher size of 40nm for Pellets A. Fig. 3 shows that the pellet particles have higher mass in the smallest size range and lower mass in the 100nm region than for fuel oil and for the diesel operated on rape seed oil. It is clear that the biomass pellet particles do not coagulate as fast as diesel or fuel oil particles do. This is likely to be due to their composition differences, with the particles of fuel oil and diesel engines being predominantly carbon and those of the biomass pellets being predominantly ash.
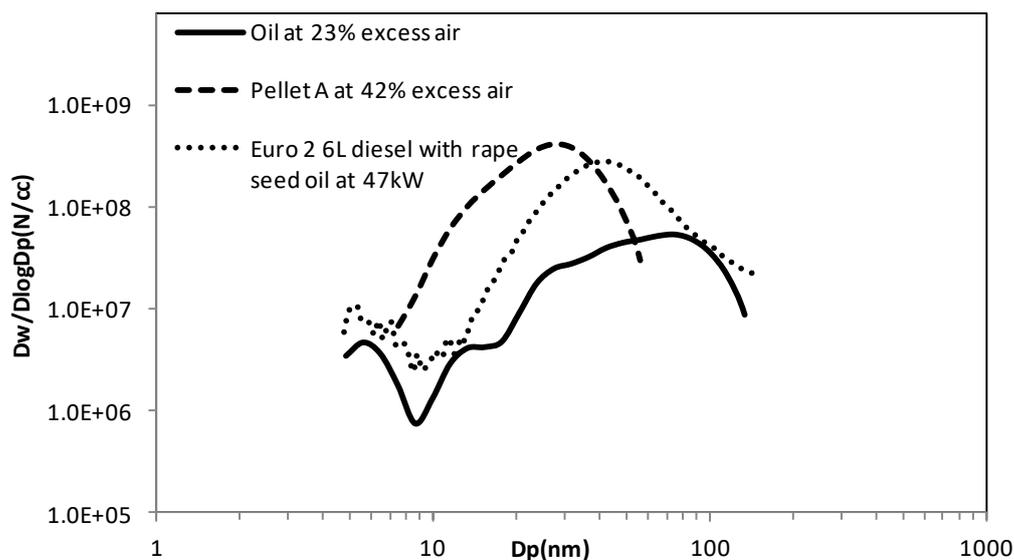
Figure 2. Particle number distrbution as a function of size for pellets A and fuel oil with a comparision with a Euro 2 diesel operated on rape seed oil

Fig. 3 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.

Fig. 4 shows the influence of excess air on the particle size distribution for Pellets A. The repeatability of the results for an excess air of 22% is shown with near identical size distributions for measurements on different days. The results for low excess air, where the particle mass was high and mainly carbon had a higher number of particles but with a similar size distribution to that with 42% excess air, where the thermal efficiency was at an optimum. The number of particles in the largest size was lower at 42% excess air than 22% excess air, but the number in the ultrafine range was a little higher. The influence of excess air on the particle mass size distribution is shown in Fig. 5. This shows that the low number of particles above 100nm have significant mass, particularly for low excess air. Thus the large increase in total particle mass with low excess air is mainly in the large accumulation mode particle size and not in the ultrafine particle size range. This was due to carbon being the predominant composition and it is carbon particles that coagulate readily. The particle size for peak mass increased from 25 nm for 42% excess air to 35nm for 22% excess air. These are still very small particles and would be invisible in the exhaust plume, as shown by photographs of the plume against white clouds.
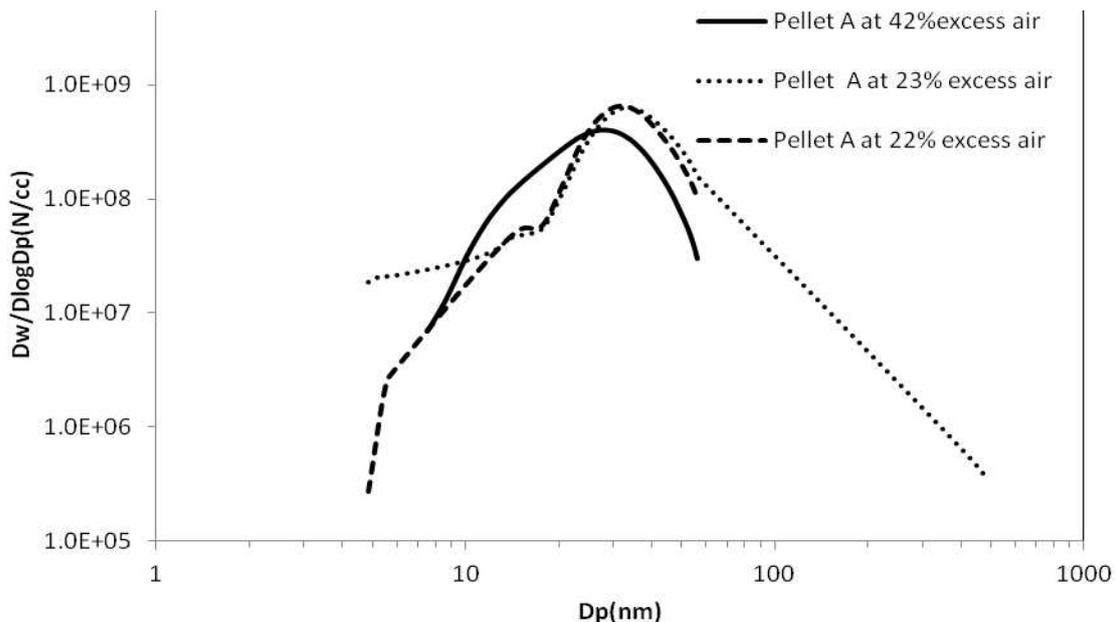
Fig. 4 Influence of excess air on particle number size distribution for Pellets A
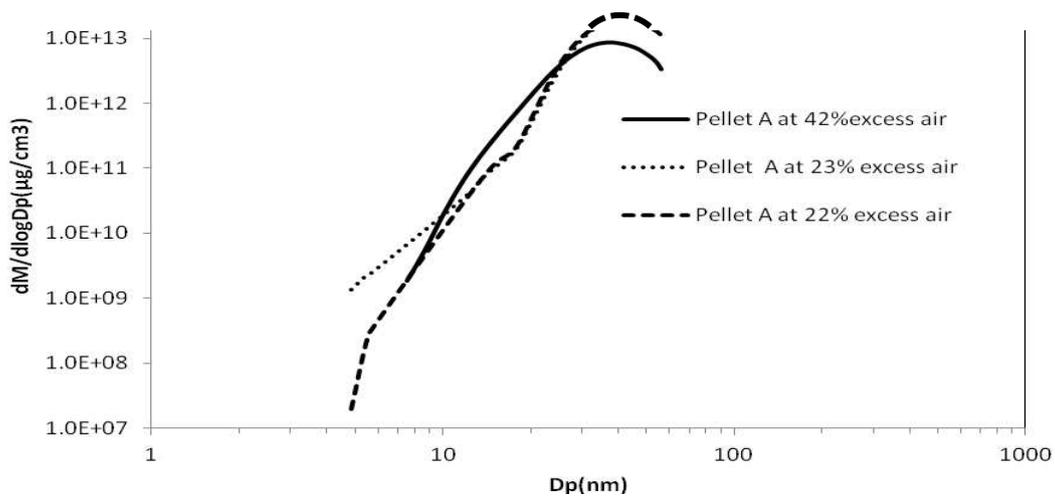
Fig. 5 Influence of excess air on particle mass size distribution for Pellets A

Fig. 6 compares the size distribution for pellets A, B and C. This was carried out at the same air flow and pellet feeder rate as for the optimum thermal efficiency for Pellets A. The changes in excess air were due to changes in the combustion stoichiometric for the different pellet compositions. This shows that the number size distributions were similar with the same size for the peak number of 25nm for pellets A and B and 30nm for pellets C, but the same peak number of 5 x 10^8. Pellet C had a slightly larger peak size and larger numbers for particle >30nm compared with pellets A and B, indicating more coagulation had occurred. This was due to the operation with an excess air of 29% on these pellets compared with 42 and 52% excess air for pellets A and B respectively, this would give carbon as the dominant particle composition and these coagulate more easily than ash particles. Fig. 7 shows that influence of pellet composition on the particle mass size distribution. Pellets A and B were very similar as they have similar excess air. However, pellet C had much higher larger size particle mass due to its much lower excess air and greater soot formation. The small size found in the present work is of potential concern as this is where the greatest health hazard has been found [9]. However, as the present particulate mass emissions are very low, particularly for carbon emissions, this is likely to be a feature of very low particulate emissions biomass heaters, their particle size will be very small.
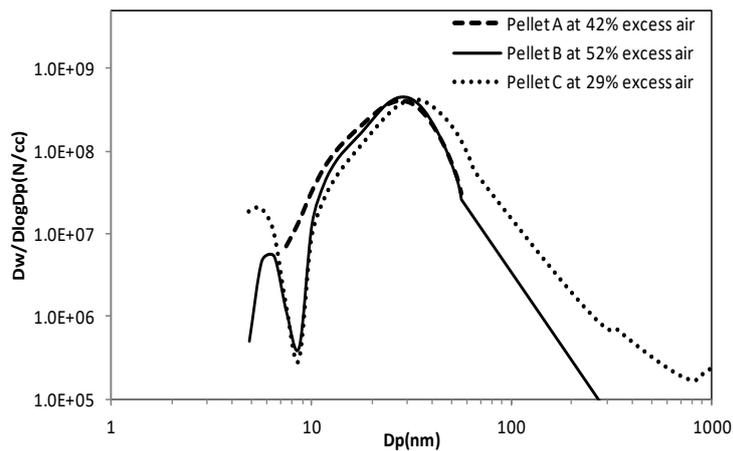
Fig. 6. Particle number as a function of size for pellets A, B& C
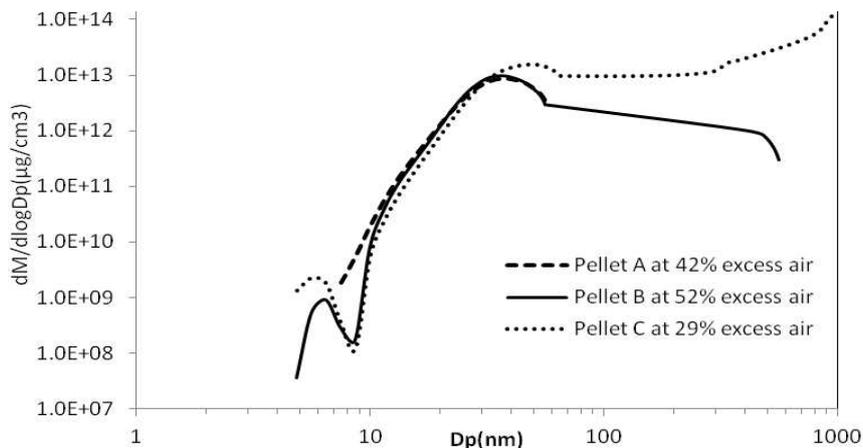
Fig. 7 Particle Mass as a function of size for pellets A, B and C at the same total air flow.

Previous work on particle number size distributions from pellet burners have produced similar results to the present work, the major differences being in the location of the size for the peak number. Migliavacci et al.[8] found a peak number of $1.55 \times 10^8/cm^3$ at 150nm. Nussbaumer and Lauber [7] also found a peak number size of 160nm but had a lower number of 8×10^7. This is a much larger size than in the present work and the lower numbers would be due to particle coagulation. The mass at this larger size would be much greater than in the present work. Bologna et al. [5] found a peak particle number of $5 \times 10^7/cm^3$ at 60nm. This is one tenth of the present peak number but at double the particle size. The reduced number would be due to more particle coagulation and the mass would be similar to the present work as a size difference of a factor of two gives a factor of 8 differences in number for the same total mass. The present air heater pellet boiler operated at higher flue gas temperatures than for pellet water heaters, >300°C compared with about 150°C for water heaters. It is possible that this temperature difference produced a difference in particle coagulation and hence the observed smaller sizes reported here.

Michel et al. [16] determined the particle size distribution for a 50 kW pellet boiler for pellets made from poplar wood and for torrefied poplar pellets. Their results show that the particle size where the peak number of particles occurred was 65 nm for the raw pellets and 55 nm for the torrefied biomass pellets. The peak number of particles was similar for the torrefied biomass at $3.2 – 4.4 \times 10^8/cc$ compared with $3.1 – 3.7 \times 10^8/cc$ for the raw biomass. Comparison with the present size distributions for three pellet compositions in Fig. 6 shows that the present results are very similar to those found by Michel et al. [16] in their 50 kW boiler, which was about 20% of the thermal power of the 270kW operational condition of the present work. The present peak particle size at 30nm was much smaller than in the work of Michel et al. [16] but the peak numbers were similar at $5 \times 10^8/cc$. This would result in a lower particle mass as was shown in the above review of particle mass emissions.

5. Conclusions

1. The composition of biomass wood pellets is extremely variable and this leads to variability in the stocihiometric A/F ratio. A burner optimised for maximum thermal efficiency and minimum emissions on one pellet composition will not operate at this optimum excess air if the pellet composition is changed, without oxygen feedback control of the air flow to maintain the same excess air. This was not available for the commercial boiler used in the present work. 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.

2. A two stage gasification/oxidation pellet heater was investigated at 250kW power and compared with the equivalent gas oil burner for the same heating purpose. It was shown that if the pellet burner was operated with less than the optimum excess air for that pellet composition, then the CO and particulate mass increases and high levels of black soot were generated.

3. The gaseous emissions were strongly dependent on the excess air and NOx emissions were strongly influenced by the pellet N composition, which was high for two of the pellets tested and these had high NOx. The NOx emissions increased with excess air due to the rich/lean operation of the gasification/oxidation combustion. As

the excess air increase the rich zone moved towards stoichiometric and more of the FBN was converted into NO. Also thermal NOx increases with excess air increase in rich/lean burners. For low FBN of <0.6% the NOx emissions were well inside the 2013 EU regulation of 150 g/GJ at 71 – 76 g/GJ. However, these NOx emissions were higher than the 56 g/GJ for gas oil burning, where FBN was <<0.1%. For the two high FBN pellets where FBN was 1.2 – 1.4% the NOx emissions were 77 g/GJ on 42% excess air for the reference pellet which is inside the EU NOx regulations. This increase to 228 g/GJ when the burner was operated with 75% excess air on the same pellets. At the 42% excess air optimum for the reference pellet the second pellets (B) with a high N content operated at 52% excess air and the NOx increased to 176 g/GJ and failed the EU emissions regulations of 150 g/GJ.

4. 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 lower than most in the literature. The 2013 EU standard for particle mass emissions of 30 g/GJ was easily met with no exhaust filtration.

5. The pellet particulate composition was dominated by ash with 20% hydrocarbon volatiles, 78% ash and 1.5% carbon. The carbon emissions were substantially below those of an equivalent fuel oil burner, but the total particle mass was higher than the 12 mg/m^3 of the oil burner. The oil PM was 80% carbon and hence more harmful to the environment.

6. The particle size distribution on a number basis showed the peak number occurred in the nano-particle size range of 25–30nm, depending on the pellet composition. This is significantly smaller than has been reported for pellet fired water heaters where 60 – 160nm have been found. As a consequence the peak number was higher in the present work at 5×10^8 /cm^3 compared with $0.5 – 1.5 \times 10^8$/cm^3 found for pellet water heaters.

7. The pellet burner could be used to replace oil burners for process heat and achieve equivalent performance, apart from higher NOx emissions. Changing the oil burners to pellet burners would give a significant CO_2 benefit.

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