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Study of the effects of temperature on syngas composition from pyrolysis of wood pellets using a nitrogen plasma torch reactor

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ABSTRACT

This work shows work flows supported by experimental work to analyse the efficiency of a plasma system in biomass conversion processes. The most common set of problems encountered when using biomass-to-energy (BTE) processes relate to tar formation and product gas composition. However, using plasma technology to convert biomass provides a solution because it unlocks more energy than can be achieved by other BTE systems by using a heat supply derived from electricity. The research presented in this paper focuses on the conversion of biomass to chemical energy (in gaseous form) with the aid of the electrical energy supplied by a water-cooled nitrogen plasma torch. The authors conducted a series of experiments in a continuous pyrolysis set up in which wood pellets were converted to syngas in a small-scale laboratory nitrogen plasma torch reactor with a maximum power supply of 15 kW. The efficiency of the process was measured in terms of the carbon conversion to all product gases which changed from 43 to 77%, at temperatures ranging from 400 °C to 1000 °C respectively. The combined carbon monoxide and hydrogen mole concentration in the product gas (without nitrogen) was 86% at 1:1 ratio for all temperatures studied. Syngas yield increased with increase in temperature. The overall biomass conversion obtained increased from 46% to 82% for the temperatures 400 °C to 1000 °C respectively, with the balance comprising carbon-rich solid residue and liquid. The work flow shows that a plasma system can get to high temperatures but work is also degraded in the overall process. Exergy analysis shows that the work lost by the overall process decreases with increase in process temperature.

1. Introduction

Plasma technology makes it possible to decompose biomass through pyrolysis in order to produce high quality syngas which is a blend of carbon monoxide and hydrogen gases [1]. In this process, the plasma supplies all the energy needed for pyrolysis resulting in no energy from combustion is required for the decomposition of the biomass material. Syngas is produced from the C, H and O elements that are present in the biomass material, without the need to add any oxidising media [2]. The product gas perhaps contains less carbon dioxide because no extra oxygen is added to the process and this results in high calorific value of the syngas produced. According to a model by Schuster et al., the oxygen content of biomass has a considerable influence on the chemical efficiency of the biomass conversion system. However, the authors attribute temperature as the strongest effect on chemical efficiency [3].

Another notable difference between the use of plasma and conventional pyrolysis processes is that the gas produced by the latter is usually contaminated with tars and has therefore to be cleaned before being sent on for downstream processing. Also, tars are abrasive and increase the maintenance cost of conventional systems. Plasma reactors, on the other hand, can make the gas cleaning process unnecessary as the high temperatures and high heating rate they can achieve are not reliant on a combustion process but produce clean syngas with a high calorific value [2,4]. The biomass plasma process is also more efficient than the combustion method of BTE because it helps to convert the chemical potential in the solid feed to syngas. This reduces the chemical potential that remains in the solid chars after pyrolysis which in turn results in a higher chemical energy output in the syngas [2].

In the pyrolysis process, thermal decomposition, reforming, water gas shift reactions, recombination of radicals and dehydrations can occur as functions of residence time, temperature and pressure profiles [5]. For instance, syngas can be used for power generation via a turbine, and as feedstock for the production of synthetic liquid fuels in the Fischer-Tropsch process.

The advantage of using a plasma reactor is that the plasma torch is

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an independent and direct heat source. This allows the controlling of reactor temperature independent of fluctuations in the feed quality and also the use of possibly different reactants [6]. This is different form the case in conventional processes where the reactor is designed for a certain feed and the calorific value of the feed materials is required for the heat source [7]. The analysis made by Lapuerta et al. indicated that the influence of the reaction temperature on the gasification/pyrolysis characteristics was not as significant as that of the biomass/air ratio for conventional biomass processes [8].

The possible feed rate is determined by the plasma power available for biomass pyrolysis. Conversely, this power requirement is affected by the amount of moisture in the biomass material. Usually, plasma systems for biomass conversion processes are operated at temperatures higher than 900 °C in order to produce syngas with a low methane content. In addition, high pyrolysis temperatures are required for thermodynamic and kinetic reasons [2]. Hence, there is little scope for use of catalysts in the reactors [9,10].

The energy efficiency of biomass conversion processes varies from 75 to 80%, depending on the composition and heat capacity of the raw material [11]. Janajreh et al. have carried out some modelling and simulations using Gibbs Energy minimization to compare the energy efficiency of the plasma process to the conventional air gasification process. The authors recorded that the average plasma efficiency was 42% compared to 72% for the conventional method for converting biomass, oil shale, tire and coal to syngas [12]. This was due to the high energy supplied to the plasma system when air or steam are used as plasma gas. In addition, a model by Schuster et al. shows that a net electric efficiency of about 20% can be achieved in a plasma system [3]. According to Fabry et al., gasification by thermochemical decomposition of biomass material produces syngas in which one can recover up to 80% of the chemical energy contained in the organic matter initially treated [2]. Hrabovsky showed that a gas composition containing a high concentration of hydrogen and carbon monoxide can be achieved at temperatures above 900 °C with a steam/argon plasma [13]. At even higher temperatures, the composition of hydrogen and carbon monoxide obtained from plasma gasification/pyrolysis of dry wood biomass remains fairly constant at 0.42 and 0.55 respectively [1]. The increase in temperature favours the boudouard reaction. Hence, it increases the CO/CO_2 ratio which raises the heating value of syngas [6]. It has also been shown through Aspen simulations that a high Equivalence Ratio (ER) reduces hydrogen production while a high Steam-to-Biomass Ratio (SBR) increases hydrogen production [14]. The latter authors have further shown that the Lower Heating Value (LHV) of the product gas decrease with increase in ER and SBR, but increaseS with temperature. Another simulation in Aspen shows that temperature increases production of CO and H_2 (syngas), while increasing ER decreases both the syngas production as well as the Cold Gas Efficiency (CGE) [15]. Hlina et al. carried out experiments on wood pellets using a water-argon DC plasma arc and obtained a LHV of 157.4 kW h/kg for syngas from a feed of wood pellets with LHV of 145.1 kW h/kg [16]. The latter authors also attributed the overall low energy efficient of the plasma system to the electricity energy requirement (100–110 kW) despite having obtained a syngas composition of 90% by volume. Je-Lueng Shie et al. shows that the overall syngas yield increased with temperature on plasma pyrolysis of sunflower oil cake and that CO and H_2 have equal volume fractions of ~49% at 600 °C [17]. Research has shown that the amount of product gas during pyrolysis can reach up to 80% of the feed mass [18]. The syngas produced can reach up to 94% by volume of the total gas produced from plasma pyrolysis of rice straw biomass using nitrogen as a carrier gas in a batch process [4]. Zhao et al. obtained a maximum carbon and oxygen conversion of 79% and 72% respectively from pyrolysis of wood and rice husks using an argon/hydrogen plasma system [19].

According to Hrabovsky, all carbon and hydrogen atoms from biomass material can be converted into syngas, provided the biomass is heated to a sufficiently high temperature [13]. Higman and Van der Burgt reported that the temperature range at which all volatile matter of any biomass material is converted to synthesis gas is around 800–900 °C [9]. At temperatures higher than 800 °C, soot formation begin to compete with oxidation processes. Gasification/pyrolysis at higher temperatures also prevents the production of higher hydrocarbons [20]. However, standard gasification technologies operate the reactor in the 400–850 °C range [21]. These low temperatures cannot break down all the biomass materials. Hence, the product at low temperatures constitute of tars that are difficult to remove and also other contaminants that must be further cleaned [3]. The char residue is up to 15% of the weight of the feed material and must be disposed of in a landfill [21]. Tars form when a reaction occurs between a heated carbon source and a limited amount of oxygen [13]. However, when a plasma pyrolysis system is used, the extreme temperature of the plasma tail-flame which gets in direct contact with the feed materials inside the reactor also prevents tars and other long chain carbon compounds from forming.

This explains the investigation into the results of increasing process temperature that forms the basis of this research paper. The prerequisite for the experiments was to use a plasma reactor to reach higher temperatures (above 800 °C) at which equilibrium is reached and compare the results with that of lower temperatures [22]. The work presents experimental results obtained from a small-scale nitrogen plasma reactor with a power range of 1.8–15 kW and a water-cooled plasma torch. Electricity was used to supply energy to the process. Wood pellets were converted via pyrolysis in a nitrogen plasma reactor at temperatures of 400 °C, 600 °C, 800 °C and 1000 °C and the yields of gaseous, liquid and char products for each temperature were compared. Most of the research that is available in this field has been carried out on steam/argon plasmas [1,16,7]. Steam contains hydrogen and oxygen that may also take part in the reaction to make syngas while argon is chemically inert. However, in this study, a pure nitrogen plasma in a continuous system was used. This was due to its higher enthalpy as it can achieve a higher temperature compared to an argon/steam plasma for the same current input. For this reason, a lower current setting can be used to reach the desired power input. Various researchers have expressed the opinion that at a lower current, electrode erosion is minimised due to a lower current density on the arc attachment points, which extends the lifespan of the electrodes [23,24]. For this reason also, a nitrogen plasma was chosen for this study. According to a critical review by Gomeza et al., economic and socio-political drivers are encouraging the adoption of using plasma conversion processes as compared to alternative waste treatment/disposal options [25].

2. Process materials and experimental method

2.1. The plasma reactor system

The plasma system shown in Fig. 1 constitutes a water-cooled, DC, non-transfer arc, thermal plasma torch **(1)** with copper electrodes mounted on top of a reactor chamber **(2).** The reactor chamber volume is ~1.63 L and is made of a 25 mm thick ceramic wall. Silica sand fills the 40 mm thick gap between the side of the ceramic wall and the outside steel casing to reduce heat loses. The top part of the reactor chamber is covered with a ceramic crucible lid 25 mm thick with holes to accommodate only the plasma torch, feed inlet and product outlet sections, a view port **(3)** and a type R thermocouple. A feed hopper **(4)** with a nominal capacity of 96.4 L and fitted with a variable speed screw conveyer **(5)** transports the feed into the plasma reactor. In addition to this, a 15 kW max DC power supply (Jeenel Technology Services), double annulus solid-liquid quench heat exchanger and two Gortex blow-back gas filters **(6)** forms part of the system. The torch, comprising a copper anode and cathode, is water-cooled and is positioned on the top flange of the reactor chamber. Water is also used to cool the quench probe and the feed inlet pipe **(7)** leading to the reactor chamber. These cooling circuits are used to measure heat losses of the