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Submitted by:

Animesh Dutta; PhD, P.Eng
Engineering Department
Nova Scotia Agricultural College
Truro, NS, B2N 5E3, Canada

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EXECUTIVE SUMMARY

The purpose of this study was to investigate the potential of burning grass pellet efficiently and cleanly in an innovative pellet furnace. This study presents steady state test results performed on a prototype pellet furnace with 7-22 kW capacity designed for burning high ash content grass pellet fuels. One grass pellet and three wood pellets (two premium grades and one industrial grade) were tested to compare their combustion and emission performances. The fuels were characterized first by means of higher heating value (HHV), proximate and ultimate analyses. For each pellet type, the furnace was tested at five feed rates. Grass pellets showed very similar performance to that of wood pellets. Maximum overall furnace efficiency with different pellets was obtained as 73-75% based on HHV of fuel under high load operations, although the carbon monoxide (CO) level tended to be high. Oxides of nitrogen (NOx) emissions were found to be proportional with the N_2 content in the fuel. Sulphur dioxide (SO_2) emissions were negligible. No ash sintering was observed and ash discharge was in the form of powder instead of lumped particles, which are usually observed for high ash biomass fuel. The results indicate that grass pellets can be burned successfully and reliably in this furnace.

1. INTRODUCTION

Bio-energy is already seen as an option to mitigate green house gas (GHG) emissions and substitute fossil fuels. For the European Union (EU), targets have been set for bio-energy: in 2010 almost 10% of the energy supply of the EU is to come from biomass [1]. A country like Sweden formulated that 40% of its primary energy supply should be provided through the use of biomass by 2020 [2].

Combustion is one of the main technological options of biomass conversion [3]. Wood, with fuel characteristics of low ash and low sulfur content allow a direct comparison with coal, oil, and gas. The most important aspect of wood as a renewable energy carrier is its nearly closed carbon-circle. Moreover, the cost of wood burning with good heating performance is lower than that of heating oil [3]. Wood pellets are in the form of compacted biomass in order to increase the density of the fuel. Most pellets are made from sawdust and ground wood chips, which are waste materials, and using pellets helps reduce the costs and problems of waste disposal. Since the start of the pellet fuels market, the emphasis has always been on wood which creates the lowest ash content pellet. However, there is a limited supply of these resources to meet future market demands. Therefore other forms of biomass must be used to create sustainable pellet markets.

Grass pellet fuel has a great prospect in pellet industry due to its lower cost and higher GHG mitigation ability [4]. The major constraint to developing grasses for bioheat applications is its difficulty for efficient combustion in conventional boilers due to high ash content, clinker formation and corrosion of the boilers. Through management and breeding, grass biomass composition can be modified to minimize ash content and clinkering problems. Although grass compositional improvements are worthwhile, a more robust solution is to modify appliances to burn a variety of feed stocks. Fluidized bed combustor might be a solution, but its cost is a constraint for domestic use. Another option is using a two-stage combustion approach, where temperature in the primary combustion bed is lower, and secondary air is provided to burn volatile gases above the fuel bed, transferring more of the heat to the secondary burn. This approach alone is not sufficient to develop a stove suitable for grass pellets. Agitation of fuel and/or ash bed to disrupt agglomeration is another choice. Vibrating grate firing and combustion chamber agitation can serve the purpose to avoid ash agglomeration.

Currently there are few companies manufacturing stoves specifically designed to burn grass pellets, but some wood pellet and corn stoves have been adapted and used to burn grass pellets [5]. A recent study in Cornell University [6] found that even the best performing pellet burning equipment (multi-fuel stoves and boilers designed for pellets and grains) must be serviced on regular intervals (usually everyday) if using grass pellets. Gonzalez [7] investigated combustion of different biomass residue pellets (tomato, olive stone and cardoon) for domestic heating and compared them with forest pellets. The efficiencies of the three residues were found similar to that of forest pellet with a maximum fuel mass flow and minimum draft. Although they reported high efficiency, the emission of CO was very high, as high as 5000 ppm or more in some cases. A pellet boiler was tested with four different types of pellets showing a similar thermal performance with boiler efficiencies up to 77% [8]. Minimum values of CO were achieved for O_2 concentrations in the flue-gases around 13%. Olsson [9] investigated wheat straw and peat pellet combustion. The results indicated that wheat straw and peat pellets are fuels with relatively low emissions during combustion. However, wood pellets burned efficiently with even lower emissions than straw and peat pellets during flaming burning. Slagging tendencies of wood pellet ash during combustion were investigated [10]. The results showed that the slagging properties were relatively sensitive to the variations in total ash content and ash forming elements of the fuel. It is therefore recommended that ash rich fuels like bark and logging residues should not be used in the existing residential pellet burners. The results also indicated that the Si-content in the fuel correlated well to the sintering tendencies in the burners. Andreasen [11] presented straw pellet combustion and compared it with the wood pellet. Five types of straw and wood pellets made with different binders and antislag agents were tested as fuel in five different types of boilers in test firings at 50% and 100% nominal boiler output. The tests proved that the wood pellets could be used in all the boilers tested without any operational problems. There were many other studies that dealt with biomass pellet combustion and emissions including different types of grass pellets [12-17]. The CO_2 emissions with grass pellet combustion reduced by 90% as compared to coal combustion [13] and the energy balance of grass pellets was found distinctly superior to other biofuels production route such as corn ethanol and biodiesel [15]. Spring harvested reed canary grass showed improved combustion and less ash agglomeration due to reduced concentration of elements that are undesirable in combustion, and the initial ash deformation temperature was increased [16, 17].

Observation from the literature review is that biomass, especially in pellet form as heating fuel has great potential to substitute fossil fuel cost effectively with significant GHG mitigation. The use of grass pellets in combination with wood pellets can help increase the longevity of forest wood and may even prevent price increases of limited wood supply. Grass pellet production and its use in heating appliances can also help the local community in income generating activities with active participation in global warming abatement. Most of the burners developed so far commercially are able to handle premium wood pellet or low ash content wood pellets only. Current burners are quickly fouled by ash build-up and melting in the burn pot when using high-ash content pellets. Therefore, there is a need to develop a furnace that can efficiently, cleanly and reliably burn pellets from grass and agricultural wastes. This study presented a prototype furnace developed and patented by LST energy [18]. A special type burn pot with a rotating agitator served to avoid ash agglomeration and adequate ash removal. This also helped better pellet mixing with incoming air producing proper combustion and high furnace temperature.

2. MATERIALS AND METHODS

Measurement of physical properties, proximate analysis, higher heating value, and performance and emission analysis of pellet combustion has been performed in the biomass conversion and biofuels laboratory of Nova Scotia Agricultural College (NSAC). Ultimate analyses were performed by the Guelph Chemical Laboratories Ltd, Ontario, Canada.

2.1 Pellets

Four pellets: one grass pellet, two premium grade wood pellets and one industrial grade wood pellet were used in this study. The pellets are commercialized in Canada and designated here as grass pellet, grade 1 wood pellet, grade 2 wood pellet and grade 3 wood pellet. Grass pellet, and grade 1 and 2 wood pellets have a diameter of ¼ inch. (6.35 mm), but grade 3 wood pellet has a diameter of 5/16 inch. (about 8 mm). The bulk density of grass pellet was 566 kg/m^3 and that of wood pellets were 648 kg/m^3 for grade 1, 636 kg/m^3 for grade 2 and 653 kg/m^3 for grade 3. Fig 1 shows a photograph of different pellet fuels.

2.2 Fuel Characterization

Different pellet fuels were characterized by proximate and ultimate analysis, and higher heating value, the results of which are listed in Table 1. It can be seen that all wood pellets have similar composition and heating values with very low N_2 contents. The main difference in their composition is the ash content that is high for grade 3 wood pellet, because it is a bark mixed wood pellet. On the other hand, grass pellet has the highest ash and moisture content with lower heating value than any of the wood pellets. Its N_2 content is also significantly higher than wood pellets.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

LST energy's pellet furnace with 7-22 kW capacity was used to perform the combustion experiments of this study. Figure 2 shows the schematic diagram of the furnace, which consists of: (1) a hopper/bin with capacity for 140 kg of pellets and a motor-controlled feed auger to introduce the pellet into the burn pot, (2) a control panel to control the feed rate (not shown in the Fig.), (3) an ash receiver to gather the ash produced in the combustion with an auto ash removal auger (constant augur speed of 6 rpm), (4) a burn pot with rotating agitator (constant agitator speed of 2 rpm), (5) a hot water heat exchanger to collect heat of combustion, (6) an induced draft fan to control draft, and (7) a double-walled stainless steel chimney of 20 cm inner diameter and 5 m height connected by 15 cm flue pipe from furnace outlet.

The burn pot is specially designed and separately shown in Fig. 3. It is a 20 cm diameter burn pot. Top and side cutaway views are shown. There is an agitator for continuous agitation of fuel to avoid ash agglomeration. There are a number of ash slots for ash to drop down when agitated. There is a weighted door to let a large clinker out. There are a large number of concave depressions on the bottom of the burn pot to help grind the clinker when the agitator passes over them. There are also a large number of combustion air holes of 5/16 inch. (about 8 mm) diameter.

Type K thermocouples were used to record various temperatures (bed temperature, maximum furnace temperature, etc). The flue gas composition and temperatures were measured by a Unigas 3000^+ flue gas analyzer. In gas composition O_2, CO_2, CO, NO, NOx and SO_2 were measured. Experiments were conducted for each fuel with different fuel mass flow rates to find the optimum condition for efficiency and emissions. Scanning electronic microscopy (SEM) was performed to investigate ash sintering.

4. THERMAL ANALYSIS OF COMBUSTION

The purpose of thermal analysis of combustion is to determine the overall efficiency and different losses. Basically efficiency can be tested by the direct method where the energy gain of the working fluid is compared with the energy content of the fuel, and by the indirect method where the efficiency is the difference between the losses and the energy input. This study used the indirect method to calculate overall efficiency. An important advantage of this method is that the errors in measurement do not make significant change in efficiency. The following are the pertinent losses.

1) Dry flue gas loss
2) Wet flue gas loss
3) Unburned carbon and CO loss and
4) Radiation and unaccounted loss

Overall efficiency by indirect method = 100- (sum of losses).

Theoretical (stoichiometric) air fuel ratio and excess air supplied are to be determined first for computing the losses. Theoretical air required for combustion is determined from stoichiometric calculation with fuels ultimate/proximate analysis data. Excess air supplied is measured from flue gas analysis. Dry flue gas loss is the greatest loss and can be calculated from mass of dry flue gas, specific heat of flue gas, and the difference between flue gas temperature and ambient temperature. Wet flue gas loss is the 2nd largest loss. Water vapor is produced from hydrogen in fuel, moisture present in fuel and air during the combustion. The losses due to these components are separately calculated and their sum is taken as a wet flue gas loss. Unburnt carbon in ash is measured, and loss due to this is also calculated. Loss due to CO production is also calculated. The share of unburnt carbon in ash and CO in flue gas loss is very small in most of the cases. However, at high load conditions unburnt carbon loss and CO loss is significant, especially for industrial grade wood pellet. A typical radiation and unaccounted loss of 2% is assumed. It should be noted that presently so called combustion efficiency of the boiler is determined by flue gas analyzer [7, 19]. This doesn't give actual overall efficiency of the system. Gas analyzer only accounts dry flue gas loss using Siegert's formula. Wet flue gas loss is another significant loss in case of biomass combustion. In ref. [19] efficiency was shown to be greater than 82% and in ref. [7] greater than 91%. This study presents actual overall efficiency considering all losses.

5. STEADY STATE TEST

At each fuel flow rate, the performance was tested under steady state condition. Steady state was considered when there was almost no change in flue gas temperatures and emission parameters. It took an hour to reach steady state condition. Five fuel flow rates from 2 kg/hr to

6 kg/hr were tested. The input thermal energy at the feed rates ranged from 10-31 kW. The thermal performance of the furnace is illustrated by Fig. 4, which presents the overall furnace efficiency and total losses, as a function of the thermal input to the furnace based on the higher heating value of the fuel. Combustion efficiency varied from 69% to 75% depending on pellet types and loads. Maximum efficiency was obtained for thermal inputs from 15 to 27 kW (moderate to high loads). Grass and wood pellets showed very similar efficiency. Total losses showed the minimum values from 15 to 27 kW. At low load (10-11.5 kW), total loss is higher due to higher dry flue gas loss. At maximum loading condition, grade 3 wood pellet produced very high level of CO, and CO loss was more than 2%. Unburnt carbon loss is more than 1% at high load operations for grade 3 wood pellet and grass pellet. The detailed account of overall efficiency and different losses is presented in Table 2.

Excess oxygen or air in flue gas is an important indicator of overall efficiency and a factor to avoid. The excess air simply carries heat up the stack and away from the burner. A fine line must always be drawn between high excess air and incomplete combustion, which will manifest in high levels of CO. Figure 5 shows the measured oxygen concentration in the flue gases as a function of the thermal input. A linear relationship was found between O_2 concentration and thermal input. Excess oxygen dropped from 16.9% to 10.5% when the load was increased from minimum to maximum. Due to excessively lean combustion at the lowest feed rate, the dry flue gas loss was the highest and combustion efficiency was the lowest.

Figure 6 shows bed temperature and the maximum furnace temperature at different loads for different fuels. At minimum load, average bed temperature was approximately 1000ºC. Average bed temperature increased to 1075ºC for the load of 14 kW or above. Grade 1 and 2 wood pellets showed higher bed temperatures compared to grade 3 wood pellet and grass pellet. In fact grass pellet showed the lowest bed temperatures. At minimum load, average maximum furnace temperature was 1075ºC. Average maximum furnace temperature increased to 1300ºC for the load of 21.5 kW or above. Wood pellet 1 and 2 again showed higher temperatures than those of grade 3 wood pellet and grass pellet, and again grass pellet showed the lowest temperatures. The lowest bed and furnace temperature of grass pellet is due to the lower heating value and higher moisture content. It is observed that maximum furnace temperature is more than 200ºC higher than the average bed temperatures in some conditions. This is a two-stage combustion pattern, where temperature in the primary combustion bed is less, and secondary air is provided to burn volatile gases above the fuel bed, transferring more of the heat to the secondary burn. This is a desirable pattern for good combustion. For wood pellets and spring harvested grass pellets the ash sintering temperature was reported 1100ºC or higher [10, 17]. One reason for no ash agglomeration in this study could be due to the average bed temperature of 1075ºC or lower. However, the main reason is thought to be the rotation of the agitator over the concave depressions on the bottom of the burn pot which ground the larger ash lumps into powder form.

Owing to the linear relationship between O_2 concentration and the actual furnace load, the pollutant emissions are analyzed as a function of the O_2 in the flue gases. Figure 7 shows the emissions of CO, NOx and SO_2 at different excess O_2 in the flue gas. O_2 in the flue gas 11.5% or higher produced minimum CO in the exhaust. When the O_2 was further decreased, a sharp increase in CO was observed. Grass pellet showed a slightly higher CO than grade 1 and 2 pellets, but it did show lower CO emissions than grade 3 pellet. Figure 6 also shows the NOx emissions for various fuels at different excess O_2 in the flue gas. NOx emissions were increased with increased thermal input (less excess O_2) for all pellet fuels. And NOx emissions with grass pellet (higher fuel bound N_2 than wood pellets) are much higher than that of wood pellets. It seems that combustion temperature and fuel bound N_2 both are responsible for NOx production. However, the effect of fuel bound N_2 is dominating over combustion temperature effect. The production of higher NOx with higher fuel bound N_2 is consistent with the results described in Ref. [20], where it was shown that a higher formation of NOx was found for the straw fuel (0.58% fuel nitrogen) than for the bark/wood chip fuels (≈0.25% fuel nitrogen). Figure 6 shows SO_2 emissions for various fuels at different O_2 in flue gases. At low load conditions there was no SO_2 obtained, while at high load there was only 3 to 5 ppm of SO_2 with different pellet combustion. Therefore, the SO_2 emissions from pellet burning are insignificant.

Figure 8 shows the effect of fuel bound N_2 on NOx production for different pellets at different loads. Wood pellets have fuel bound N_2 from 0.05 to 0.19% and that of grass pellet 0.87%. Three load conditions: low, moderate and high are shown. NOx was increased with the increase in fuel bound N_2 at all loads. The rate of increase in NOx up to 0.19% fuel bound N_2 is 60-90% higher than that of 0.87% fuel bound N_2 depending on loads. This implies that the NOx emission increases with increasing nitrogen content whereas the fuel nitrogen conversion to NOx decreases. This is very consistent with the results described in Ref. [21]. As the maximum flame temperature recorded was less than 1500ºC, no significant thermal NOx can be expected. Therefore, most of the NOx production of biomass combustion comes from fuel bound N_2.

Figure 9 shows photographs of grass pellet ash for this study and grass briquette ash (chunk) obtained from a conventional wood stove. Grass pellet ash is in powder form, whereas the conventional wood stove produced chunks of agglomerated ash. A similar photograph of a chunk of agglomerated ash was presented in Ref. [22] for reed canary grass combustion. In this study, the rotating agitator and a large number of concave depressions on the bottom of the burn pot helped grind the clinker when the agitator passed over them.

Figure 10 shows SEM images of different pellet ash samples at different running conditions. It was found that grass pellet ash from low temperature operation (Fig. 9 (a)) is of smaller particle size with almost no tendency of ash sintering. However, Fig. 9(b) shows that when the furnace was operated at high load and high temperature condition, the ash tended to form some sintering spots, although the sintering is not significant enough to produce any agglomeration. The images of wood pellet ash samples are from high temperature conditions (Fig. 9 (c), (d) and (e)). There is still no ash sintering tendency due to higher ash sintering temperature of wood pellets. Fig. 9 (f) shows an image of a chunk of agglomerated ash produced from briquetted grass burnt in a conventional wood stove. SEM analysis proved that grass pellet of this study burns well without ash agglomeration. All of the results in the form of deliverable are included in Appendix 1.

6. CONCLUSIONS

Grass pellet combustion, emissions and ash sintering was compared with that of three other wood pellets in a prototype grass pellet furnace. Ash content more than 2% in grass and 1.86% in barked wood pellet (grade 3 wood pellet) was burnt without any ash agglomeration problem. A rotating agitator with concave depressions on the bottom of the burn pot did not allow the ash to be agglomerated. Grass pellets showed a similar thermal performance to that of wood pellets with overall furnace efficiency of 73% or more. Lower furnace temperature with grass pellet for the similar thermal input was observed due to its lower heating value and higher moisture and ash content. In most cases, average CO emissions under steady state conditions were less than 150 ppm, with minimum values being achieved for O_2

concentrations in the flue-gases 11.5% or higher. NOx emissions, under steady state conditions, correlate well with nitrogen content of pellets, and showed a minimum in the case of grade 1 wood pellets. Grass pellets however showed higher NOx than that of wood pellets due to higher fuel bound N_2. This project demonstrates the potential use of grass pellets as a fuel source if burned in appropriate combustion technology.

ACKNOWLEDGMENT

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Grass pellet   Grade 1 wood pellet   Grade 2 wood pellet   Grade 3 wood pellet

Fig. 1: Photograph of different pellets

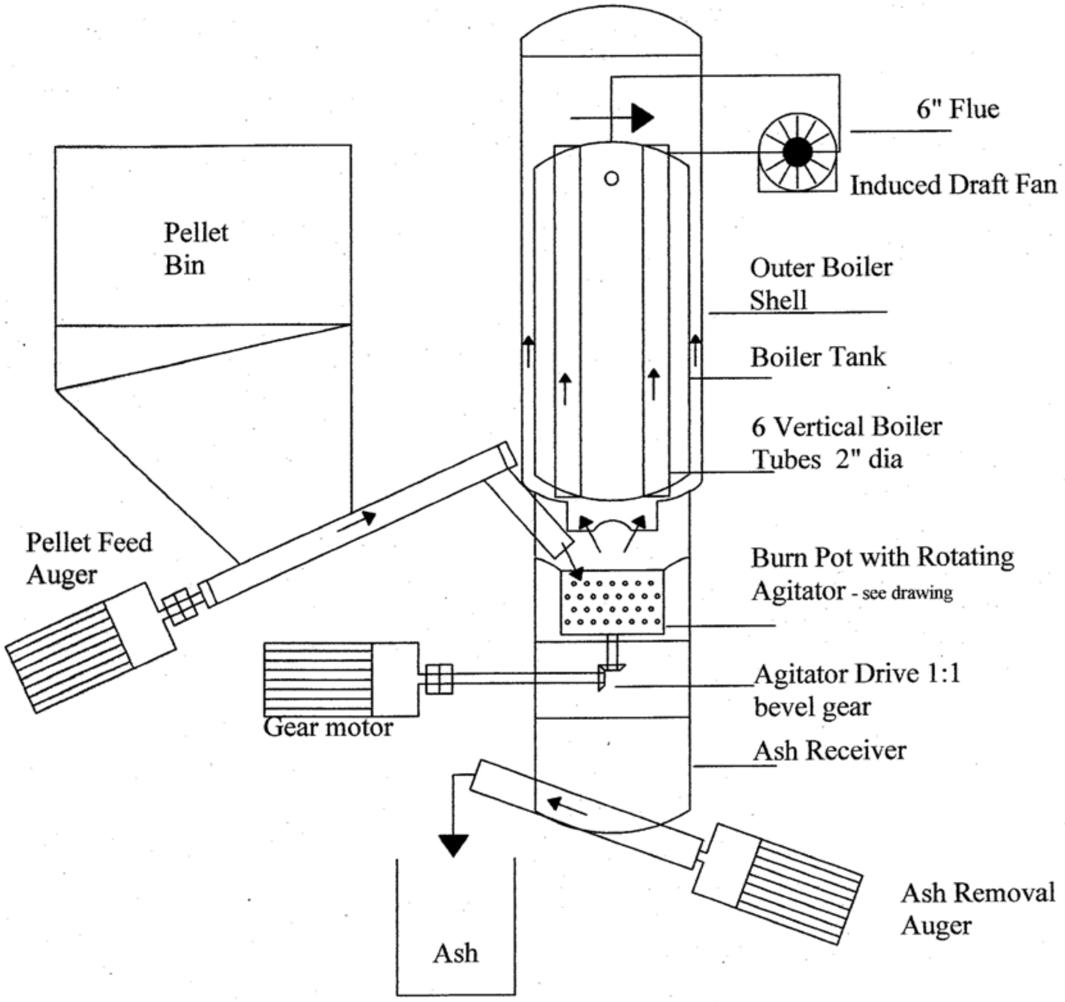
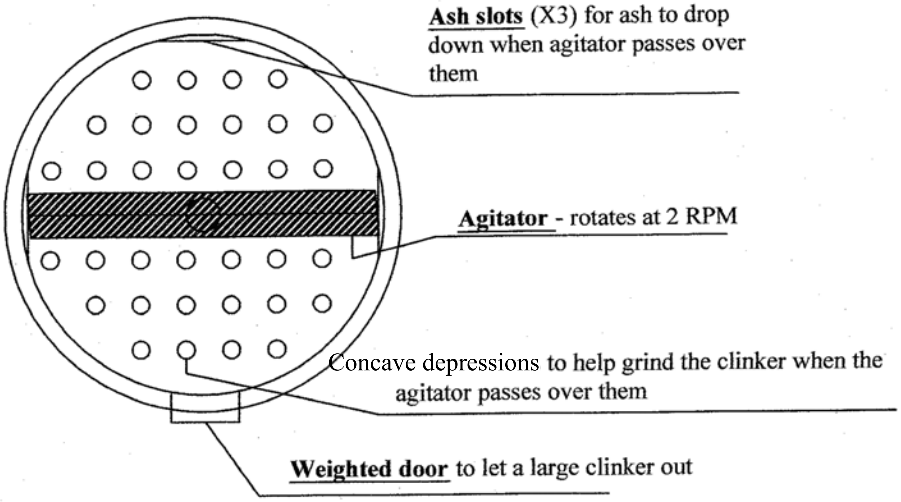


Fig. 2: Schematic diagram of LST energy's grass pellet furnace

Top View



Side View Cutaway

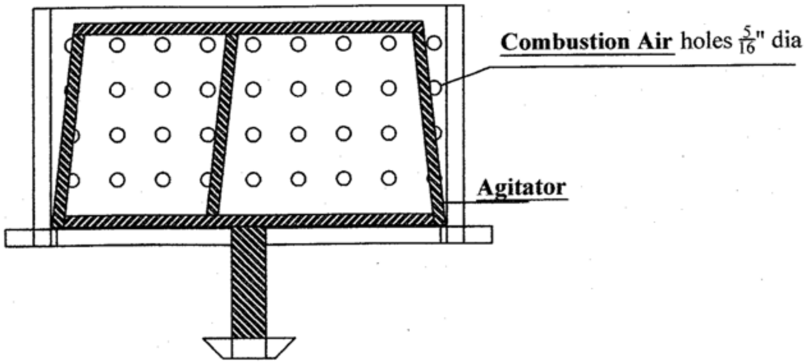


Figure 3: Top and side cutaway view of the burn pot

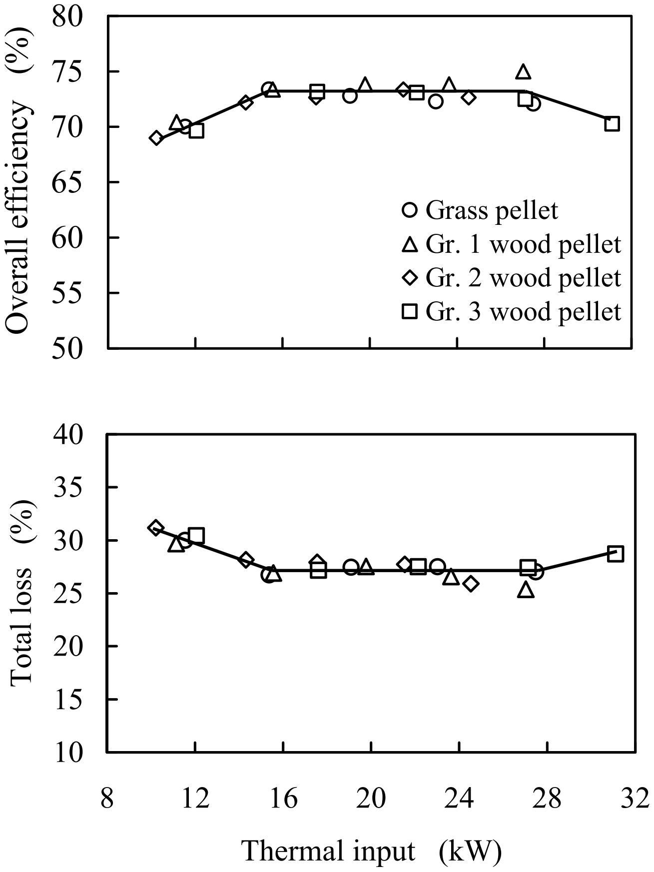


Figure 4: Overall furnace efficiency and total losses at different thermal inputs

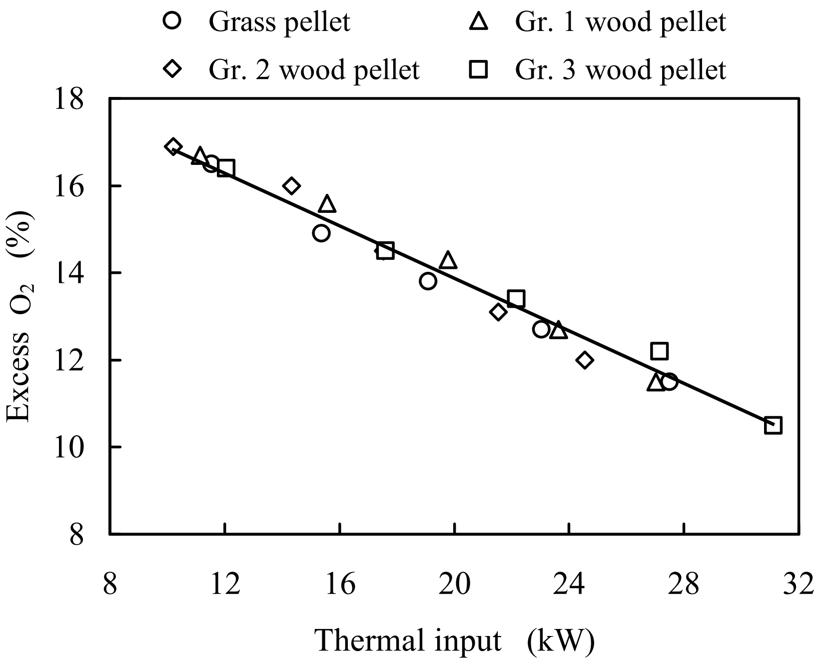


Figure 5: O_2 concentration in the flue gas at different thermal inputs

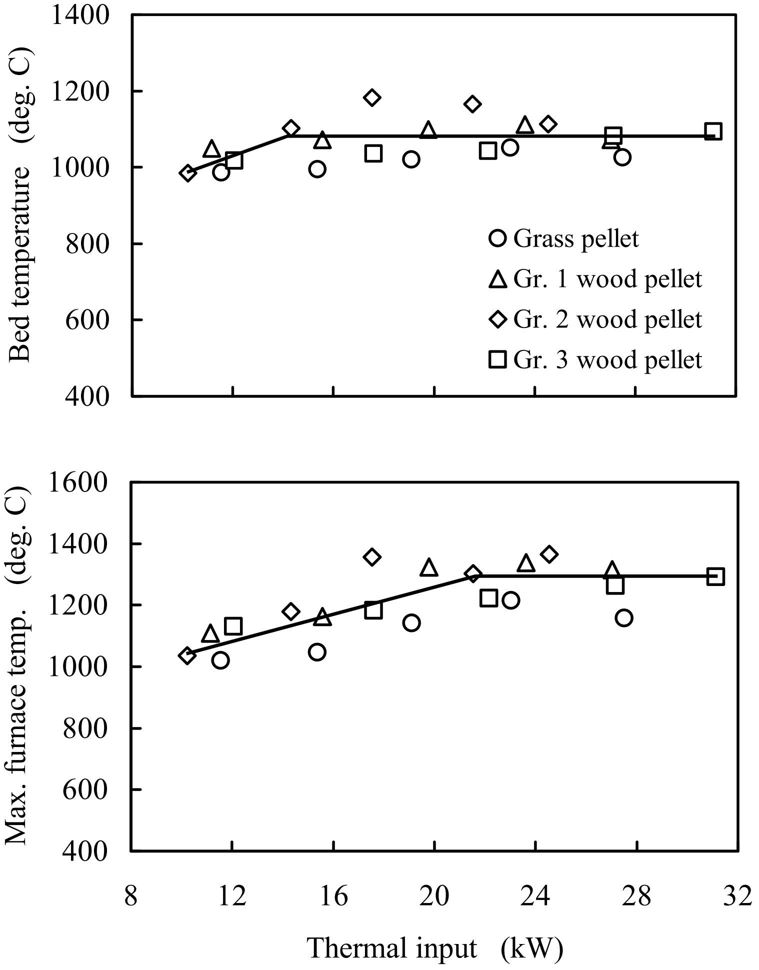


Figure 6: Bed temperature and maximum furnace temperature at different loads

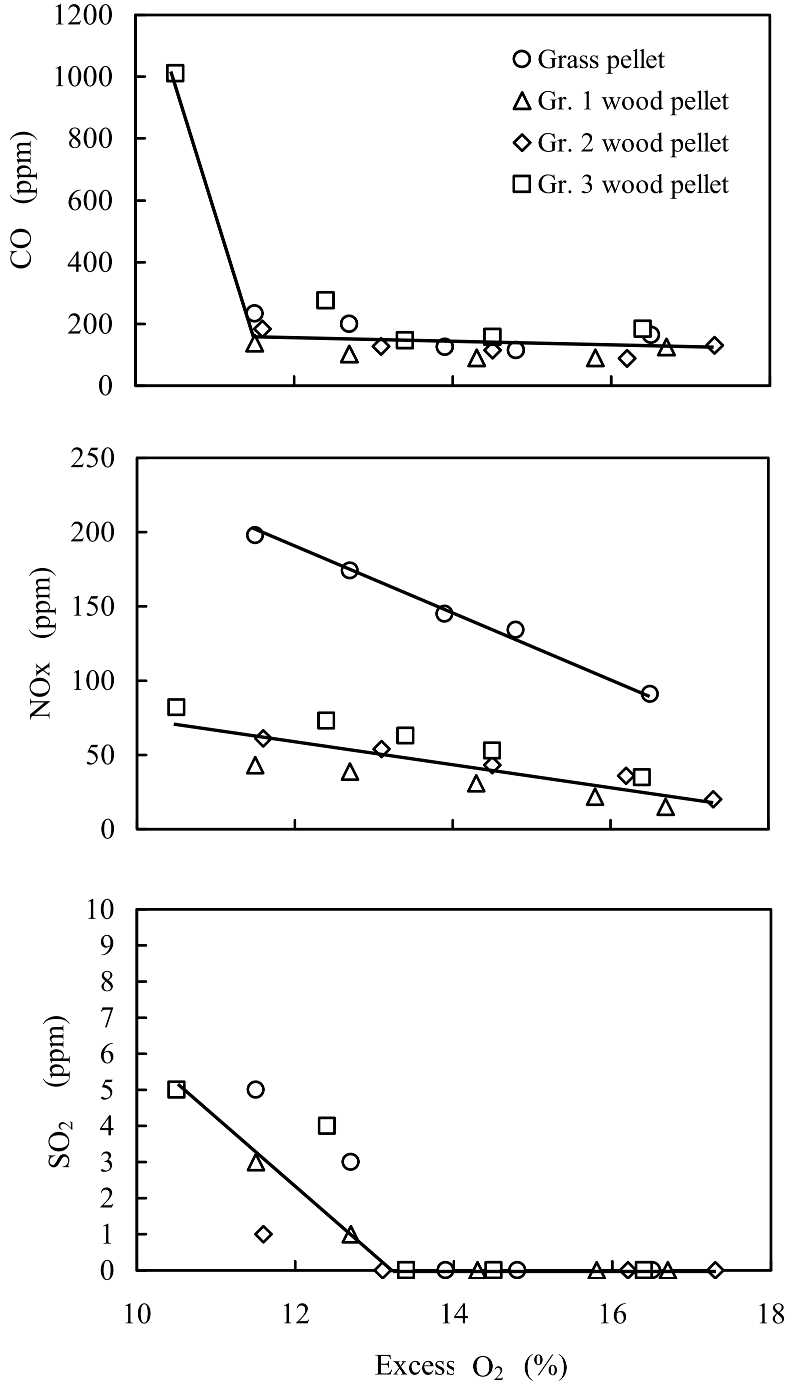


Figure 7: Emissions of CO, NOx and SO_2 at different excess O_2 in the flue gas

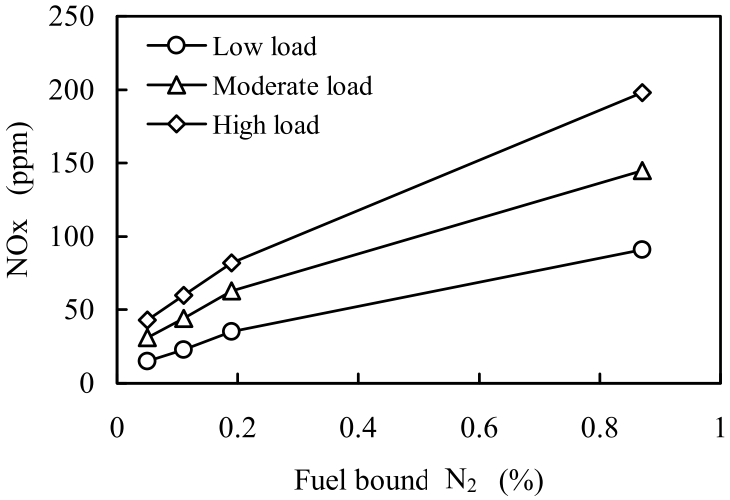


Figure 8: Effect of fuel bound N_2 on NOx production for different pellets at different loads

Fig 9: Photograph of grass pellet ash for this study (a), and grass briquette ash from conventional wood stove (b)

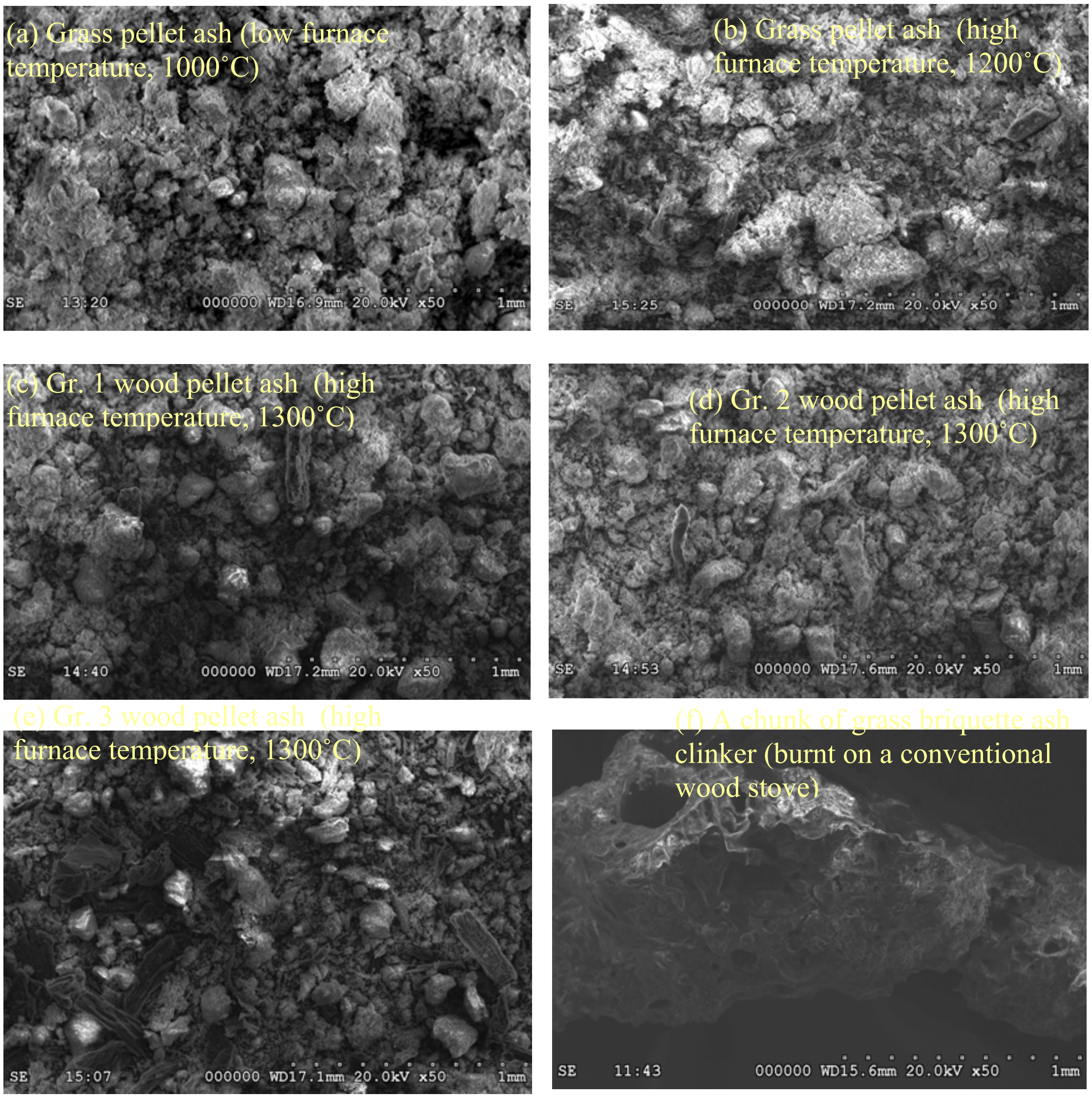


Figure 10: SEM image of different pellet ash samples at different running conditions

Table 1: Ultimate and proximate analyses and the higher heating value (HHV) of different pellet fuels

Analysis	**Pellets**			
Ultimate analysis, db (%)	Grass pellet	Grade 1 wood pellet	Grade 2 wood pellet	Grade 3 wood pellet
C	45.50	48.75	47.75	48.38
H	6.59	6.54	6.53	6.58
N	0.87	0.05	0.11	0.19
S	0.27	0.24	<0.10	<0.10
O (by difference)	44.61	44.12	44.89	42.89
Proximate analysis (%)				
Moisture	8.74	5.00	4.64	4.90
Ash	2.16	0.30	0.62	1.86
Volatile matter	80.47	85.31	85.56	83.75
Fixed carbon	8.63	9.39	9.18	9.49
HHV (MJ/kg)	17.15	18.90	18.68	18.94

Table 2: Overall efficiency and losses at different running conditions for different pellets

Pellet type	Thermal input (kW)	Overall eff. (%)	Dry flue loss (%)	Wet gas loss (%)	Unburnt C loss (%)	CO loss (%)	Radiation & unacc-ounted loss (%)	Total loss (%)
Grass	11.55	70.01	14.16	13.33	0.13	0.37	2	29.99
	15.38	73.34	11.78	12.48	0.14	0.26	2	26.65
	19.10	72.74	12.52	12.31	0.16	0.28	2	27.24
	23.04	72.26	12.49	12.18	0.62	0.45	2	27.74
	27.50	72.06	11.85	12.03	1.53	0.53	2	27.94
Gr. 1 wood	11.15	70.45	14.91	12.36	0.0026	0.28	2	29.55
	15.56	72.42	13.60	11.77	0.0028	0.21	2	27.58
	19.78	73.81	12.68	11.30	0.003	0.21	2	26.19
	23.63	73.81	12.81	10.99	0.16	0.23	2	26.19
	27.03	75.00	11.58	10.76	0.35	0.31	2	25.00
Gr. 2 wood	10.22	69.00	15.69	13.02	0.0042	0.29	2	31.00
	14.32	72.18	13.55	12.07	0.0045	0.2	2	27.82
	17.54	72.61	13.71	11.42	0.005	0.26	2	27.39
	21.53	73.36	13.02	11.12	0.21	0.29	2	26.64
	24.54	72.65	13.55	10.85	0.53	0.42	2	27.35
Gr. 3 wood	12.06	69.64	15.52	12.24	0.19	0.41	2	30.36
	17.61	73.16	12.97	11.33	0.21	0.36	2	26.82
	22.16	73.00	13.27	11.15	0.25	0.33	2	26.94
	27.15	72.49	12.66	11.10	1.13	0.62	2	27.51
	31.12	70.26	12.28	10.83	2.35	2.28	2	29.74

Appendix 1: Deliverables

Physical and Chemical Properties of Pellet Fuels:

Grass pellet, and grade 1 and 2 wood pellets have the diameter of ¼ inch. (6.35 mm), but grade 3 wood pellet has the diameter of 5/16 inch. (about 8 mm). The bulk density of grass pellet was 566 kg/m^3 and that of wood pellets were 648 kg/m^3 for grade 1, 636 kg/m^3 for grade 2 and 653 kg/m^3 for grade 3 wood pellet.

Different pellet fuels were characterized by proximate and ultimate analysis, and higher heating value (HHV) was determined. Table 1 shows proximate and ultimate analyses, and higher heating value of different pellet fuels.

Table 1: Ultimate and proximate analyses and the higher heating value (HHV) of different pellet fuels

Analysis	**Pellets**			
Ultimate analysis, db (%)	Grass pellet	Grade 1 wood pellet	Grade 2 wood pellet	Grade 3 wood pellet
C	45.50	48.75	47.75	48.38
H	6.59	6.54	6.53	6.58
N	0.87	0.05	0.11	0.19
S	0.27	0.24	<0.10	<0.10
O (by difference)	44.61	44.12	44.89	42.89
Proximate analysis (%)				
Moisture	8.74	5.00	4.64	4.90
Ash	2.16	0.30	0.62	1.86
Volatile matter	80.47	85.31	85.56	83.75
Fixed carbon	8.63	9.39	9.18	9.49
HHV (MJ/kg)	17.15	18.90	18.68	18.94

Combustion and Emission Performance:

Table 2 shows bed temperature and maximum furnace temperature for various pellets at different thermal inputs.

Table 2: Bed and maximum furnace temperature

Input, kW (grass)	Bed temp (C)	Max. temp (C)	Input, kW (gr. 1)	Bed temp (C)	Max. temp (C)	Input, kW (gr. 2)	Bed temp (C)	Max. temp (C)	Input, kW (gr. 3)	Bed temp (C)	Max. temp (C)
11.55	986	1020	11.15	1050	1109	10.22	985	1035	12.06	1017	1130
15.38	995	1046	15.56	1073	1163	14.32	1102	1180	17.61	1035	1182
19.1	1020	1141	19.78	1099	1325	17.54	1182	1357	22.16	1042	1222
23.04	1051	1215	23.63	1112	1339	21.53	1165	1303	27.15	1082	1263
27.5	1026	1158	27.03	1072	1316	24.54	1113	1366	31.12	1094	1292

Table 3 (a-d) shows different emissions for various pellet fuels at different thermal inputs.

Table 3(a): Grass pellet emissions

Input, kW (grass)	O_2 %	CO (ppm)	NOx (ppm)	SO_2 (ppm)
11.55	16.5	164	91	0
15.38	14.9	114	134	0
19.1	13.8	126	145	0
23.04	12.7	199	174	3
27.5	11.5	234	198	5

Table 3(b): Gr. 1 wood pellet emissions

Input, kW (gr. 1)	O_2 %	CO (ppm)	NOx (ppm)	SO_2 (ppm)
11.15	16.7	125	15	0
15.56	15.6	91	22	0
19.78	14.3	90	31	0
23.63	12.7	103	39	1
27.03	11.5	137	43	3

Table 3(c): Gr. 2 wood pellet emissions

Input, kW (gr. 2)	O_2 %	CO (ppm)	NOx (ppm)	SO_2 (ppm)
10.22	16.9	130	20	0
14.32	16	89	36	0
17.54	14.5	114	43	0
21.53	13.1	128	54	0
24.54	12	184	61	1

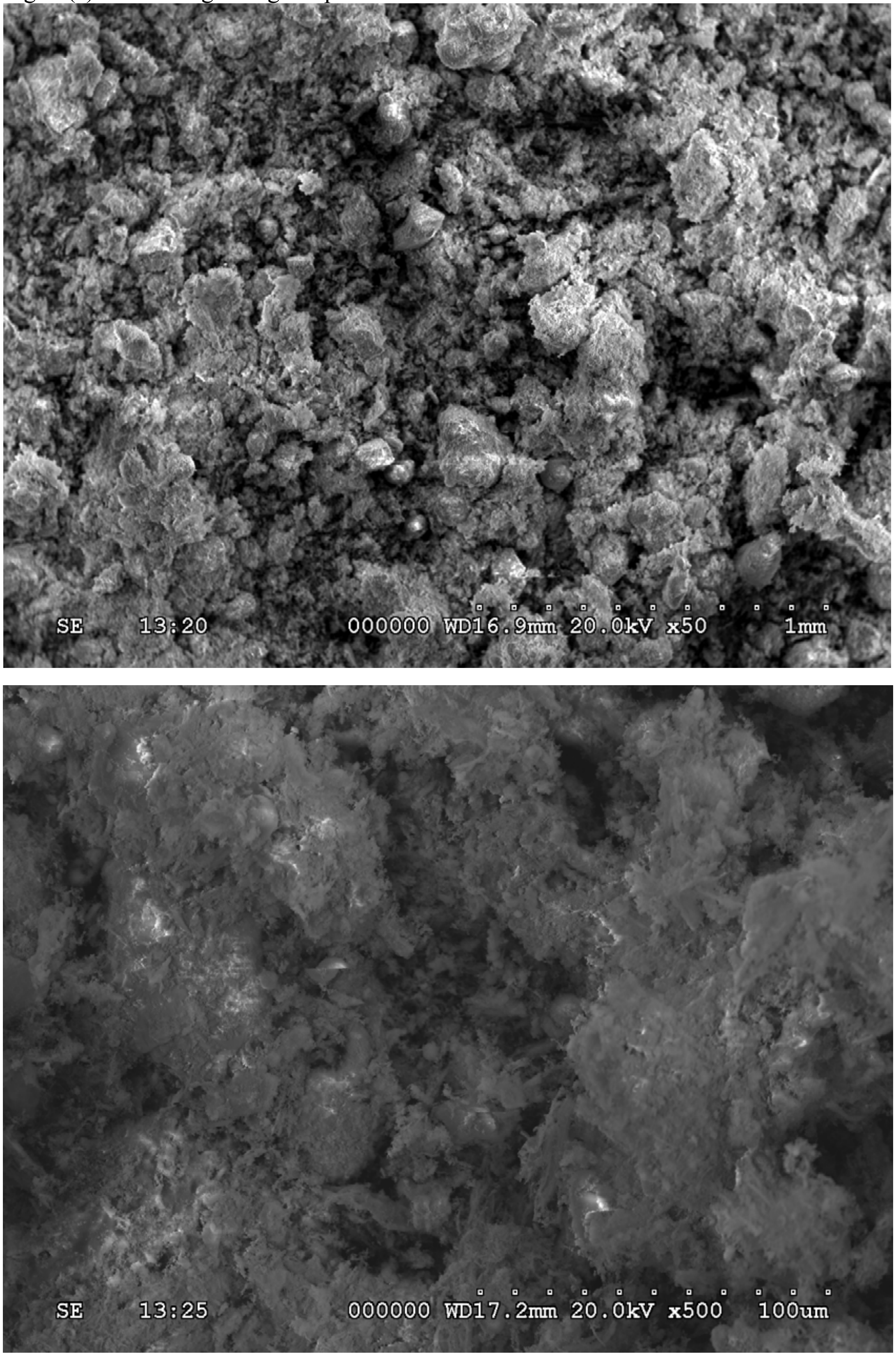
Table 3(d): Gr. 3 wood pellet emissions

Input, kW (gr. 3)	O_2 %	CO (ppm)	NOx (ppm)	SO_2 (ppm)
12.06	16.4	183	35	0
17.61	14.5	158	53	0
22.16	13.4	147	63	0
27.15	12.2	275	73	4
31.12	10.5	1011	82	5

Agglomeration Tendency of Ash in the Bed:

There was no ash agglomeration in the bed. Figure 4 (a-d) shows SEM images of different pellets' ash samples. No tendency of ash agglomeration was observed.

Fig. 4 (a): SEM images of grass pellet ash



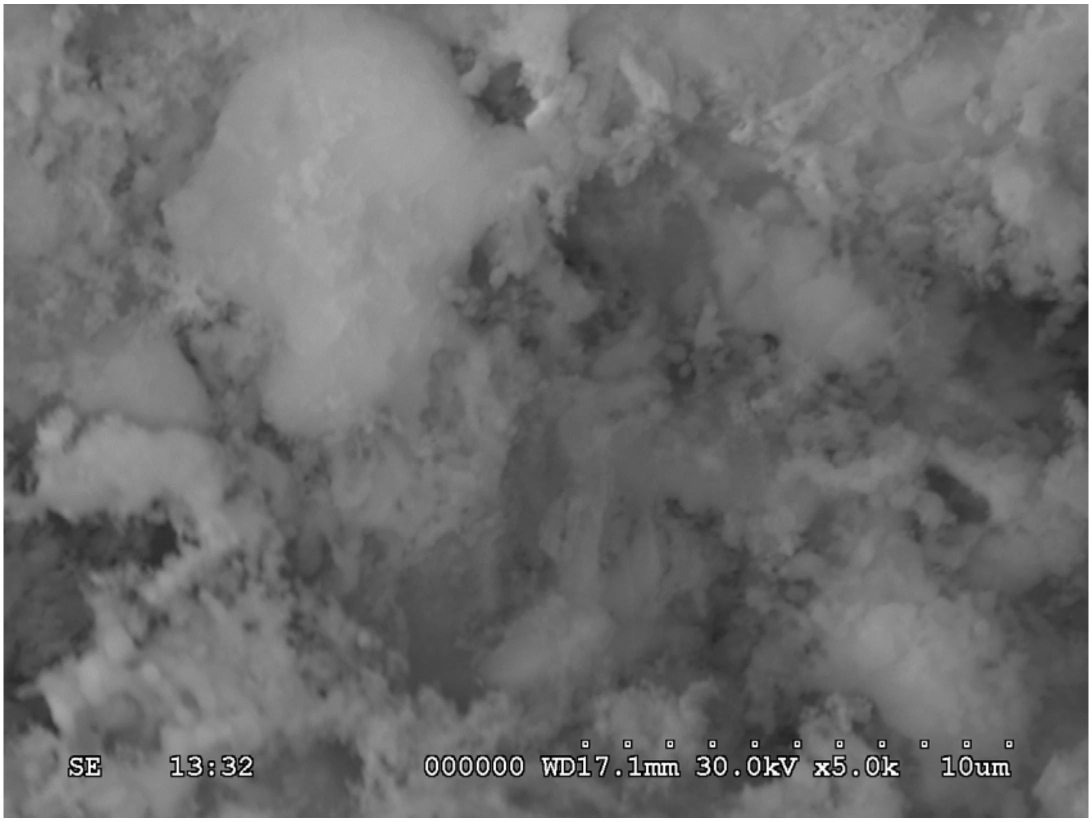
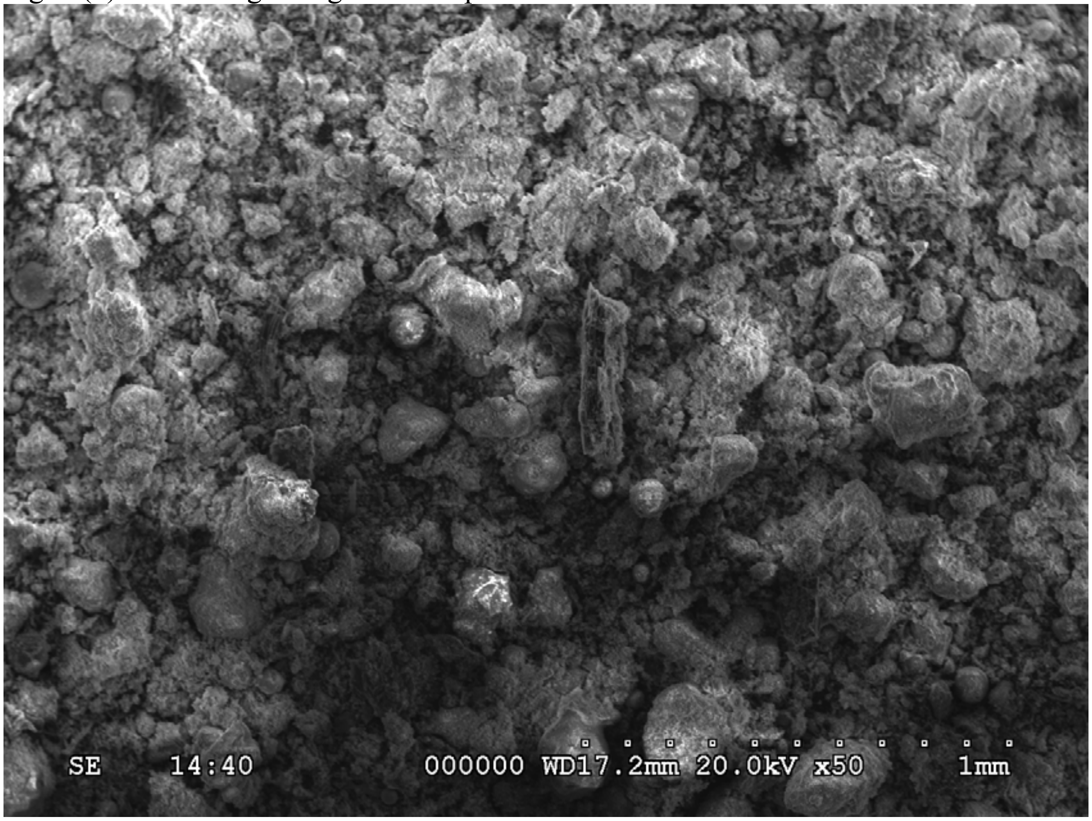
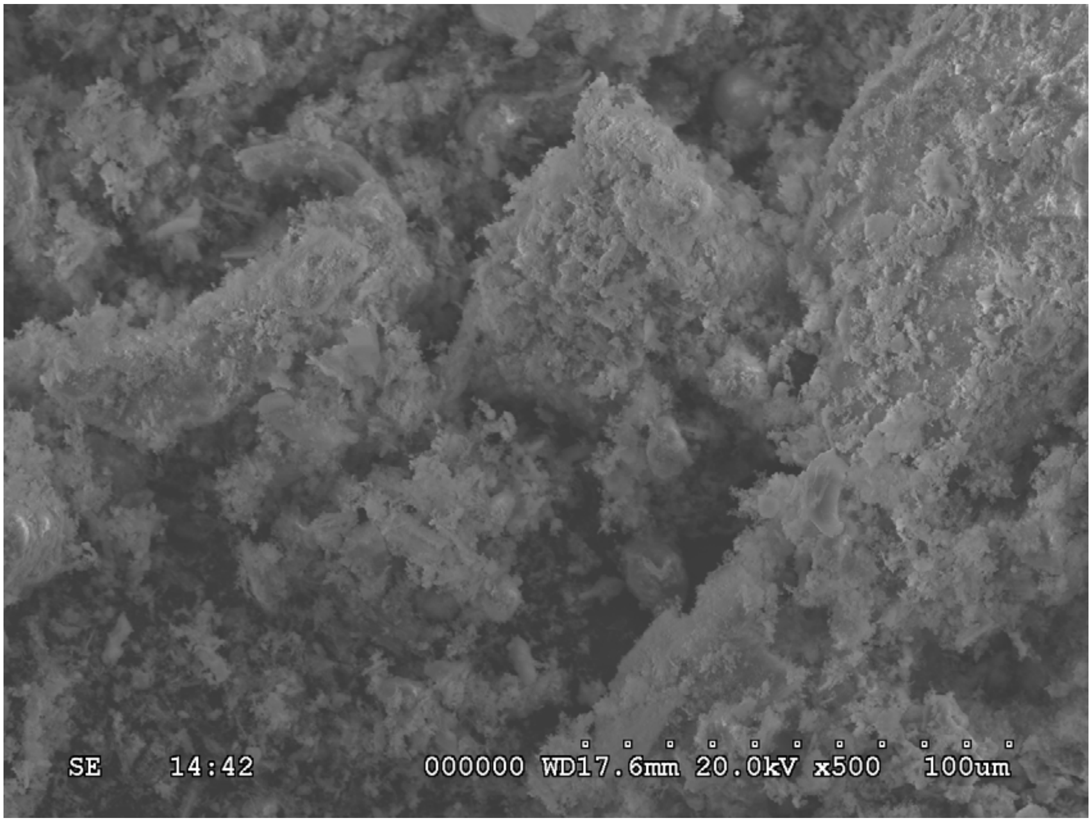


Fig. 4 (b): SEM images of gr. 1 wood pellet ash

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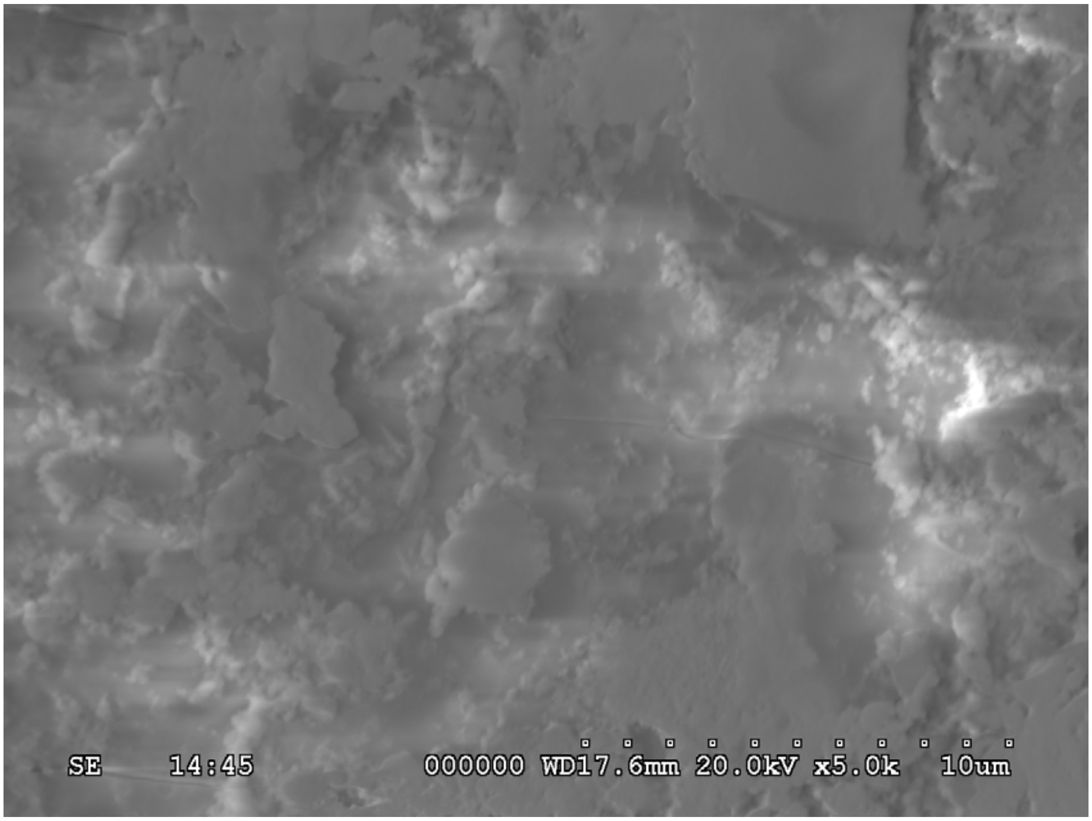
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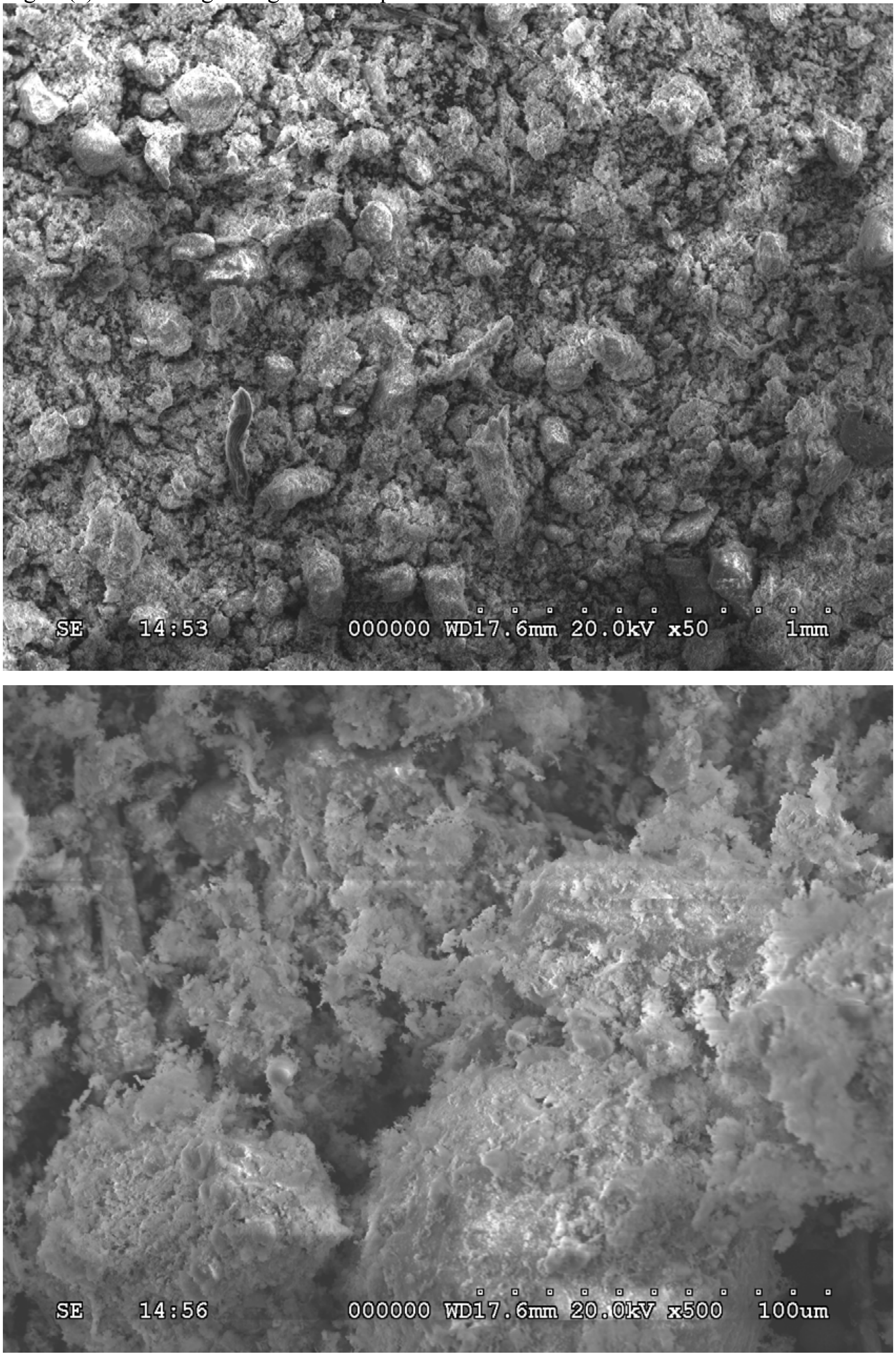
Fig. 4 (c): SEM images of gr. 2 wood pellet ash



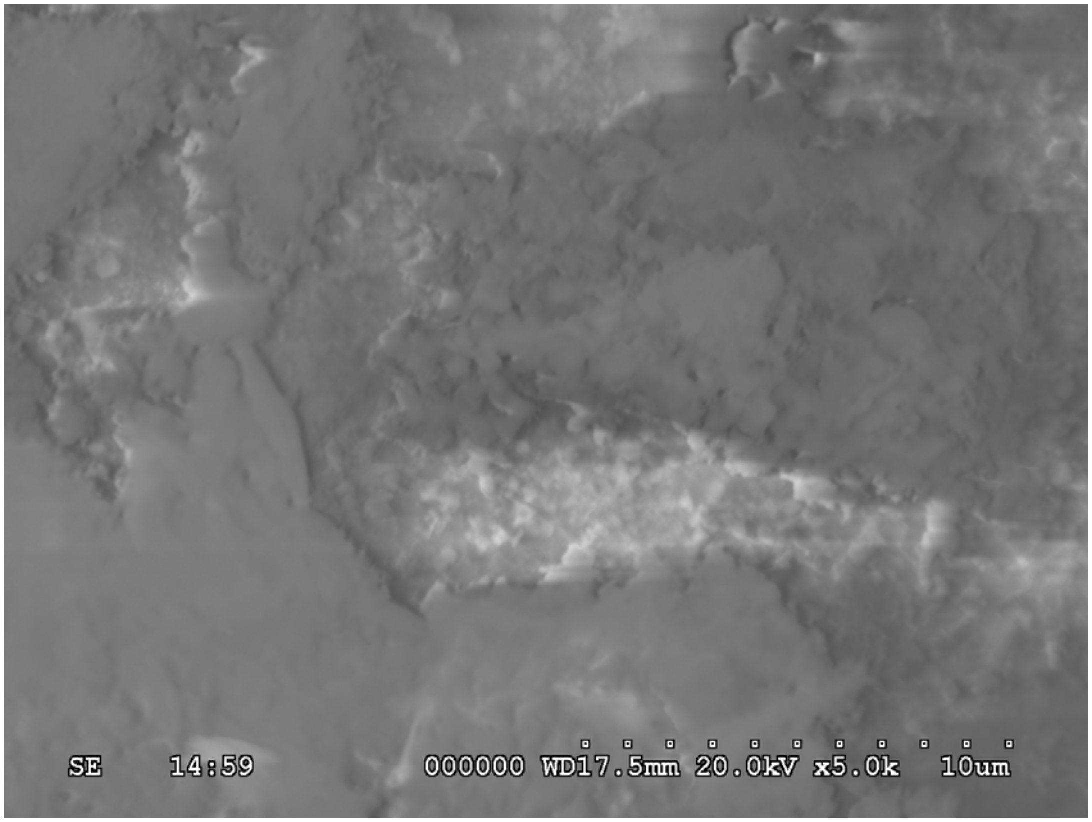
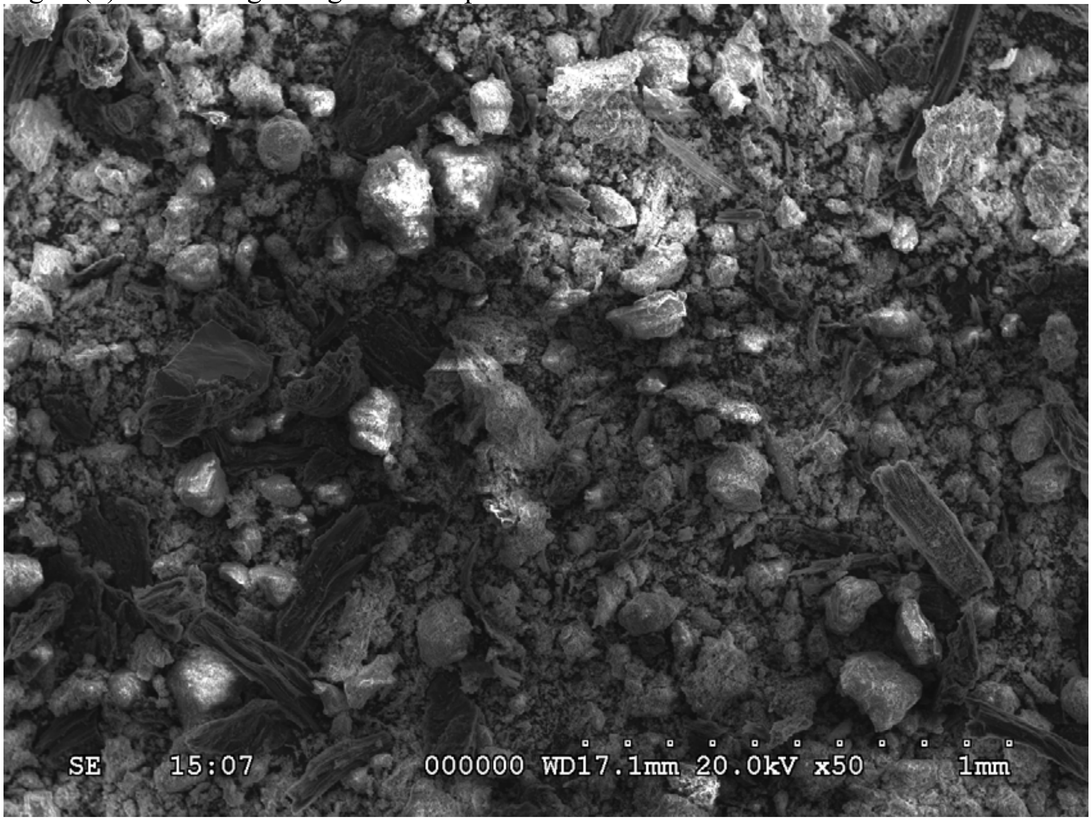
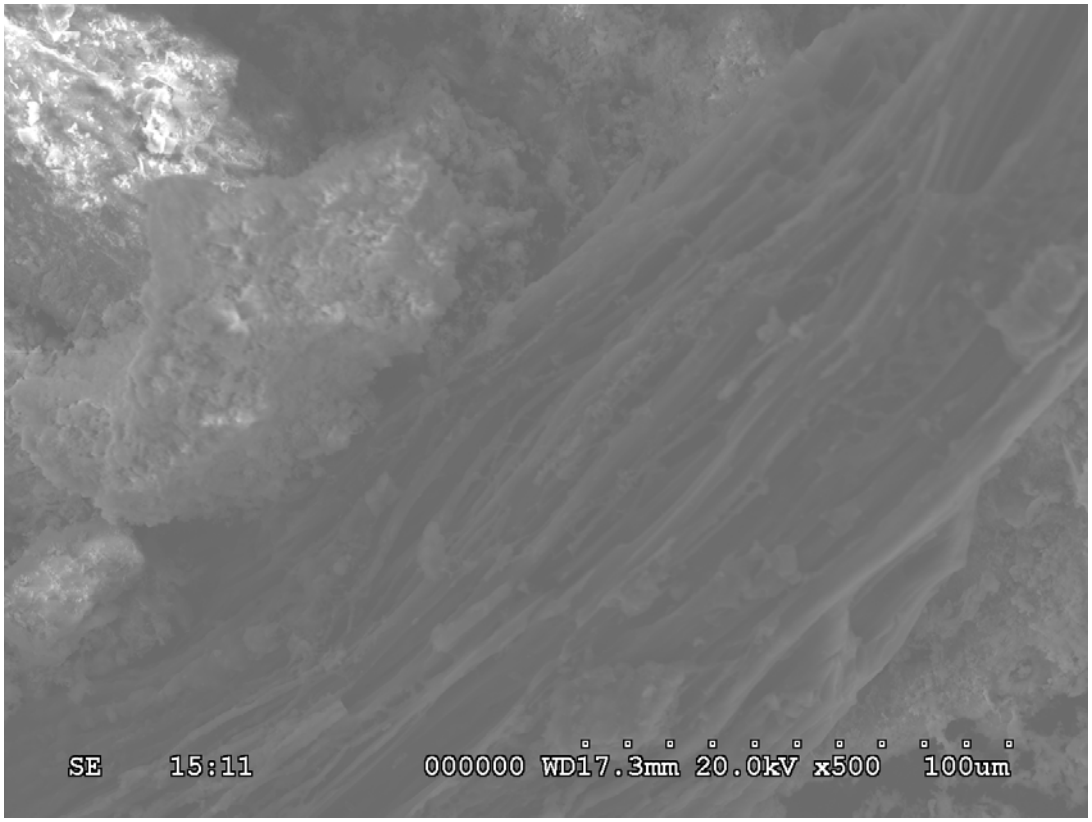


Fig. 4 (d): SEM images of gr. 3 wood pellet ash

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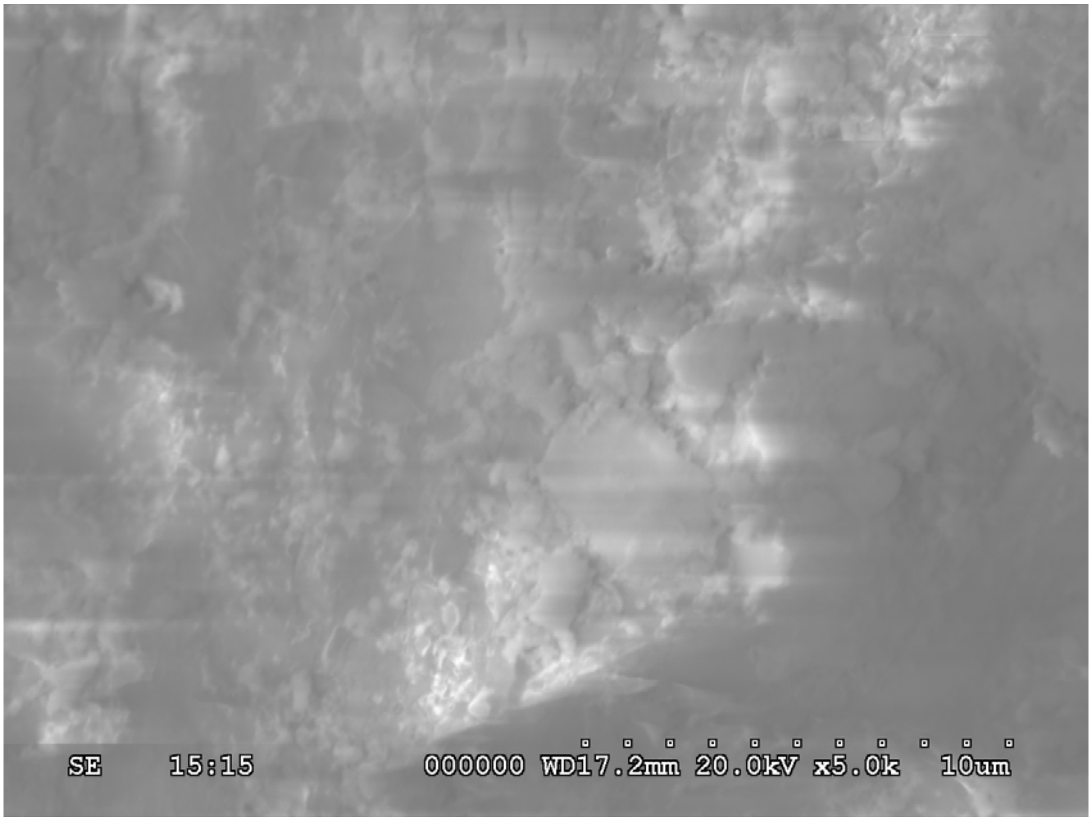
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Stoichiometric Analysis with Energy Balance for Overall Furnace Efficiency and Losses:

The detailed account of overall furnace efficiency and different losses is presented in Table 2. This is done from stoichiometric analysis and energy balance.

Table 2: Overall efficiency and losses at different running conditions for different pellets

Pellet type	Thermal input (kW)	Overall eff. (%)	Dry flue loss (%)	Wet gas loss (%)	Unburnt C loss (%)	CO loss (%)	Radiation & unacc-ounted loss (%)	Total loss (%)
Grass	11.55	70.01	14.16	13.33	0.13	0.37	2	29.99
	15.38	73.34	11.78	12.48	0.14	0.26	2	26.65
	19.10	72.74	12.52	12.31	0.16	0.28	2	27.24
	23.04	72.26	12.49	12.18	0.62	0.45	2	27.74
	27.50	72.06	11.85	12.03	1.53	0.53	2	27.94
Gr. 1 wood	11.15	70.45	14.91	12.36	0.0026	0.28	2	29.55
	15.56	72.42	13.60	11.77	0.0028	0.21	2	27.58
	19.78	73.81	12.68	11.30	0.003	0.21	2	26.19
	23.63	73.81	12.81	10.99	0.16	0.23	2	26.19
	27.03	75.00	11.58	10.76	0.35	0.31	2	25.00
Gr. 2 wood	10.22	69.00	15.69	13.02	0.0042	0.29	2	31.00
	14.32	72.18	13.55	12.07	0.0045	0.2	2	27.82
	17.54	72.61	13.71	11.42	0.005	0.26	2	27.39
	21.53	73.36	13.02	11.12	0.21	0.29	2	26.64
	24.54	72.65	13.55	10.85	0.53	0.42	2	27.35
Gr. 3 wood	12.06	69.64	15.52	12.24	0.19	0.41	2	30.36
	17.61	73.16	12.97	11.33	0.21	0.36	2	26.82
	22.16	73.00	13.27	11.15	0.25	0.33	2	26.94
	27.15	72.49	12.66	11.10	1.13	0.62	2	27.51
	31.12	70.26	12.28	10.83	2.35	2.28	2	29.74

Comparison of Results with Others:

Currently no company is manufacturing stoves specifically designed to burn grass pellets, but some wood pellet and corn stoves have been adapted and used to burn grass pellets [5]. A recent study in Cornell University [6] found that even the best performing pellet burning equipment (multi-fuel stoves and boilers designed for pellets and grains) must be serviced on regular intervals (usually everyday) if using grass pellets. Ref. [7] investigated combustion of different biomass residue pellets (tomato, olive stone and cardoon) for domestic heating and compared with that of the forest pellet. The efficiencies of the three residues were found similar to that of the forest pellet with the maximum fuel mass flow (100%) and minimum draught (0%). Although they reported high efficiency, the emission of CO was very high, as high as 5000 ppm or more in some cases. A pellet boiler was tested with four different types of pellets showing a similar thermal performance with boiler efficiencies up to 77% [8]. Minimum values of CO were achieved for O_2 concentrations in the flue-gases around 13%. Ref. [9] investigated wheat straw and peat pellet combustion. The results indicated that wheat straw and peat pellets are fuels with relatively low emissions during combustion. However, wood pellets burned efficiently and with even lower emissions than straw and peat pellets during flaming burning. Slagging tendencies of wood pellet ash during combustion were investigated [10]. The results showed that the slagging properties were relatively sensitive to the variations in total ash content and ash forming elements of the fuel. It is therefore recommended that ash rich fuels like bark and logging residues should not be used in the existing residential pellet burners. The results also indicated that the Si-content in the fuel correlated well to the sintering tendencies in the burners. It should be noted that presently so called combustion efficiency of the boiler is determined by flue gas analyzer [7, 19]. This doesn’t give actual overall efficiency of the system. Gas analyzer only accounts dry flue gas loss using Siegert’s formula. Wet flue gas loss is another big loss in case of biomass combustion. In ref. [19] efficiency was shown more than 82% and that in ref. [7] even more than 91%. This study presents actual overall efficiency considering all losses.

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