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Influence from fuel type on the performance of an air-blown cyclone gasifier

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HIGHLIGHTS

- Performance of an air-blown cyclone gasifier have been investigated for different fuels.
- Cleaning system performance have been investigated with SMPS.
- Carbon conversion varied between 70% and 95% for the different fuels.

ARTICLE INFO

ABSTRACT

Entrained flow gasification of biomass using the cyclone principle has been proposed in combination with a gas engine as a method for combined heat and power production in small to medium scale (<20 MW). This type of gasifier also has the potential to operate using ash rich fuels since the reactor temperature is lower than the ash melting temperature and the ash can be separated after being collected at the bottom of the cyclone. The purpose of this work was to assess the fuel flexibility of cyclone gasification by performing tests with five different types of fuels; torrefied spruce, peat, rice husk, bark and wood. All of the fuels were dried to below 15% moisture content and milled to a powder with a maximum particle size of around 1 mm. The experiments were carried out in a 500 kW$_{th}$ pilot gasifier with a 3-step gas cleaning process consisting of a multi-cyclone for removal of coarse particles, a bio-scrubber for tar removal and a wet electrostatic precipitator for removal of fine particles and droplets from the oil scrubber (aerosols). The lower heating value (LHV) of the clean producer gas was 4.09, 4.54, 4.84 and 4.57 MJ/Nm^3 for peat, rice husk, bark and wood, respectively, at a fuel load of 400 kW and an equivalence ratio of 0.27. Torrefied fuel was gasified at an equivalence ratio of 0.2 which resulted in a LHV of 5.75 MJ/Nm^3 which can be compared to 5.50 MJ/Nm^3 for wood powder that was gasified at the same equivalence ratio. A particle sampling system was designed in order to collect ultrafine particles upstream and downstream the gasifier cleaning device. The results revealed that the gas cleaning successfully removed >99.9% of the particulate matter smaller than 1 μm.

1. Introduction

The installed capacity of combined heat and power (CHP) in Sweden is more than 4000 MW at around 160 plants [1]. The overall efficiency (thermal- and electric efficiency) that can be achieved with this type of plant is 85–90% [2] and it is of interest to apply the concept for all domestic and industrial heating. At present, almost all the possible sites for large scale heating in Sweden have been developed but there are still a large number of possible sites where heating demand is above 1 MW [3]. However, when CHP is produced in smaller scale, the relative cost for operations and maintenance increases significantly [4], while the power efficiency goes down [4]. One way to improve power efficiency and potentially reduce operations cost in small scale applications (<10 MW) is to switch from the steam based systems, that are commonly used in large scale processes, to biomass gasification (in small scale) in combination with a gas engine with heat recovery from the exhaust gases.

The cost of the fuel is another important factor that affects overall costs. Therefore, the more fuel flexible a gasifier is the easier it becomes to optimize the overall process. A large number of different types of biomass gasifiers have been proposed and entrained flow gasifiers that operate like a cyclone separator have been shown to tolerate a wide range of fuels [5–11]. The focus of the present paper is to assess the fuel flexibility of a 500 kW$_{th}$ pilot

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cyclone gasifier with a complete gas cleaning system. The assessment is done with respect to use of the cleaned product gas in a gas engine, i.e. the heating value and particle content in the produced gas is determined for comparisons with target values by engine manufactures. Also, the amount of unconverted fuel is measured to make it possible to determine how well different fuels are converted in the gasifier. Another important factor that is important for the cost of gas engine maintenance is the amount and composition of the submicron particles in the cleaned product gas.

Five different fuels (stem wood, peat, rice husk, bark and torrefied spruce) were investigated. From this point on torrefied spruce is referred to as "torrefied". The fuels were selected based on their availability for small scale combined heat and power (in Sweden and elsewhere), and to present results from a wide variation in fuel properties. Torrefaction is thermal treatment of biomass at 200–300 °C [12]. Torrefied biomass is of great interest as a fuel in the energy sector in order to replace fossil fuels. Some of the advantages of torrefied material are lower power consumption during milling, less moisture absorption and higher volumetric energy density [13] which also makes the material suitable for storage and transportation over longer distances than virgin biomass. In Sweden, peat is an interesting fuel that is available at low cost [14]. There is, however, a debate as to whether peat is renewable or not. The Intergovernmental Panel on Climate Change (IPCC) changed the classification of peat from fossil to a separate category between fossil and renewable in 2006 [15]. About 2 million m^3[16] of bark, as a residue from the saw mills, is sold and supplied to heating plants in Sweden. More efficient use of low grade bark fuel is of interest. Outside Sweden, in Asia, large quantities of rice husk are available for use in combined heat and power plants [17]. Rice husk is an especially challenging fuel due to its high ash content, low bulk density and tendency to form bridges during feeding. For example, Sun et al. [10,11] previously studied the effect of secondary air on cyclone gasification of rice husk. By the early 1990s up to 150 rice husk gasifiers were in operation in China with sizes between 100 and 200 kW. However, none of these were based on the cyclone concept [18].

Reliable particle sampling for detailed characterization at high temperatures is important for evaluation and design of efficient gas cleaning devices. Particle filters have, due to the absence of a strong deposition mechanism, low particulate removal efficiency in the particle diameter range of about 0.1–0.5 μm [19]. If catalysts of different types are used for subsequent product gas refinement this fact may impact the overall process performance. Therefore, in addition to the previously mentioned objectives, this work includes high temperature sampling of ultrafine particles both

upstream and downstream of the combined multi-cyclone, bio-oil scrubber and wet electrostatic precipitator (WESP). These measurements are used to evaluate both the reliability of the applied sampling technique and the particulate removal efficiency of the product gas cleaning system.

2. Experimental

Five fuels were evaluated in these experiments. The five fuels were torrefied (Bioendev, Sweden), peat (Överkalix, Sweden), rice husk (An Giang Province, Vietnam), bark (Södra, Sweden) and ordinary stem wood from spruce and pine in approximately equal proportions (GME, Sweden). In Fig. 1 the gasifier schematics are presented. The gasifier consists of a fuel hopper (1) where the dried biomass powder was stored. Before the different powders were fed to the hopper, a hammer mill (Mafa EU-4B) was used to crush the different fuels to suitable particle sizes for cyclone gasification. During milling a sieve with a size of 2 mm was used for torrefied material, peat, bark and wood, and a sieve size of 1.5 mm for rice husk. A sieve stack (Fritsch Analysett 3) was used to determine the particle size distribution of the different fuels. A Zeiss Stemi 2000-C optical microscope was used to visually observe the prepared biomass powders.

From the hopper (1) the powder was transported and metered with an auger screw (2) and fed to the gasifier using air ejectors (3). The powder was then gasified in the cyclone separator shaped reactor (4), char and ash were separated in the bottom of the cyclone (5) and product gas exited through the top of the reactor. The product gas was cooled to an intermediate temperature (300–400 °C), above the condensation temperature for tars, with an air to gas heat exchanger (6). The product gas was cleaned in three steps: (i) a multi-cyclone (7) separated remaining coarse particles into a bin (8), (ii) a bio-oil scrubber with RME (Rape Methyl Ester) as scrubber liquid (9) was used to remove the tars (11), and (iii) a wet electrostatic precipitator (10) where the remaining aerosols and small oil droplets were separated with electrostatic forces. The cleaned product gas can be used in a gas engine (12) coupled to a generator to produce electricity or it can be flared (13). In the current work the gas was flared since the aim with the experiments was to determine the gasification characteristics for the different fuels tested.

2.1. Gasification conditions and gas sampling

During the gasification tests the fuel load was 400 kW and the equivalence ratio (ER) was 0.27 for all fuels, except for torrefied
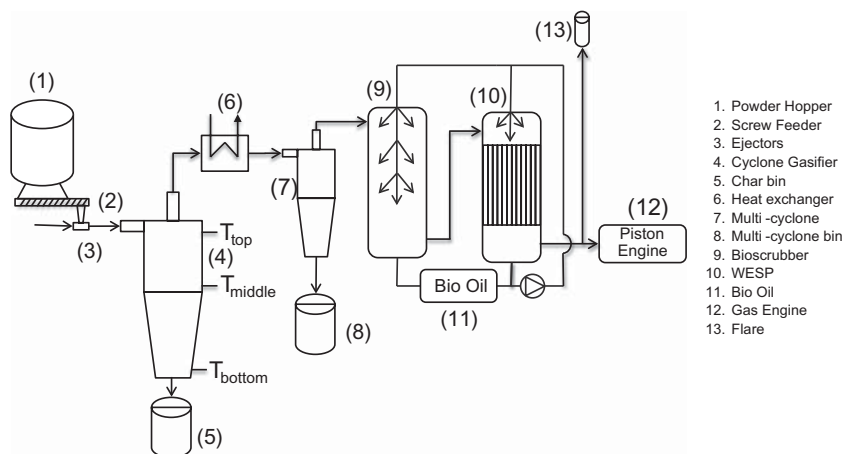

Fig. 1. Schematic of the cyclone gasifier and the gas cleaning equipment.

in which it was 0.2. Wood powder was gasified at both equivalence ratios (0.2 and 0.27). The equivalence ratio is defined as the ratio of air to fuel mass flow rate divided by the air to fuel mass flow rate that is needed for stoichiometric combustion of the fuel. Each test was started with a cold reactor that was heated over night to around 900 °C with an oil burner that was inserted in the lower part of the reactor. The oil burner was then removed and replaced with a ceramic plug made from the same material as the reactor refractory lining. Typically, the reactor temperature dropped 20 °C during this operation. Gasification was then initiated by starting fuel feeding which resulted in ignition of a steady flame in the upper part of the reactor. The gasification process was allowed to continue for about half an hour in order to achieve a stable temperature before the gas sampling was started. However, in all cases the reactor internal wall temperature was still changing slowly as described below. The residues collected in the char bin were analyzed to determine the fuel conversion efficiency. The char bin was purged with nitrogen and then the residues were removed and analyzed for ash amount and element composition by inductively coupled plasma sector field mass spectroscopy. The residues found in the char bin contained a mixture of char and ash. The char was assumed to contain only carbon, whereas the ash contain different ash elements. The char + ash yield was calculated, defined as the ratio of the mass of residues found in the char bin after the experiment and total fuel mass fed to the gasifier during the experiments. In addition, the char and ash yields were calculated separately based on the ash content of the residues collected in the char bin. Since char (and ash) is collected during the whole gasification experiment, the composition of the residues (char and ash) is a time average measurement over the whole gasification time.

The gas composition was analyzed with respect to CO, H_2, CO_2, N_2, O_2, CH_4, C_2H_4 and C_2H_2 using a micro-gas chromatograph (Varian 490-GC) with two thermal conductivity detectors (TCD). The particle concentration was determined by passing a slipstream of the cleaned product gas through a mini-cyclone and an absolute filter (Munktell MG 160) that was heated to 250 °C. A vacuum pump (Gast-72R655-V10-C222TX) was used to pass the slipstream through the filter and a mini cyclone. A gas meter (Gallus 2000) was used to determine the flow rate after the gas had been cooled. The reactor temperature in the top, middle and at the bottom of the cyclone reactor (see Fig. 1) was measured with thermocouples mounted inside the cyclone wall. The calculated cold gas efficiency

(CGE) is the percent of fuel heating value converted into heating value of the produced gas:

$$CGE(\%) = \frac{\dot{m}_g \text{LHV}_g}{\dot{m}_f \text{LHV}_f} \times 100 \qquad (1)$$

where $\dot{m}_g$ and $\dot{m}_f$ is the mass flow rate (kg/s) of the produced gas and fuel, respectively. LHV_g and LHV_f is the lower heating value (MJ/kg) of the product gas and fuel, respectively. The producer gas mass flow rate was estimated based on the amount of nitrogen added to the gasifier with the air, fuel and inert nitrogen in various locations in the plant, and the concentration of nitrogen in the gas measured with the micro-gas chromatograph.

The carbon conversion was determined from the carbon in the gasifier residue in accordance with the calculation from Higman [20], which is based on the amount carbon in the residues collected in the char bin and the amount of carbon in the fuel as:

$$\text{carbon conversion } (\%) = \left(1 - \frac{\dot{m}_{residue}\omega_{Cr}}{\dot{m}_f\omega_{Cf}}\right) \times 100 \qquad (2)$$

where ω_{Cf} is the mass fraction of carbon in the fuel and ω_{Cr} is the mass fraction of char in the residue; $\dot{m}_{residue}$ is the mass flow rate of residue into the char bin and $\dot{m}_f$ is the mass flow rate of fuel into the gasifier. In this definition of carbon conversion the char was assumed to consist only of carbon which results in a conservative estimate of the carbon conversion. The carbon conversion can also be determined based on the carbon in the synthesis gas in accordance with Weiland et al. [21]. However, since only the product gas flow rate could be estimated in the current pilot plant, the carbon conversion was determined in accordance with Higman [20].

2.2. Particle sampling system

The dilution system used for extraction of particles from the gasifier product gas is illustrated in Fig. 2. The main parts were a high temperature dilution probe, a container with activated carbon granules and an ejector diluter. Similar systems for sample dilution and tar absorption have previously been evaluated [22–24].

The dilution probe (length 300 mm) was constructed of a high-temperature resistant stainless-steel alloy (Inconel 600) and consisted of an outer tube (i.d. 12 mm) surrounding an inner tube (i.d. 8 mm). Dilution was achieved at the tip of the probe where the sample flow was mixed with N_2. The entire probe, including
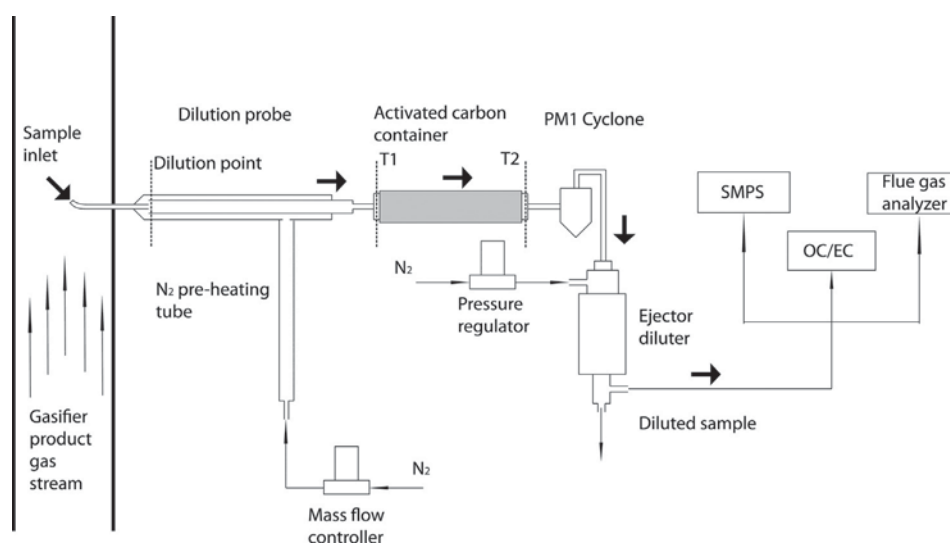

Fig. 2. Schematic of the high temperature particle sampling system. T1 and T2 are the inlet and outlet temperatures of the activated carbon container.

the sample inlet and the dilution nitrogen were heated to a temperature corresponding to the temperature of the sampled gas.

The sampling point was chosen such that sampling could be performed both with and without the gas cleaning system at the same sampling location. With the cleaning system by-passed the temperature of the product gas at the sampling point was 400 °C. With the cleaning system in use the gas temperature was about 50 °C. The dilution temperatures during the two cases were set accordingly. Downstream of the dilution probe the sample dilute sample gas entered a container with activated carbon. The container consisted of a stainless steel pipe (length 300 mm, i.d. 21 mm) filled with activated carbon granules (Norit RB4).

The inlet and the outlet temperature of the carbon container were continuously monitored with two separate K-type thermocouples. When the probe dilution temperature was 400 °C the carbon inlet temperature (T1) was 250 °C and the outlet temperature (T2) was 60 °C. When the probe dilution temperature was 50 °C the inlet temperature was 50 °C and the outlet temperature was 30 °C. By keeping the temperature of the diluted sample high enough at the carbon inlet pre-condensation of tar components on the solid aerosol particles was minimized. Ideally, the dilution temperature should be slightly lower than the sample temperature since condensation is a function of vapor pressure rather than temperature.

A PM1 cyclone was used downstream the carbon container to protect subsequent particle analysis equipment and to avoid clogging of the ejector diluter (Dekati Inc.), which was used to further dilute the sample to 30 °C. The N_2 flow rate was controlled by a mass flow controller (F-201CV, Bronkhorst Inc.) and the pressure applied to the ejector was controlled by a pressure controller (P-602C, Bronkhorst Inc.). Typical N_2 flow rate supplied to the dilution probe was 6.5 lpm.

The total dilution ratio in the sampling setup ranged between 100 and 150 (6 times in the ejector diluter) and was determined by measuring the CO concentration in the undiluted product gas and in the diluted gas downstream the ejector. CO levels downstream of the ejector were monitored with a flue gas analyzer (Testo 350XL, Nordtec Inc.). Particle analysis was performed with a scanning mobility particle sizer (SMPS) and by filter sampling for determination of ratios of elemental carbon and organic carbon (EC/OC). The SMPS consisted of a bipolar charger (Ni-64), a Differential mobility analyzer (DMA, Model 3071, TSI Inc.) and a Condensation particle counter (CPC, Model 3010, TSI Inc.). The SMPS determines the particle size distributions with regards to the particle mobility diameter (d_m). The SMPS was operating at a sheath flow rate of 5.0 or 3.0 lpm and an aerosol flow rate of 1.0 or 0.6 lpm, giving the measured particle size intervals of 11–514 nm and 14–790 nm respectively. EC/OC filter sampling was performed in a tandem filter setup with a Teflon filter followed by a quartz filter in one sampling line and a single quartz filter in a parallel line. The flow rate through each EC/OC sampling line was 5 lpm. A 1.5 sqcm sample punch from each quartz filter was analyzed by a thermo-optical method with a Sunset Lab Dual Analyzer (Sunset laboratory Inc.) using the EUSAAR_2 protocol. Correction for pyrolysis during the temperature stepping in the protocol was done by measuring the laser transmission of the filter. A further description of the thermal optical method for EC/OC determination can be found in Birch and Cary [25].

3. Results and discussion

3.1. Fuel characterization

Table 1 shows the ultimate analysis results of the different fuels gasified. The ultimate analysis shows that rice husk has highest H/C and O/C ratio. This is explained by the lower C content in the rice

Table 1
Ultimate-, proximate analysis and lower heating value of the different fuels.

	Torrefied	Peat	Rice husk	Bark	Wood
Ultimate analysis (wt% dry ash free)					
C	54.9	56.9	49.2	53.1	50.6
H	6.0	6.0	6.1	6.0	6.2
O	38.7	34.1	43.9	40.5	42.9
N	0.1	2.6	0.4	0.4	0.1
S	N.D.	0.3	0.0	0.0	0.0
Proximate analysis (wt% dry)					
Volatiles	77.9	67.9	66.0	70.7	83.9
Fixed C	21.8	26.1	14.7	26.3	15.5
Ash	0.3	6.0	19.3	3.0	0.6
LHV (MJ/kg dry)	20.7	19.6	14.9	18.7	19.1

husk compared to the other fuels, see Table 1. As expected, the torrefied material has H/C and O/C ratios lower than bark, wood and rice husk but not as low as peat. The lower ratios in torrefied, compared to wood, indicate that O and H have been removed during the torrefaction process. Rice husk had similar ratios to those of stem wood.

The proximate analyses of the fuels are also given in Table 1. The rice husk sample contains a significant amount of ash (19.3%). In contrast, the torrefied material only contained 0.3% ash but has a higher volatile fraction than the other fuels, except of course as compared to the virgin wood. The rice husk sample had a lower heating value (14.9 MJ/kg) compared to the other four fuels (18.7–20.7 MJ/kg). In addition, the moisture content of all fuels was below 15%.

Four main steps are involved in the gasification process: (1) drying, (2) pyrolysis, (3) gas phase reactions (homogeneous reactions) and (4) char gasification (heterogeneous reactions). Char gasification is usually the slowest step, determines the overall conversion rate for gasification, and is considered as the rate determining step for gasification [26]. The gasification performance is affected by the fuel properties, presented in Table 1, together with other parameters like wall temperature, equivalence ratio, particle reactivity and particles size.

3.2. Particle size distribution

The particle size distributions of the fuels are shown in Fig. 3. Most of the particles were below 1000 μm. The five fuels had similar particle size distributions with one exception. Peat had more fine (<75 μm) particles compared to the other fuels. Both bark and rice husk had a peak in the particle size distribution for particles between 500 and 1000 μm. The torrefied material was slightly
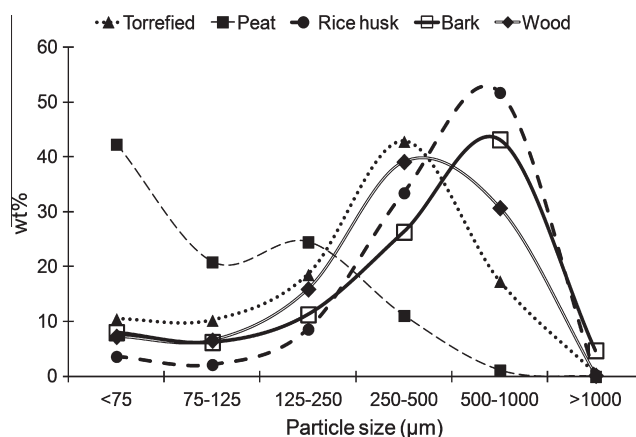

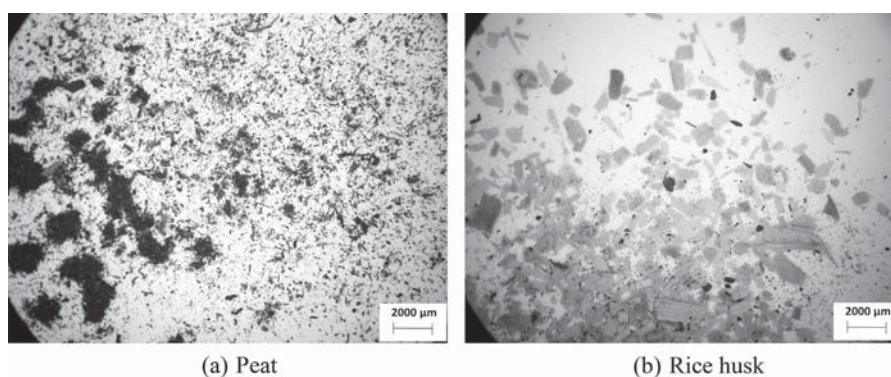**Fig. 3.** Particle size distributions of the fuels tested.

Fig. 4. Optical light microscope images of peat (a) and rice husk (b).

shifted to finer particles than bark, rice husk and stem wood powder, probably as a result of its more brittle mechanical behavior.

Fig. 4 shows optical microscope images of the fuel with the smallest particle size distribution (peat) and largest size distribution (rice husk). It can be seen that peat has a high amount of small particles compared to rice husks which has a high amount of big, flat particles, in accordance with the data in Fig. 3. The other fuels had particle size distributions between these fuels but the particles size distributions were more similar to the rice husk.

3.3. Gasification temperature and main gas components

Fig. 5 presents the gasification temperature in the wall at three different heights (bottom, middle, and top of the gasifier, respectively) for each fuel during 60 min of continuous operation. The thermocouples were mounted inside the wall and therefore the measured temperature will in these experiments be lower than the temperature inside the reactor. The measured temperature can be used to determine if the reactor has reached stable condition and if the temperature inside the reactor is different for different fuels but should not be treated as the real gas temperatures. The temperature at the bottom part of the gasifier is stable for all the fuels at around 650 °C, except for bark which showed 550 °C and wood with equivalence ratio 0.2 where the temperature decreased below 550 °C. In the middle of the gasifier the torrefied and peat had stable temperatures of about 800 °C while the temperature was unsteady and decreasing for rice husk, bark and wood. The temperature decrease is the highest for wood at the lower equivalence ratio. At the top of the gasifier the rice husk, bark and wood (ER = 0.2) have reached stable temperature, while for torrefied it was decreasing. For peat and wood (ER = 0.27) the top temperature was increasing during the gasification. Bark and wood (ER = 0.2) had the lowest overall temperature during gasification (the gasification was started at a lower temperature). For wood gasification at ER = 0.27 an increase in the temperature at the top of the reactor was observed (see Fig. 5f). Similar phenomenon was observed for peat. This is slightly unexpected but could be due to higher flame temperatures than the other cases and hence more radiation which increase the temperature in the top of the reactor.

The main gas components of the producer gas during each gasification test are reported in Table 2. The reported gas components are average values during the test with standard deviation figures based on 10, 17, 17, 17, 4 and 17 samples with a gas sampling cycle time of 3 min for torrefied, peat, rice husk, bark, wood (ER = 0.2) and wood (ER = 0.27), respectively. Gasification of the torrefied material resulted in a product gas with the highest LHV, 5.75 MJ/Nm³. The LHV for torrefied is higher than for stem wood at the same equivalence ratio (0.2). Also the CO and H_2 contents were

higher which indicate higher gasification efficiency than for stem wood.

The other fuels produced gas with a LHV from 4.09 to 4.84 MJ/Nm³, which is at the same level as stem wood powder at the same equivalence ratio (0.27). The higher LHV for torrefied was primarily due to a higher CO content in the gas; 20.1% compared to 15.0–16.9% for the other fuels, mainly because of the lower equivalence ratio (0.2). The concentration of C_2H_4 was 0.52–1.25 mol% and C_2H_2 concentration was 0.3–0.8 mol% for the different fuel tested. It is expected that the gas composition will change with temperature inside the gasifier, but no clear trend was observed for the individual gas components during gasification. This indicates that the overall gasification temperature does not vary significantly during operation. Also, note that the temperature given is the temperature measured by the thermocouples located at the wall and not necessary the actual gas temperatures.

For comparison, the produced gas in the rice husk gasification tests by Sun et al. [10,11] had a LHV of 3.5 MJ/Nm³ when the equivalence ratio was 0.26, which is lower than in the present study. In the present study a higher fuel load of rice husk was used, 400 kW, compared to 100 kW together with a larger gasifier. This will give lower heat losses through the wall since the surface area to volume is smaller for larger gasifiers. Lower heat losses will increase the fuel conversion and give higher LHV for larger cyclones. Also smaller particles were used in the present case which gives higher fuel conversion and higher LHV.

3.4. Char characteristics, carbon conversion and cold gas efficiency

The characteristics of the residues collected in the char bin are shown in Table 3. As expected, the char + ash yield was highest in the rice husk gasification; 22.6%, i.e. 22.6% of incoming rice husk fuel ended up in the char bin. The char + ash yield in the torrefied gasification test was on the other hand much lower, 4.6%, which is equal to the amount for wood gasification at same equivalence ratio. Wood gasification with an equivalence ratio of 0.27 gives the lowest char + ash yield (2.5 wt%). The residue (char + ash) from the char bin was a black, dry and odorless powder for all fuels. The char yield was highest for bark (14.1 wt%) while for wood the char yield was only 2.3 wt%.

The high char yield for bark (14.1%), compared to the other fuels (2.3–7.3%), is probably caused by a high amount of fixed carbon (see Table 1), which needs to be converted by heterogeneous reactions that is usually the slowest step during gasification, together with lower wall temperatures during gasification.

The ash yields observed are in general as expected based on the ash content of the fuel, compare Tables 1 and 3. For torrefied and peat the ash yield was 0.3 and 3.8 wt%, respectively, which corresponds to 100 wt% and 63 wt% of the ash in the fuel. For rice husk
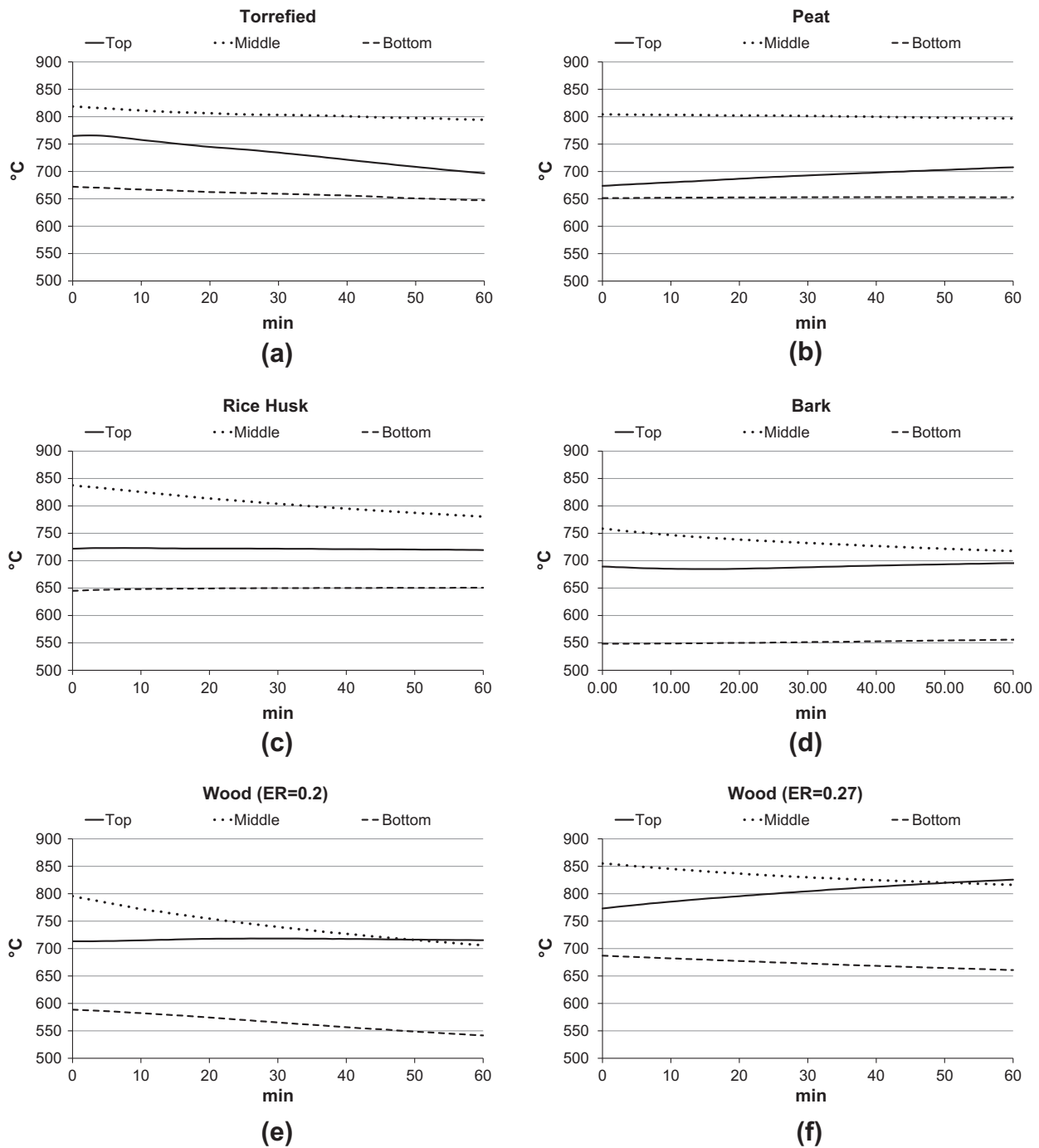
Fig. 5. Gasification temperatures for the different gasification tests in the top, middle and bottom of the gasifier.

Table 2
Gas composition for the different fuels and heating value of the gas after the gas cleaning equipment.

	CO_2 (mol%)	CO (mol%)	H_2 (mol%)	CH_4 (mol%)	C_2H_4 (mol%)	$C_2H_{2\%}$(mol)	LHV (MJ/N m^3)
Torrefied (ER = 0.2)	10.8 ± 0.27	20.1 ± 0.83	9.2 ± 0.20	3.3 ± 0.25	1.25 ± 0.18	0.66 ± 0.08	5.75
Peat (ER = 0.27)	12.0 ± 0.05	15.7 ± 0.12	10.5 ± 0.16	1.5 ± 0.02	0.57 ± 0.02	0.30 ± 0.01	4.09
Rice husk (ER = 0.27)	14.1 ± 0.13	15.1 ± 0.29	6.8 ± 0.14	2.7 ± 0.07	0.99 ± 0.04	0.72 ± 0.01	4.54
Bark (ER = 0.27)	12.9 ± 0.19	16.9 ± 0.35	6.6 ± 0.13	2.7 ± 0.05	1.20 ± 0.03	0.65 ± 0.05	4.84
Wood (ER = 0.2)	12.6 ± 0.11	18.9 ± 0.19	7.7 ± 0.06	3.3 ± 0.10	1.28 ± 0.04	0.78 ± 0.05	5.50
Wood (ER = 0.27)	12.1 ± 0.20	16.0 ± 0.73	8.5 ± 0.41	2.2 ± 0.17	0.52 ± 0.03	0.80 ± 0.02	4.57

the ash yield was 15.3 wt%, which corresponds to 80 wt% of the ash in the fuel. The remaining ash probably follows the product gas as

particles or may be evaporated to the gas phase and ends up in the gas cleaning system. For bark, the estimated amount of ash

Table 3
Char + ash yield, char yield, ash yield, carbon conversion and cold gas efficiency for the different fuels tested.

	Char + ash yield (wt%)	Char yield (wt%)	Ash yield (wt%)	Carbon conversion (wt%)	Cold gas efficiency (%)
Torrefied (ER = 0.2)	4.6	4.3	0.3	91	47
Peat (ER = 0.27)	10.1	6.3	3.8	85	43
Rice husk (ER = 0.27)	22.6	7.3	15.3	79	44
Bark (ER = 0.27)	20.4	14.1	6.3	70	43
Wood (ER = 0.2)	4.6	4.2	0.4	91	49
Wood (ER = 0.27)	2.5	2.3	0.2	95	52

collected in the bottom corresponds to a higher amount of ash than in the bark fed to the gasifier. In these type of pilot scale trials, and especially ash rich fuels, it is more difficult to collect fully representative samples than in a small scale test unit which produces much less material. For example, during start up and shut down more unconverted carbon could end up in the char bin and this will affect the ash yield which is calculated from the mass of ash in the residues found in the char bin.

The carbon conversion was between 70 and 95 wt% for the fuels tested, see Table 3. For torrefied the carbon conversion was 91 wt% which is equal to that for wood (91 wt%) at the same equivalence ratio (0.2). In Fig. 3 it can be seen that the average particle size is smaller for the torrefied compared to the wood sample. It is therefore expected that the carbon conversion will be higher for the torrefied fuel. On the other hand, torrefied has a higher amount of fixed carbon than the wood fuel, see Table 1, which takes longer time to convert and therefore could decrease the carbon conversion. These two effects have the possibility to cancel each other out resulting in similar carbon conversions for torrefied and wood. At an equivalence ratio of 0.27 the carbon conversions were 85, 79, 70, 95 wt% for peat, rice husk, bark and wood, respectively. The low carbon conversion for bark is probably due to the high amount of fixed carbon in the fuel together with a relatively high amount of large particles in the fuel. Peat has a higher carbon conversion compared to bark which has nearly the same amount of fixed carbon. This could be explained by the fact that peat has a smaller average particle size than bark. For peat, the carbon conversion was on the other hand lower than for wood. One explanation for this behavior could be that char reactivity for peat decreases with increasing conversion while wood has the opposite behavior [27]. Also peat has a higher amount of fixed carbon compared to wood. The lower carbon conversion for rice husk compared to wood is probably due to the larger particle size distribution. In the present work it is difficult to separate the effect of fuel reactivity and particle size. However, Guo et al. [28] found that carbon conversion was increased from 59.95 wt% to 82.69 wt%, and gasification efficiency was increased from 39.11% to 52.99% when the particle size was decreased about 4 times.

In the calculation of carbon conversion the amount of particles in the product gas has not been included as unconverted carbon. The amount of particles in the product gas flow has been measured to be around 1 wt% of the fuel input. If the particles are assumed to consist only of carbon then this amount of particles in the product gas corresponds to an error in the estimation of carbon conversion between 2% and 3% for the different cases.

The cold gas efficiency for the 4 tests were 47%, 43%, 44%, 43%, 49% and 52% for torrefied, peat, rice husk, bark, wood (ER = 0.2) and wood (ER = 0.27) respectively. The cold gas efficiency has a relatively large uncertainty since the producer gas flow rate was estimated from the concentration of nitrogen (as reference) in the product gas and from the nitrogen added to the gasifier plant. Also, the amount of tar formed was not taken into account. For comparison, in the cyclone gasification tests with rice husk in Ref. [10], the cold gas efficiency was 32% at the same equivalence ratio used here

(0.27). At lower equivalence ratios (0.21) a much higher cold gas efficiency (64%) was observed [10]. Zhao et al. [29] found out a maximum cold gas efficiency of 63.7% for their cyclone gasification experiments with rice husk at a fuel load of 130 kW and an equivalence ratio of 0.26 where they used fuel and air staging to increase the gasification efficiency. The amount of tar measured by other authors for cyclone gasification of wood powder and rice husk have been in the range 1-3 g/Nm^3[9,29].

A mass balance over the gasifier estimated that the mass flow out from the gasifier was 9 wt%, 7 wt%, 9 wt%, 1 wt%, 9 wt% and 5 wt% lower than the total mass flow into the gasifier for torrefied, peat, rice husk, bark, wood (ER = 0.2) and wood (ER = 0.27), respectively. One possible source of inaccuracies is measurement errors in the air flow controller. The product gas flow is therefore also underestimated and the cold gas efficiency is also probably underestimated. Also, the equivalence ratio is therefore also probably slightly higher for all experiments. For example if the mass flow rate of air is underestimated by 10 wt% the estimated cold gas efficiency is assumed to increase by 4%. A mass balance of carbon over the gasifier estimated that mass flow of carbon out from the gasifier was 18 wt%, 15 wt%, 6 wt%, 16 wt% and 8 wt% lower than the mass flow of carbon into the gasifier for torrefied, peat, rice husk, wood (ER = 0.2) and wood (ER = 0.27). For bark the estimated carbon mass flow out from the gasifier was 6 wt% higher the carbon mass flow into the gasifier. The inaccuracy in the carbon balance comes mainly from the inaccuracies the predicated product gas flow mention above, together with that the amount of tar in product gas was not measured. The estimated higher mass flow of carbon out from gasifier for bark case is possibly due to a not fully representative ash+char sample mentioned before.

The composition of the residues obtained in the char bin is given by the data in Table 4 for torrefied, peat, rice husk and bark. Most of the residue from the rice husk test is composed of Si as expected. Peat and bark also had a significant amount of Si in the residue but also some Al, Ca, Fe and K. The torrefied material had low amount of ash, where most of it was Si and Ca. For stem wood the ash composition was not measured.

Table 4
Analysis results of char + ash (as is).

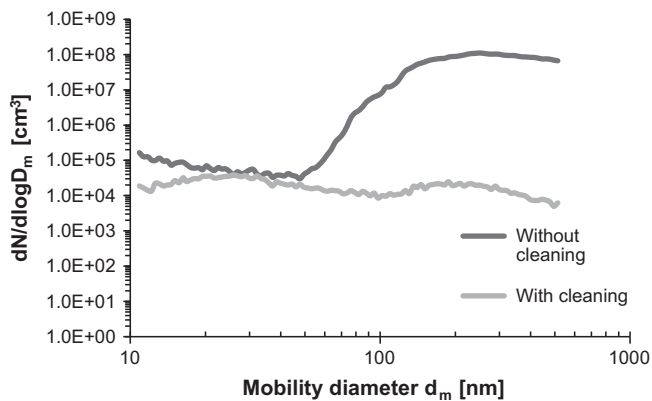| Element	Rice husk	Peat	Bark	Torrefied
Char (wt%)	32.3	62.3	68.8	94.1
Ash 1000 °C (wt%)	67.7	37.7	31.2	5.9
Si (wt%)	30.71	8.32	8.98	1.09
Al (wt%)	0.04	2.86	1.44	0.09
Ca (wt%)	0.22	3.00	3.02	0.98
Fe (wt%)	0.14	5.48	0.71	0.41
K (wt%)	0.78	0.30	1.22	0.39
Mg (wt%)	0.10	0.36	0.41	0.18
Mn (wt%)	0.06	0.05	0.26	0.08
Na (wt%)	0.09	0.28	0.55	0.08
P (wt%)	0.08	0.27	0.16	0.11
Ti (wt%)	0.00	0.07	0.06	0.00
O (wt%)	35.47	16.70	14.39	2.48

Fig. 6. Particle size distributions obtained upstream and downstream gasifier cleaning system (oil scrubber and WESP) during rice husk gasification.

3.5. Sub-micron particulate matter measurements

The dust load in the cleaned gas was 43, 9, 16 and 13 mg/Nm³ for torrefied, peat, rice husk and bark respectively measured by letting a side stream passing the particle through a mini cyclone and a particle filter.

Fig. 6 depicts the sub-micron (<1 μm) particle size distributions obtained upstream and downstream of the gasifier cleaning system, including the oil scrubber and WESP. The fuel used for gasification was rice husk.

A particulate removal efficiency >99.9% is observed, in terms of total particle number concentrations, with a total concentration of 4×10^7 particles/cm³ ($d_m < 514$ nm) for no gas cleaning and 3×10^4 particles/cm³ with gas cleaning. Assuming unit particle density (1 g/cm³) the total particle mass concentration was 880 mg/m³ and 0.2 mg/m³ respectively. Since the measurements were meant for a relative comparison and not absolute quantitative determinations particle losses in the sampling system were not considered.

Fig. 7 shows results from SMPS measurements downstream of the WESP during bark gasification. The dilution temperature and the temperature into the carbon container were altered in order to make an evaluation of the volatility of the particles.

As the inlet temperature of the activated carbon container (Fig. 7a) was allowed to decrease, the geometric mean diameter (GMD) increased. This is mainly explained by increased condensation as the temperature decreased. Above 200 °C the size distribution is bimodal with a nucleation mode and an accumulation mode (Fig. 7b). A higher temperature of the diluted gas into the carbon
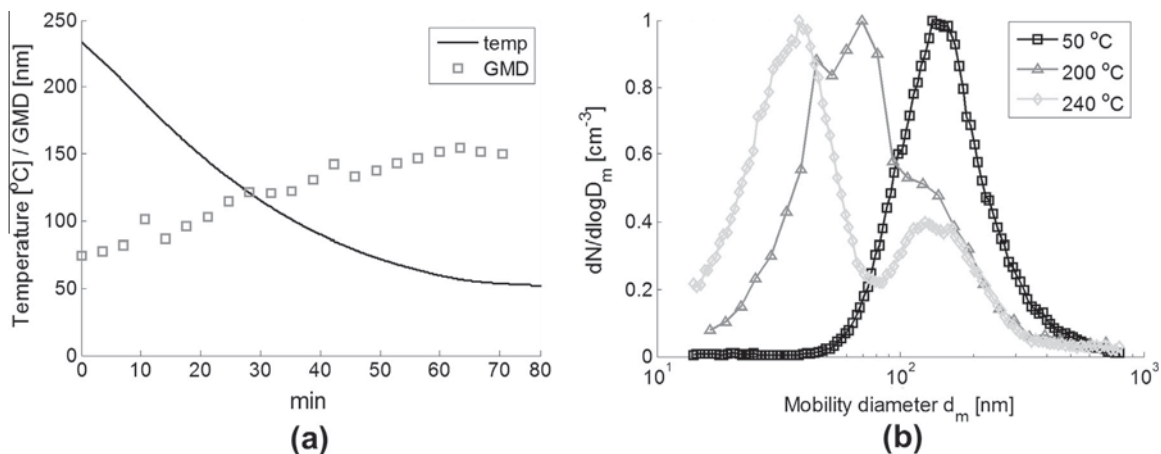
container means that more volatile material is kept in vapor phase, which subsequently can be absorbed by the carbon granules as the temperature is lowered across the carbon container. With lower temperatures pre-condensation on the existing aerosol particles and nucleation of new particles occur. The fact that the accumulation mode did not significantly increase in mean diameter (~130 nm) indicates that these particles were solid agglomerates [22]. The results imply that the particulate matter downstream the WESP in terms of mass to a large degree consisted of volatile material which can be argued to originate from the bio-oil being used in the scrubber.

Filter samples for determination of the fraction of elemental carbon (EC) and organic carbon (OC) were collected during bark gasification upstream the bioscrubber. The EC/OC ratio on the quartz filters was determined to 1.3 ± 0.7 indicating that the particulate matter present at the sample temperature (400 °C) consisted of roughly equal amounts of EC and OC. 10% of the total carbon content on the filter was detected below 300 °C in the EUSAAR-2 temperature stepping procedure. This shows that the sampling system, with a combined dilution probe and a carbon container, successfully absorbed most of the volatile organics that condensed below the sampling temperature. Since the surface area available for condensation is much higher on the carbon granules, compared to the aerosol particles, condensation of the tars preferably occurs on the granules. At high sampling temperatures (>250 °C) a temperature decrease is necessary prior to the carbon container. During this temperature decrease undesired condensation of OC on the aerosol particles may occur. If higher temperatures could be used at the carbon container inlet the absorption capacity could be increased. However, with the current sampling design, a longer container would have been necessary to keep the carbon outlet temperature at the same level, which would come with the cost of higher particle losses.

4. Conclusions

In this work gasification of torrefied spruce, peat, rice husk and bark were performed in a cyclone gasifier at a fuel load of 400 kW. The lower heating value (LHV) of the clean producer gas was 4.09, 4.54, 4.84 and 4.57 MJ/Nm³ for peat, rice husk, bark and wood respectively at a fuel load of 400 kW and an equivalence ratio of 0.27. Torrefied spruce was gasified at an equivalence ratio of 0.2 which resulted in a LHV of 5.75 MJ/Nm³ which can be compared to 5.5 MJ/Nm³ for wood powder that was gasified at the same equivalence ratio.

The estimated cold gas efficiency for the fuels tested were 47%, 43%, 44%, 43%, 49% and 52% for torrefied, peat, rice husk, bark, wood (ER = 0.2) and wood (ER = 0.27), respectively. The cold gas

Fig. 7. (a) Geometric mean diameter (GMD) of sampled particles as the temperature at the activated carbon inlet during bark gasification was decreased. (b) Normalized particle number distributions at three different carbon bed inlet temperatures.

efficiency was calculated from indirectly measured gas flow rates and further work is needed to determine it more accurately. However, a preliminary analysis with estimated errors in the gas flow rate indicates that the real cold gas efficiency is about 4% higher than the values above. The gasification tests indicate that a higher amount of fixed carbon in the fuel decrease the fuel conversion and fuels with smaller particle size gives higher fuel conversion.

The particle measurement with SMPS shows that the gas cleaning efficiency of sub-micron particles with a combined oil scrubber and WESP is >99.9% in terms of both particle number and mass. The particle sampling technique that was applied was found to be effective in preventing volatile material, which existed in gas phase at the sampled temperature, from condensing on the existing particles during sampling. Undesired condensation during the sampling process changes the obtained particle size distribution. This is important to consider when evaluations of cleaning devices are performed at high temperatures.

Acknowledgements

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