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Plasma gasification of refuse derived fuel in a single-stage system using different gasifying agents

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ABSTRACT

The renewable evolution in the energy industry and the depletion of natural resources are putting pressure on the waste industry to shift towards flexible treatment technologies with efficient materials and/or energy recovery. In this context, a thermochemical conversion method of recent interest is plasma gasification, which is capable of producing syngas from a wide variety of waste streams. The produced syngas can be valorized for both energetic (heat and/or electricity) and chemical (ammonia, hydrogen or liquid hydrocarbons) end-purposes. This paper evaluates the performance of experiments on a single-stage plasma gasification system for the treatment of refuse-derived fuel (RDF) from excavated waste. A comparative analysis of the syngas characteristics and process yields was done for seven cases with different types of gasifying agents ($CO_2 + O_2$, H_2O, $CO_2 + H_2O$ and $O_2 + H_2O$). The syngas compositions were compared to the thermodynamic equilibrium compositions and the performance of the single-stage plasma gasification of RDF was compared to that of similar experiments with biomass and to the performance of a two-stage plasma gasification process with RDF. The temperature range of the experiment was from 1400 to 1600 K and for all cases, a medium calorific value syngas was produced with lower heating values up to 10.9 MJ/Nm^3, low levels of tar, high levels of CO and H_2 and which composition was in good agreement to the equilibrium composition. The carbon conversion efficiency ranged from 80% to 100% and maximum cold gas efficiency and mechanical gasification efficiency of respectively 56% and 95%, were registered. Overall, the treatment of RDF proved to be less performant than that of biomass in the same system. Compared to a two-stage plasma gasification system, the produced syngas from the single-stage reactor showed more favourable characteristics, while the recovery of the solid residue as a vitrified slag is an advantage of the two-stage set-up.

1. Introduction

The emission of greenhouse gases, created by exploitation of fossil fuels, has been rising exponentially since the industrial revolution (Marland et al., 2008). This pollution poses serious risks for ecosystems and to human health and is threatening to cause an anthropogenic climate change. This has initiated a shift towards heat and electricity generation systems based on renewable energy sources (Creutzig et al., 2014). Concurrently, the depletion of coal, gas, oil and other natural resources makes the extraction of raw materials more difficult and more energy-intensive, which results in additional environmental burden (Hoel and Kverndokk, 1996). The global demand for resources (energy and materials) will continue to grow, driven by the fast-expanding world population and urbanization, while their future availability is limited. There is a broad consensus that a transition towards a resource efficient circular economy is necessary in this context of increasing material demands. Sustainable waste management is an important aspect in this transition as it aims at the integral valorization of waste streams and at closing the material loop (Wilson, 2007).

Waste is considered a very promising renewable resource, both for energy as for material purposes. It will be an abundant resource for the future, since the global solid waste generation is rapidly accelerating, due to the economic development and increased

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buying power in current developing countries. Nowadays a large amount of waste is still being landfilled. One of the reasons for this is the limited range of waste streams which can be processed with the currently available conversion technologies. The most common method to process waste is incineration, which mainly focuses on energy recovery (electricity and heat production), but it is associated with an extensive gas cleaning of large volumes of off-gases to remove hazardous emissions. The aforementioned factors have led the waste industry to phase out unsustainable waste-management practices (e.g. landfills) and move towards more resource-efficient and environmental-friendly technologies (Bosmans et al., 2013). Plasma gasification is a promising alternative for conventional thermochemical conversion technologies as it offers a substantially higher resource recovery potential.

Plasma gasification is an allothermal process (by means of a plasma torch) in which the organic fraction of the waste is thermally decomposed into their constituent elements (syngas). Plasma acts as a reforming agent for the gas phase by breaking down unwanted complex hydrocarbons in the syngas. Depending on the configuration, the reforming aspect of plasma can also be applied on the solid phase, by melting the inorganic fraction and converting it into a dense, inert, non-leachable vitrified slag. Furthermore, the use of plasma as an energy source allows the processing of a wide range of waste materials – including wastes with a high inorganics fraction – since the gasification is independent of the energy content of the feedstock. Syngas as the principal product can be used as feedstock for the production of chemicals such as hydrogen, ammonia, methanol or other liquid hydrocarbons (via Fischer–Tropsch process). Alternatively, it can be used for electricity production in steam turbines, gas turbines or fuel cells (Wang et al., 2008). The vitrified slag can be re-used as a secondary product (e.g. interlocking blocks, tiles and bricks). The versatile plasma gasification technology can overcome several limitations of conventional autothermal gasification, such as material yield, syngas purity, dynamic response, compactness and flexibility (Fabry et al., 2013) and offer the possibility of integrated resource recovery (both energy and materials). A detailed overview of possible system configurations and material types processed by plasma gasification can be found in the comprehensive reviews by Heberlein and Murphy (2008) and by Gomez et al. (2009).

The materials stream of interest in this work is refuse-derived fuel (RDF), which is a fuel obtained after processing of certain waste materials (e.g. municipal solid waste (MSW) and industrial waste (IW)). The research on plasma gasification of RDF is limited. In a pilot installation adapted from a system for metallurgical applications, Lemmens et al. (2007) treated RDF with a transferred arc. The residual slag from the experiment was characterized to comply with the Flemish legislation for use as a secondary building material, however, no conclusive results were obtained about the performance of syngas production, because of the non-optimal design. Taylor et al. (2013) treated RDF from MSW with the Gasplasma process, which comprises an oxy-steam bubbling fluidised bed gasifier and the subsequent plasma converter. The results of experiments on this two-step system show the effective generation of a clean syngas with high carbon and energy conversion efficiencies, and which composition compares well with theoretical predictions. Other research (Galeno et al., 2011; Achinas and Kapetanios, 2013) focused on analyzing the performance of RDF plasma gasification with thermodynamic equilibrium models. Galeno et al. discussed the integration between a fluidized bed plasma torch gasification unit and a solid oxide fuel cell, which was calculated to produce a net energy output of about 4.2 MJ kg^{-1} and would have a net electric efficiency of 33%.

Since 2005, research on the plasma gasification unit at the Institute of Plasma Physics (IPP) of the Academy of Science of the Czech Republic (ASCR) has been performed (Van Oost et al., 2005). This reactor is equipped with a unique DC hybrid water/gas stabilized torch, creating a high enthalpy high velocity plasma, ideal for waste treatment (Březina et al., 2001). In this single-stage system, the material fed to the reactor is partially gasified in-flight when it passes the high-temperature region created by the plasma. With this set-up, different types of material, i.e. biomass (sawdust and pellets) (Hrabovský et al., 2006; Van Oost et al., 2006; Hrabovský et al., 2009; Van Oost et al., 2008), oil (Hrabovský et al., 2011) and plastics (Hrabovský et al., 2010) have been successfully converted to syngas in which the sum of carbon monoxide and hydrogen amounted up to 90 vol%.

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. The results from several cases with different mixtures of gasifying agents are analyzed and their performance assessed. The measured composition of the produced syngas is compared to the theoretical composition at thermodynamic equilibrium. Additionally, process yields (e.g. carbon conversion efficiency) and energy efficiencies are calculated. Furthermore, the influence of the type of material gasified on the performance of the plasma gasification system is investigated by comparing the results of RDF experiments with previously published results from experiments with biomass. Finally, the output of these experiments is compared to that of experiments with RDF from other plasma gasification facilities.

2. Material and methods

2.1. The reactor system

The experiments were performed on the plasma gasification reactor PLASGAS at IPP. A schematic overview of the system is shown in Fig. 1, reproduced from Hrabovský et al. (2006). The reactor has an inner volume of 0.22 m^3 and is coated with special refractory ceramics. Four layers of different insulation materials with a total thickness of 400 mm separate the inner surface of the reactor from the water-cooled outer walls to reduce the heat losses from the reactor. The temperature of the inner wall of the reactor is measured in six positions by thermocouples (WRe5–WRe26 and PtRh30–PtRh6) in a ceramic sheath. To prevent destruction of the ceramic coating, the reactor is pre-heated by an electric rod prior to the experiments for 24 h to temperatures of about 1200 K. Further heating is produced by the plasma torch.

The hybrid DC water/argon stabilized plasma torch is mounted on top of the volume and can operate at currents between 350 A to 550 A and arc powers of 90–160 kW. The anode of the torch is a rotating water-cooled copper disc, positioned outside of the arc chamber. This configuration generates an oxygen–hydrogen–argon plasma jet which offers a wide range of performance characteristics (Hrabovský et al., 2006). Both the heat losses from the reactor wall and the energy losses inside the arc chamber are determined from calorimetric measurements on the respective cooling circuits.

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. The gas inlets for the gasifying agents (O_2 and CO_2) are located in the upper part of the reactor. The volumetric flow rates of these oxidizing gases (F_{O_2} and F_{CO_2}) are set using thermal gas mass flow controllers (Aalborg GFC-57 and Aalborg GFC-47 respectively). The inflow of liquid water as gasifying agent is positioned at the top of the reactor and the mass flow rate (Q_{H_2O}) is measured by weight difference.

The outlet for the produced gas is positioned in the upper part of the reactor, so that the syngas passes through the high-temperature plasma jet region before exiting the volume.

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