DISPOSAL OF PYROLYSIS RESIDUE BY INCINERATION

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ABSTRACT

In order to exploit all the energy potential that lies in the processing of waste material or biomass, there is a public pressure to recover as much of the material as possible before the landfill process takes place. One widespread method is the gasification process, which can generate a potentially energy-harvestable gas or liquid based on the set gasification conditions. The only waste material is the solid residue (char), which often contains large amounts of carbon (up to 84%), making it suitable for further use. One way of using char is to burn it in an experimental fluidisation unit, which is suitable for burning up to 3 kg·h of char and generating an equivalent gas (flue gas). The fully controllable fluidised bed combustion unit has a diameter of 140 mm and a height of up to 350 cm, and the fluidised bed consists of ST 54 glass sand with a mean grain size of 0.22 mm. This combustion process reduces the volume of the original material by up to 95%. The gas generated by the combustion process represents a potential for use in heat exchangers for heating feed water, in drying plants or cement plants. The quantitative and qualitative evaluation of the resulting thermal process products is described in this paper, as is the pyrolysis and combustion unit. The average low heating value (LHV) for pyrolysis char is 20.3 MJ kg^{-1}, which represents a great potential in terms of its energy recovery. The reduction in volume of the original sample is 52.9–91.6%, where the heat output of the flue gas is 5.54–15.27 MJ kg^{-1}.

Keywords: pyrolysis, char, incineration.

1 INTRODUCTION

Today, electricity consumption is growing and in 2018 was 23.4 trillion kilowatt hours compared to 2000 when global consumption was 13.3 trillion kilowatt hours, an increase of 76% [1]. Hand in hand with this fact, waste production is also increasing, with the current production of two billion tons of waste per year [2]. In this sense, great emphasis is placed on the recovery of waste, primarily for reuse, recycling or energy recovery. Pyrolysis is one of the ways to use waste or biomass for energy purposes [3].

Pyrolysis is the thermochemical decomposition of organic matter into noncondensable gases, condensable liquids and solid residual coproduct (char) [4]. This treatment is characterised by exposing the material to high temperatures in the absence of airborne oxygen. During the process, the feedstock undergoes physical and chemical degradation into different molecules. It is an endothermic process that is achieved by the high energy content of the common materials [5]. This study focuses on the pyrolysis process of six feedstocks, namely: solid recovered fuel (SRF), digestate, straw, polyethylene, hay pellets and tires.

The solid residual coproduct called char is mainly perceived as a by-product of the pyrolysis process, but it also carries a relatively large amount of energy that could be used [6]. This study works with the concept of combustion of char in an experimental fluidized bed unit, which produces a gas (flue gas) that is further suitable for energy recovery in thermal or electrical power generation. This experimental fluidized bed combustion unit is characterized by its versatility, therefore a wide range of materials can be burned in it as the paper shows [7].

WIT Transactions on Ecology and the Environment, Vol 260, © 2022 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SC220221

The resulting combustion process is monitored by pressure sensors, flow meters and thermocouples located along the entire length of the combustion unit. For quantitative and qualitative evaluation of the composition of the exhaust gas, an analyser based on the FTIR atmosFIRt by protea principle is applied. This analyser is capable of detecting CO_2, CO, H_2O, NO, NO_2, N_2O, SO_2, NH_3, HCl, HF, CH_4, C_2H_6 and O_2 [8].

The novelty of this study lies in the determination of the mass loss of char due to its combustion in an experimental fluidization unit to form an energy gas. The percentage loss of char, the flue gas production due to the combustion of 1 kg of char in six different feedstocks and the energy potential of the flue gas in terms of use in feedwater preheating, evaporator or steam superheater are described [9].

2 EXPERIMENTAL WORK

2.1 Pyrolysis unit

The experimental process was carried out on a laboratory pyrolysis unit (Fig. 1). It is a small batch reactor with the possibility of reaching a maximum temperature of 900°C. The advantage of the unit is its smaller scale, which allows flexible operations and to perform more tests in less time. The packed bed reactor can hold fuel in the range of 100–1000 g depending on the granulometry and density of the fuel. The laboratory unit can be divided into multiple process units such as reactor, product cooler, pyrolysis gas cleaning with subsequent analysis. For ease of handling, the fuel is loaded in a steel liner. The reactor is composed of two parts – the vessel body itself and the lid. Two electrical elements are located on the outside of the vessel. The first is wound on the cylindrical part of the reactor, under which a thermocouple is placed to monitor the temperature of the reactor shell. The second element is placed on the bottom of the reactor. The individual heating elements can be independently controlled to adjust the temperature in the reactor. A pipeline for the pyrolysis products and the inerting gas supply is located at the top of the reactor.

All configuration and process settings are done via a PLC control unit that is connected to a computer. In the user interface of the computer, it is possible to observe the data in real time, while at the same time the data is stored on disk.

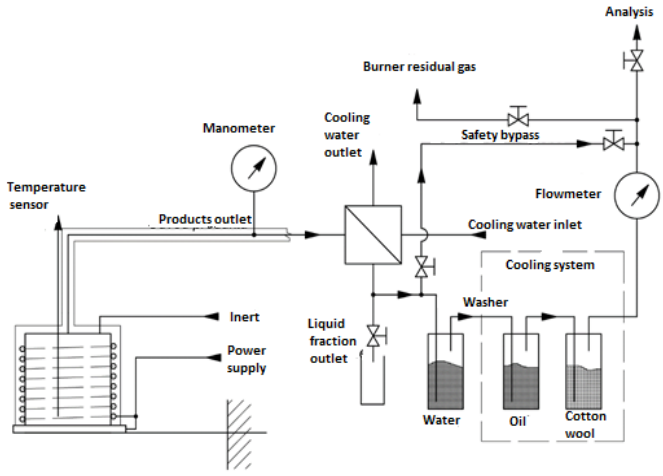

Figure 1: Scheme of pyrolysis experimental setup [10].

2.2 Incineration experimental setup

The experimental combustion unit (Fig. 2) is situated as a fluidized bed reactor with a stationary fluidized bed. Fuel input is provided by two screw conveyors with a conveying capacity of up to 3 kg·h^{-1}. The controllability of the conveyors is in the range of 0–100%. Combustion air conveyance is provided by a blower with a capacity of 57 m^3·h^{-1}, which is also adjustable between 0–100%. The air blower is followed by a combustion air preheater which can operate in the range 0–500°C. To monitor the combustion air flow rate, an air flow meter is located behind the air preheater. Ensuring the required temperature for fuel ignition is achieved by resistance heaters with a total power input of 8.8 kW. The unit is also equipped with a secondary air source that can be used for CO afterburning or primary/secondary air splitting. The underpressure in the whole system is created by a smoke fan with an output of 300 m^3·h^{-1}.

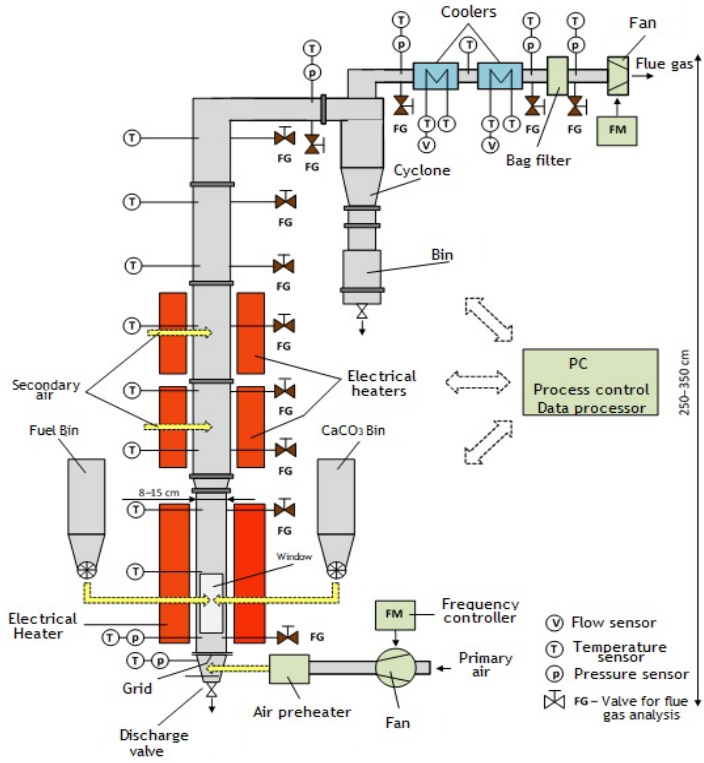

Figure 2: Scheme of experimental incineration unit [7].

The fluidized bed is made up of ST 54 glass sand with an average grain size of 0.22 mm. The base height of the fluidised bed in steady state is 100–140 mm depending on the type of fuel and mainly the ash content. As it is a stationary fluidised bed without continuous drainage, it must be taken into account that during combustion the ash produced is deposited in the fluidised bed, whereby the bed is gradually degraded. For this reason, the operating time of the unit is a maximum of five operating hours, considering the ash content of the fuel.

2.3 Combustion equation

To determine the total heat output of the flue gas, it is necessary to perform a stoichiometric calculation of perfect combustion and determine the required volume of combustion air [11]. Minimum dry air volume $V_{air,min}$ for the ideal combustion of 1 kg of fuel is based on the equation:

$$V_{air,min} = \frac{100}{21}\left(22.39 \cdot \left(\frac{C^r}{12.01} + \frac{H^r}{4.032} + \frac{S^r}{32.06} - \frac{O^r}{32}\right)\right), \quad (\mathrm{m^3_N \cdot kg^{-1}}) \quad (1)$$

where C^r, H^r, S^r, O^r (–) represent, respectively, the relative concentrations of carbon, hydrogen, sulphur and oxygen in the raw sample.

The real amount of combustion air $V_{air,r}$ is based on the equation:

$$V_{air,r} = V_{air,min} \cdot \lambda \cdot \nu, \quad (\mathrm{m^3_N \cdot kg^{-1}}) \quad (2)$$

where λ is the equivalence ratio and ν the proportional increase in air volume due to moisture content.

The amount of water in the flue gas is determined from the equation:

$$V_{H2O} = \frac{44.8}{4.032} H^r + \frac{22{,}4}{18.016} w^r + (\nu - 1) V_{air,min}, \quad (\mathrm{m^3_N \cdot kg^{-1}}) \quad (3)$$

where w^r represents the relative moisture content.

An essential parameter for the assessment of fuel quality is the determination of low heating value (LHV) by Dulonga [12]:

$$LHV^r = 33.91C^r + 121.42H^r + 10.47S^r - 15.18O^r - 2.45w^r. \quad (\mathrm{MJ \cdot kg^{-1}}) \quad (4)$$

For flue gas heat utilisation purposes, the specific enthalpy of the flue gas needs to be determined depending on its temperature and composition. The specific enthalpy of the flue gas can be expressed as the sum of the enthalpies of the gas components. It is necessary to define the specific enthalpy of the stoichiometric flue gas $h_{fg,min,s}$ for $\lambda = 1$, the enthalpy of the minimum amount of air $h_{air,min}$, flue gas enthalpy $h_{fg,r}$ of a given temperature when burning 1 kg of fuel with excess air α and heat output of flue gases Q_{fg}:

$$\begin{aligned} h_{fg,min,s} = {} & V_{CO2} \cdot h^t_{CO2} + V_{SO2} \cdot h^t_{SO2} + V_{CO} \cdot h^t_{CO} + V_{NOx} \cdot h^t_{NOx} + V_{N2} \\ & \cdot h^t_{N2} + V_{CH4} \cdot h^t_{CH4} + V_{NH3} \cdot h^t_{NH3} + V_{HCl} \cdot h^t_{HCl} + V_{H2O} \\ & \cdot h^t_{H2O} + a_{fa} \cdot A^r \cdot h^t_{fa} \end{aligned} \quad (\mathrm{MJ \cdot m^{-3}_N}) \quad (5)$$

$$h_{air,min} = V_{air,min} \cdot h^t_{air} + (\nu - 1) V_{air,min} \cdot h^t_{H2O}, \quad (\mathrm{MJ \cdot m^{-3}_N}) \quad (6)$$

$$h_{fg,r} = h_{fg,min,S} + (\lambda - 1) \cdot h_{air,min}, \quad (\mathrm{MJ \cdot m^{-3}_N}) \quad (7)$$

$$Q_{fg} = V_{spal} \cdot h_{fg,S}, \quad (\mathrm{MJ \cdot kg^{-1}}) \quad (8)$$

where V_{CO2}, V_{SO2}, V_{CO}, V_{NOx}, V_{H2O}, V_{N2}, V_{CH4}, V_{NH3}, V_{HCl} represent the relative volume fractions in 1 m^{-3}_N of the individual components in the flue gas, h^t_{CO2}, h^t_{SO2}, h^t_{CO}, h^t_{NOx}, h^t_{H2O}, h^t_{N2}, h^t_{CH4}, h^t_{NH3}, h^t_{HCl} (kJ m^{-3}) represent the enthalpies of the individual components as a function of temperature, a_{fa} represents the relative fly ash drift, A^r is the relative ash content of the fuel, h^t_{fa} (kJ m^{-3}) is the enthalpy of fly ash and V_{spal} ($m^3 \cdot kg^{-1}$) is the amount of flue gas generated by incineration of 1 kg of fuel.

3 RESULTS AND DISCUSSION

3.1 Pyrolysis process

As these are quite diverse materials, each fuel needs to be treated individually. For example, the carbon content of the raw material ranged from 38.6% to 78.8% and the hydrogen content from 2.43% to 5.59%. The ash content was also very variable, ranging from 34.59% for polyethylene to only 6% for tyres.

Another important aspect is the residence time of the fuel in the reactor, with the longest residence time for straw and specifically 190 minutes and the shortest, 90 minutes, for polyethylene. The long residence time for straw was due to the lower process temperature of 350°C compared to the others, which ranged from 430°C to 600°C, which agrees with other studies [13], [14]. The weight of the batch was always selected individually depending on the specific volume of the material so that the reactor was suitably filled.

The output yields of the different fractions also varied. The highest proportion of char was in SRF, up to 77 wt.%, while the lowest proportion of solid residue was in polyethylene, 16 wt.%. As for the gas fraction, the yields ranged from 15 to 30 wt.% except for SRF, which was the outlier with a yield of only 3%. The liquid fraction was 14 to 61 wt.% [15], [16].

Elemental analysis and determination of water and ash content were applied to define the composition of the char as a fuel for further combustion in the fluidised bed experimental unit. The resulting values are given in Table 1.

Table 1: Elemental composition of the solid residue (char) + water and ash.

Feedstock	C	H	S	N	O	Water	Ash
				(wt.%)			
SRF	40.8	5.34	0.31	0.87	12.5	4.0	36.2
Digestate	45.2	2.13	0.40	2.61	8.1	14.3	27.2
Hay pellets	43.9	10.18	0.19	1.88	7.8	4.5	31.6
Straw	38.1	4.59	0.21	0.16	9.1	2.2	45.6
Polyethylene	39.9	1.59	0.14	0.16	2.5	3.2	52.2
Tyres	82.3	1.16	2.84	0.45	2.5	0.8	10.1
Uncertainty ± (%)	0.5	2	3	3	–	2	1
Standard	EN ISO 16948	EN ISO 16948	EN ISO 16994	EN ISO 16948	EN ISO 16993	EN ISO 181234-2	EN ISO 18122

3.2 Char incineration

Fig. 3 shows the temperatures at the combustion point, in the middle of the reactor and at the reactor outlet, with thermocouples placed at 100 mm, 1100 mm and 1800 mm and the grate. The results show that the combustion temperature varies considerably due to the calorific value of the fuel and its composition. The highest temperature was for tyres, namely 1078°C, followed by hay pellets with 1042°C. This temperature was at the edge of the carrying

capacity, in the sense of melting the reactor. The combustion temperature factor affects the final flue gas temperature at the reactor outlet, with tyres at 482°C and hay pellets at 450°C. In contrast, the lowest temperatures were 589°C for polyethylene at combustion and 323°C at the outlet. The stabilisation process was complicated due to the different calorific value of the material, its size and density. The flue gas temperature had a large effect on the heat outputs [17], which is clearly seen in the results. Temperature measurements were carried out for 30 minutes for all six samples, each time from the time of stabilisation of the combustion process.

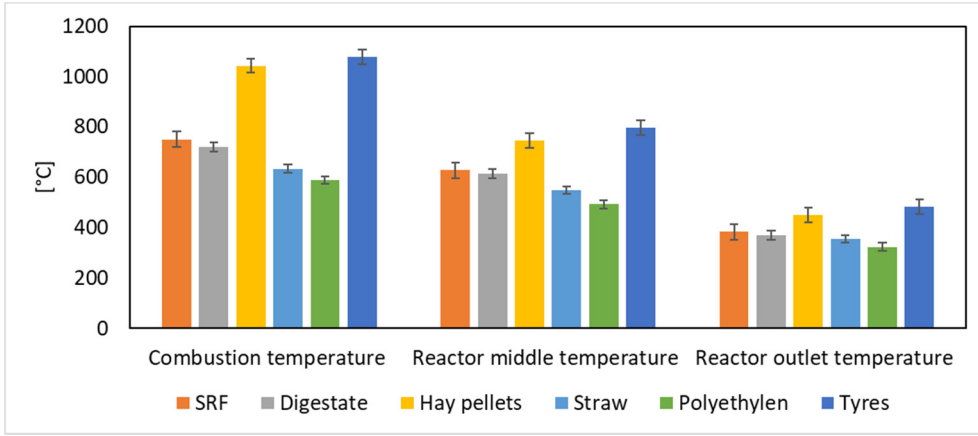

Figure 3: Temperature course in the reactor.

Table 2 shows the average concentrations of the measured flue gas components as average values over a period of 30 minutes. The slightly elevated CO concentration for hay pellets is due to the size of the pellets, which slow down the combustion process by accumulating material in the reactor hearth. The higher carbon and hydrogen content contributed to the slightly increased methane concentration in the flue gas primarily for tyres, SRF and hay pellets. The oxygen concentration range was in the range of 7.1–8.2 vol.%, resulting in a relatively stable combustion process. The high sulphur content of the fuel was reflected in the SO_2 concentration for tyres, where its concentration exceeded the others by almost a factor of two. All measured concentrations (except H_2O and O_2) were converted to normal conditions i.e. 101325 Pa, 0°C, dry condition and reference oxygen content of 6 vol.%.

Table 2: Average composition of the individual flue gas components.

Fuel	H_2O	CO_2	O_2	CO	SO_2	NO	NH_3	HCl	CH_4
	(vol. %)			($mg \cdot m^{-3}$)					
SRF	9.3	5.1	8.2	65.1	1,291.8	421.5	0.8	15.6	29.5
Digestate	8.7	5.6	8.1	57.8	1,378.9	613.8	1.0	8.4	17.5
Hay pellets	8.2	5.3	7.3	133.5	1,233.3	570.5	0.5	58.7	28.3
Straw	10.2	4.3	8.1	77.2	1,401.7	391.5	1.1	21.3	1.2
Polyethylene	7.6	3.9	7.9	88.4	1,178.5	386.1	1.3	14.7	4.3
Tyres	10.3	5.8	7.1	75.1	1,908.6	400.7	1.7	1.3	35.9

Depending on the combustion equation, the average calorific value of the fuels was determined, which depended on the elemental composition. Results from Table 3 show that the pneumatic sample has the highest LHV, namely 29.21 MJ·kg^{-1} which corresponds to a high coal content of 82.3 wt.% in the sample. Next in line are hay pellets, where the high LHV is primarily due to the high hydrogen content of the sample, 10.18 wt.%. The average LHV was 20.3 MJ·kg^{-1}. The mass reduction of the original sample was an important parameter in this study. The mass loss Δm was determined based on the balance of the ash material to the amount of ash deposited in the fluidized bed plus the amount of fly ash. It could be shown that the highest mass loss was 91.6% for the tyres sample, which is based on the relatively low ash content of the sample. The lowest mass loss was for the polyethylene sample, namely 52.9%, due to the low LHV (15.02 MJ·kg^{-1}) and the high ash content of the sample (52.2 wt.%). For the calculation of the specific enthalpy $h_{fg,r,}$ the values from the Engineering Equation Solver (EES) by F-Chart software were used depending on the reactor outlet temperature. The average value of $h_{fg,r}$ was 1.1 MJ·m$^{-3}_{N}$. Depending on the flue gas volume V_{spal} and specific enthalpy $h_{fg,r}$, the heat output Q_{fg} of each fuel was determined. The results showed that the best fuel in terms of heat output was the tyres sample, for which Q_{fg} was 15.27 MJ·kg^{-1}. Another relatively high heat output was the hay pellets sample with 12.21 MJ·kg^{-1}. The remaining samples were in the range of 5.54–8.00 MJ·kg^{-1}, and it is up for discussion whether such heat output is sufficient to be further used in heat exchangers.

Table 3: Average density ρ, LHV and particle size D of fuel. Flue gases volume V_{fg}, mass loss Δm, flue gases specific enthalpy $h_{fg,r}$ and heat output Q_{fg}.

Fuel	ρ (kg·m^{-3})	LHV (MJ·kg^{-1})	D (mm)	V_{fg} (m^3·kg^{-1})	Δm (%)	$h_{fg,r}$ (MJ·m$^{-3}_{N}$)	Q_{fg} (MJ·kg^{-1})
SRF	321.4	18.36	0.8	7.25	65.1	1.103	8.00
Digestate	286.4	16.38	1.4	6.73	74.2	1.008	6.78
Hay pellets	231.6	25.98	5.5	10.01	67.6	1.218	12.21
Straw	109.6	17.08	0.7	6.67	58.4	0.98	6.54
Polyethylene	750.0	15.02	0.4	5.86	52.9	0.945	5.54
Tyres	382.4	29.21	2.5	11.31	91.6	1.351	15.27

4 CONCLUSION

The results of the study showed that the pyrolytic residue that would have been condemned to landfill has the potential for reuse. This statement is supported by the result of the heat outputs of the flue gas, which reach values of 15.27 MJ·kg^{-1}, while the average value of heat outputs was 9.06 MJ·kg^{-1}. These values were determined by combusting six different chars in an experimental fluidization unit, which serves as a versatile device for combusting a wide range of materials with different calorific values and different particle sizes. The average LHV was 20.3 MJ·kg^{-1}, which is comparable to black coal mined in Czech mines. Another result that emerged from this study is that the mass loss of material after combustion was up to 91.6%. This study demonstrates that char is a suitable alternative fuel as a possible replacement for conventional fuels with some limitations.

ACKNOWLEDGEMENT

This work was supported by the Doctoral grant competition VSB – Technical University of Ostrava, reg. no. CZ.02.2.69/0.0/0.0/19_073/0016945 within the Operational Programme Research, Development and Education, under project DGS/TEAM/2020-036 “Gasification residue char utilisation as mercury capture sorbent in fluid boiler flue gas flow”.

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