Single-stage plasma gasification of RDF

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Abstract: Experiments with refuse-derived fuel (RDF) were performed on a single-stage plasma gasification reactor system. The performance of the process in converting the feedstock to syngas is assessed for different oxidizing agents (H_2O, CO_2 + H_2O and CO_2 + O_2). The experimental results show that syngas composition varies significantly with gasifying agent(s), while carbon conversion efficiencies vary only slightly.

Keywords: Plasma gasification, refuse-derived fuel, syngas production, single-stage

1. Introduction

The anthropogenic climate change due to greenhouse gas emissions and the depletion of fossil fuels have initiated a gradual shift towards heat and electricity generation systems based on renewable energy sources [1]. This transition in the energy industry and the depletion of natural resources in general have also triggered the waste industry to phase out unsustainable waste-management practices and move towards more resource-efficient and environmental-friendly technologies [2]. One of the possible alternatives for recovering resources from waste material to a greater degree than conventional thermochemical conversion technologies (such as mass incineration) is plasma gasification.

Plasma gasification is the process in which carbonaceous material is decomposed into syngas (consisting mainly of carbon monoxide and hydrogen) by an external supply of energy from a plasma source in the presence of stoichiometric amounts of free- or bound oxygen for the global gasification reaction.

The use of plasma for energy supply allows the processing of a wide range of waste materials (e.g. used tires [3], hazardous waste [4]) since the gasification is independent of the energy content of the feedstock.

The material stream of interest in this work is refuse-derived fuel (RDF), which is a fuel obtained by processing solid waste materials (e.g. municipal solid waste (MSW) and industrial waste (IW)) [5]. The research on RDF plasma gasification is limited. Lemmens et al. [6] reported results of RDF processing with a transferred arc, Taylor et al. [7] performed experiments with RDF on a two-stage plasma gasification reactor and other research [8, 9] focused on analysing the performance of RDF plasma gasification with thermodynamic equilibrium models.

In this paper, results from single-stage plasma gasification experiments with RDF, using a non-transferred arc, are presented. The specifics of the reactor configuration are explained in Section 2. Different gasifying agents (and combinations thereof) are tested. The resulting syngas compositions are compared to investigate the influence of gasifying agent on the process chemistry. Furthermore, energy efficiencies and other performance criteria (carbon conversion efficiency, CO yield and H_2 yield) are discussed.

2. Experimental set-up

The experiments were performed on the plasma gasification reactor PLASGAS at the Institute of Plasma Physics (IPP) in Prague. A schematic of this system is shown in **Figure 1**.

A detailed description of the reactor system was previously published by Hrabovsky et al. [10].

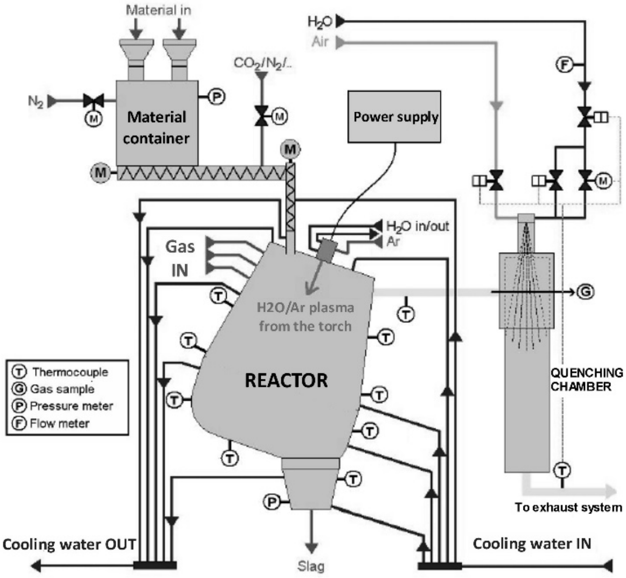

Fig. 1. Schematic of the plasma gasification reactor system PLASGAS

The reactor has an inner volume of 0.22 m^3 with thermocouples at six different positions to measure the temperature of the inner wall. At the top of the reactor, an oxygen-hydrogen-argon plasma jet is created by the DC hybrid water/argon stabilized plasma torch [11].

The material to be gasified is continuously supplied from the material container by a screw conveyer and falls into the reactor volume under gravitational force. In this single-stage plasma gasification configuration, the material travels through the reactive high-temperature plasma jet region and is partially gasified in-flight.

The inlets for the gasifying agents (O_2, H_2O and CO_2) are located in the upper part of the reactor. A specific amount of argon is also added to the reactor as internal standard. From the total amount of argon entering the reactor (i.e. internal standard and argon from the torch) and the concentration of argon in the syngas, the total flow rate of syngas can be calculated.

The outlet for the produced gas is positioned in the upper part of the reactor, to ensure the syngas passes through the high-temperature plasma jet region before exiting the volume. The gas then flows to a cylindrical quenching chamber with a length of 2 m and diameter of 0.3 m to cool the gas to 300°C.

The produced syngas is collected for on-line composition analysis by mass spectrometry at the outlet of the reactor by a sampling tube which is cooled by water spray when it crosses the quenching chamber. The mass spectrometer is calibrated to measure the relative concentrations of CO, H_2, CO_2, CH_4, O_2 and Ar.

3. Feedstock properties

The refuse-derived fuel (RDF) is processed from excavated waste from landfill sites. It is composed of municipal solid waste (MSW, 59%) and industrial waste (IW, 41%). Detailed information about the methods followed to excavate and characterize the landfill waste can be found in the study performed by Quaghebeur et al. [12]. The proximate and ultimate analyses of the RDF are summarized in **Table 1**.

The compositional analysis provides a rough estimation of the different material types the RDF material is composed of and results in 47% plastics, 24% wood and paper, 10% textiles and 18% fines on mass basis. A plastics content of 47% is a relatively large fraction when compared to the RDF materials studied by other researchers [13,14] who report plastic fractions varying from 16% to 26%. However, this follows logically from the high plastics fraction present in the industrial waste (66%), combined with the high amount of industrial waste (41%) used to produce the mixed RDF material used in these experiments.

The material has a moisture content of 4.4% on as-received basis and the lower heating value of the dry material is 22.37 MJ/kg

Table 1. Proximate and ultimate analysis of RDF

Proximate analysis		**Ultimate analysis**	
	wt% dry		wt% dry
fixed carbon	8.6	C	46.80
volatiles	69.3	H	5.70
ash	22.1	O^a	22.29
		Cl	1.60
		N	1.25
		S	0.26
		[a] by difference	

4. Gasification results

In all experimental runs, the material feed rate was 29 kg/h, the power of the plasma torch was kept at 120 kW and the flow rate of argon as internal standard was set to 87 standard litre per minute (slm). The syngas temperature, the different combinations of gasifying agents added in the experiments and the corresponding equivalence ratio (ER) can be found in **Table 2**. The temperature of the syngas is measured at the gas outlet of the reactor.

The equivalence ratio (ER) is defined as the ratio of the total amount of available moles of oxygen added to the process to the stoichiometric required amount of moles for the complete oxidation of the material. The oxidation reaction considered is displayed in **Equation 1**.

Table 2. Process parameters for the experiments

Case	**T**	F_{H2O}	F_{CO2}	F_{O2}	**ER**
	K	$ml.min^{-1}$	slm	slm	
1	1323	0	177	93	0.61
2	1307	144	178	0	0.60
3	1262	300	0	0	0.44

The syngas composition for the different cases, measured during pseudo-steady state conditions over a time period of several minutes, is shown in **Figure 2**.

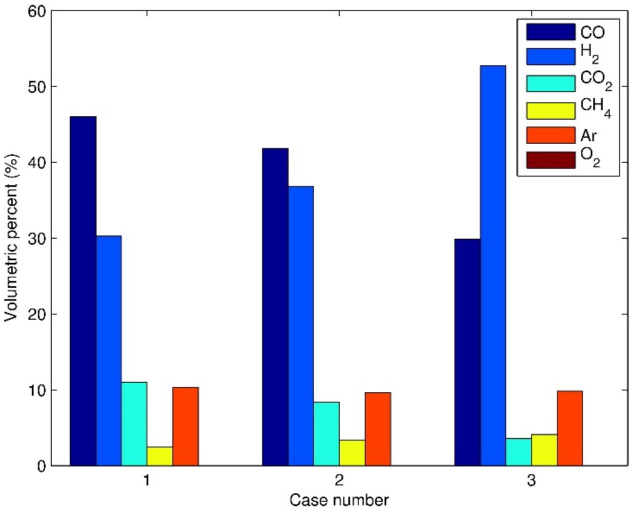

Fig. 1. Syngas composition in volumetric percent

In Case 1, the combination of carbon dioxide and oxygen as gasifying agents leads to high levels of carbon monoxide and a low H_2/CO ratio of 0.66. The CO_2 concentration is relatively high at 11.0%, most likely because of an excess of added CO_2, since the partial oxidation reaction with O_2 (**Equation 2**) is favoured over the Boudouard reaction with CO_2 (**Equation 3**). The combination of carbon dioxide with water as gasifying agents in Case 2 yields higher levels of hydrogen gas than in Case 1. This can be explained by the two important conversion reactions which take place with H_2O, namely, the steam reforming reaction (**Equation 4**) and the water-gas shift reaction (**Equation 5**). Together with the competing Boudouard reaction, these three predominant reactions lead to a higher H_2/CO ratio of 0.88 and a slightly lower CO_2 concentration of 8.4%.

Case 3 represents steam plasma gasification, which produces a syngas with a very high hydrogen fraction, a H_2/CO ratio of 1.77 and a low CO_2 concentration of only 3.6%. In all three cases, the CH_4 concentration is lower than 4%.

Besides syngas composition, other frequently used indicators for analysing the performance of plasma gasification processes are carbon conversion efficiency, CO yield and H_2 yield. Carbon conversion efficiency is defined as the ratio of the amount of carbon in the syngas to the amount of carbon in the feed (i.e. from waste and from CO_2 as gasifying agent). CO yield is the ratio of the number of carbon atoms in the CO fraction of the syngas to the total number of carbon atoms injected. The definition of H_2 yield is the ratio of the number of hydrogen atoms in the H_2 fraction of the syngas to the total number of hydrogen atoms injected. The values of these performance indicators for the three cases are plotted in **Figure 3**.

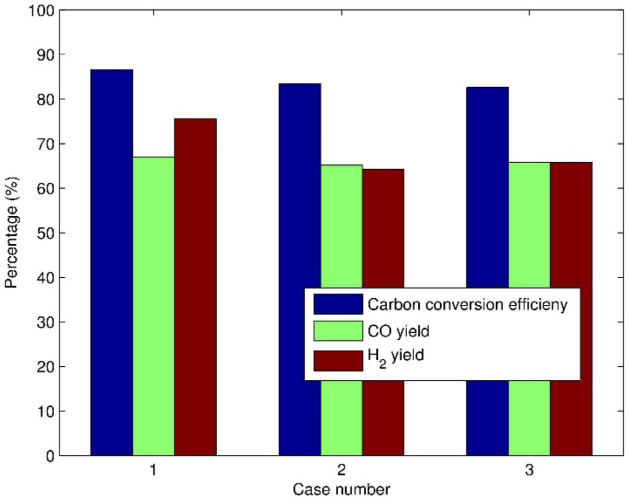

Fig. 2. Performance criteria

The CO yield is almost identical for all three cases (65%-67%), whereas the H_2 yield is clearly higher for Case 1. The lower H_2 yield in Case 2 & 3 can be explained by the use of water as (one of) the gasifying agent(s), which may not be completely consumed by the gasification reactions.

The carbon conversion efficiency achieves high values between 83% and 87% with the highest value for Case 1 by combining CO_2 and O_2 as gasifying agents.

In terms of energy efficiency, the cold gas efficiency (CGE) and mechanical gasification efficiency (MGE) for the three cases are summarized in **Table 3**, together with syngas yield and lower heating value (LHV) of the syngas. CGE is the ratio of the heating value of the produced syngas to the energy input to the system (i.e. heating value of RDF and electrical power to the plasma torch). MGE is the ratio of the heating value of the produced syngas to the heating value of the RDF.

Table 3. Energy efficiencies (CGE and MGE), syngas yield and syngas lower heating value (LHV)

Case	**CGE**	**MGE**	**Syngas yield**	**LHV**
	%	%	$m^3.kg^{-1}$	$MJ.m^{-3}$
1	48	82	1.75	9.9
2	54	92	1.87	10.5
3	56	94	1.84	10.9

Overall, the single-stage plasma gasification of RDF produces a medium calorific value syngas with a net calorific value between 10 and 11 $MJ.m^{-3}$. Case 3 reports the highest energy efficiencies and calorific value of the syngas. The lower syngas yield, the higher CO_2 concentration and lower CH_4 concentration resulted in the lowest energy efficiencies for Case 1.

5. Conclusions

Single-stage plasma gasification of RDF has been proven to produce medium calorific value syngas with high levels of CO and H_2 using different (combinations of) gasifying agents. The syngas composition varies significantly depending on the selected gasifying agent(s). Adding a combination of CO_2 and O_2 (Case 1) yields a H_2/CO ratio of 0.66, whereas syngas with a H_2/CO ratio of 1.77 is produced with pure H_2O (Case 3). Carbon conversion efficiencies vary only slightly between 83 and 87%, with the highest value for Case 1 because of the high ER and most accessible oxygen carrier (O_2).

The most performant experimental run was Case 3, which uses water as gasifying agent and which leads to cold gas- and mechanical gasification efficiencies of 56% and 94%, respectively.

In future work, these results obtained for plasma gasification of RDF will be compared to identical experiments with biomass as feedstock, as well as to other RDF plasma gasification experiments.

6. Equations

$$C_{a1}H_{a2}O_{a3}Cl_{a4}N_{a5}S_{a6}A_{a7} + xO_2 \rightarrow q_1CO_2 + q_2H_2O + q_3HCl + q_4NO + q_5SO_2 + q_6A \quad (1)$$

$$C + CO_2 \rightarrow 2CO \quad (2)$$

$$C + \frac{1}{2}O_2 \rightarrow CO \quad (3)$$

$$C + H_2O \rightarrow CO + H_2 \quad (4)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (5)$$

7. Acknowledgments

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