Preliminary Characterization of Carbon Dioxide and Steam Microwave Plasma Torch for Gasification Applications

S. Vecten[1], A. Martin[1], A. Dexter[1], B. Herbert[2], M. Wilkinson[2], N. Bimbo[1], R. Dawson[1]

[1]*Engineering Department, Lancaster University, Lancaster, United-Kingdom*
[2]*Stopford Energy & Environment, Ellesmere Port, United-Kingdom*

Abstract: Microwave-induced plasma (MIP) is an innovative technology with potential application for waste treatment and clean energy generation. The study presents the investigation of an MIP torch operated with carbon dioxide and steam. Optical spectroscopy measurements demonstrate the dissociation of CO_2 and H_2O molecules. This work shows that the MIP torch can generate a high temperature environment with very active chemical species, making it a promising technology for waste and biomass gasification.

Keywords: Microwaves, Plasma, Carbon dioxide, Steam, Gasification

1. Introduction

Waste management and energy generation are considerable greenhouse gas emissions sources causing climate change and are thus major challenges in modern society. Energy from waste is one of the solutions to those two challenges. There are large amount of waste that could be diverted from landfill for energy generation such as commercial and industrial waste (C&IW) and municipal solid waste (MSW) [1]. However, current waste-to-energy systems are mostly incineration plants that have relatively low efficiency. There is thus a need for more efficient waste conversion technologies.

Plasma is described as the fourth state of matter owning very special properties that make it a promising candidate for solid feedstock conversion [2]. In fact, plasma has exceptional characteristics with extremely high temperature and the generation of highly active chemical species such as electrons, ions, excited species and photons [2]. There are numerous technologies for plasma generation [3] whereas the microwave-induced plasma presents the advantage of being electrodeless compared to more conventional DC plasma. Several microwave-induced plasma gasification and pyrolysis experiments using different operating conditions have been described in the literature [3]. Comparison of the results shows that steam and carbon dioxide are the most promising plasma working gases because of the high calorific value of the generated syngas. Microwave induced steam plasma proved its efficiency for coal gasification generating good quality syngas due to high hydrogen content over 50% by volume [4]. The steam plasma gasification process was also proved at larger scale with a 75 kW demonstrator able to achieve almost complete conversion of coal and cold gas efficiency about 84% [5].

Syngas from plasma gasification has good calorific value thanks to its high hydrogen and carbon monoxide contents and is thus a suitable fuel for electricity generation. Syngas can be converted to electricity in conventional combustion systems whereas solid oxide fuel cells (SOFC) represent a more efficient option particularly at small scale. The main issue with SOFC is its low tolerance to impurities present in syngas such as particulate matter, tars, sulphur compounds (mainly H_2S) and hydrogen chloride [6]. It is expected that plasma gasification can consequently reduce the amount of impurities compared to conventional syngas due to its exceptional properties. For example, effective decomposition of methane can be achieved with steam [7] and carbon dioxide [8] plasmas. Plasma systems should be efficient for hydrocarbons decomposition and generate syngas with low tar content. Coupling of gasification and SOFC was successfully demonstrated using a conventional two-stage gasifier at small scale and showing an impressive overall electricity efficiency above 40% [9].

Microwave-induced steam and carbon dioxide plasma gasification is a promising technology that is expected to achieve high feedstock conversion efficiency at small scale. In addition, this technology should produce high quality syngas and thus ease its integration with fuel cells and maximise the electricity production from biomass and wastes. This study presents the preliminary characterisation of a microwave-induced plasma torch operating with carbon dioxide and steam for gasification purposes.

2. Experimental

The experimental work has been carried out using a commercially available microwave-induced plasma torch which is the Downstream plasma source from Sairem (Sairem SAS, Neyron, France). The plasma system is depicted in Fig. 1 and is composed of a 6 kW magnetron for microwave generation, manual 3-stub tuner and sliding short circuit for microwaves tuning and the Downstream plasma source.

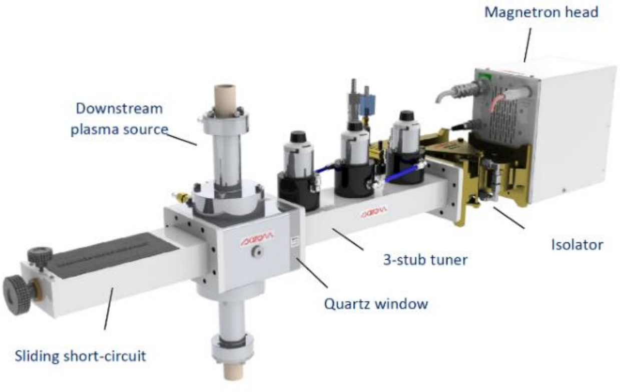

Fig. 1: Downstream plasma source system from Sairem

Carbon dioxide and steam are injected through a vortex injector in a 30 mm outer diameter quartz tube crossing the Downstream source. Plasma is generated in the quartz tube in the centre of the Downstream source and is then flowing down in the tube. The aim of the vortex injector is to create a particular gas flow in the quartz tube so that the plasma stays centred which is important to protect the quartz tube. The carbon dioxide flow rate is controlled using a mass flow controller whereas steam is generated at 150°C by a precision steam generator.

A cylindrical collection chamber was built for gas collection purpose. Plasma is generated in the chamber that is connected to the bottom of the Downstream source as shown in Fig. 2. The chamber collects the plasma gases as well as cold air injected for cooling of the bottom chimney. The chamber is 25 cm diameter and 50 cm length and is slightly insulated with a 1.5 cm layer of fibre wool for safety reasons.

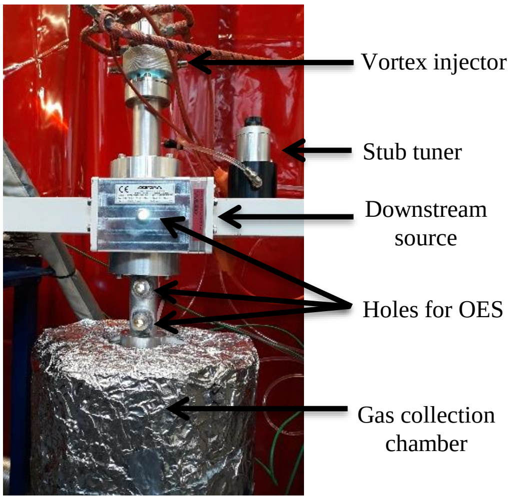

Fig. 2: CO_2 plasma operation with chamber connected

Measurement of the plasma characteristics is carried out through optical emission spectroscopy (OES). Those measurements are realized using a HR2000+ES spectrometer from Ocean Optics (Ocean Optics Inc., Florida, USA). Three holes are made for optical spectroscopy measurements purpose: one in the centre of the Downstream source and two along the bottom chimney as can be seen in Fig. 2. Two thermocouples are also placed in the collection chamber for the determination of its inside temperature.

3. Results and Discussion

Initially, the operating conditions for which a stable plasma can be generated were experimentally determined varying the carbon dioxide flow rate and the applied microwave power. Plasma is considered stable and steady when it stays centred in the quartz tube and does not show any fluctuation. Plasma is considered unsteady when it starts to fluctuate, it is generally the case when the plasma follows the vortex flow or impinge on the tube wall. Results of those experiments are presented in Fig. 3.

This characterisation study shows that with this system plasma operation is not possible at low carbon dioxide flow rate below 10 L/min and at low microwave power below 0.75 kW. It is explained by the fact that at low flow rate, the vortex effect cannot be sustained causing the plasma to impinge on the tube wall whereas low microwave power is not bringing enough energy to ionise the working gas. The plasma torch is quite a robust system that can achieve stable operation for many hours in a wide range of operating conditions. In fact, stable plasma operation is possible for microwave power ranging from 1 to 4 kW and carbon dioxide flow rate ranging from 20 to 80 L/min. In addition, the reflected microwave power could always be minimized to less than 1% of the forward microwave power using the 3-stub tuner. This shows the high efficiency of the transfer of energy from microwaves to plasma.

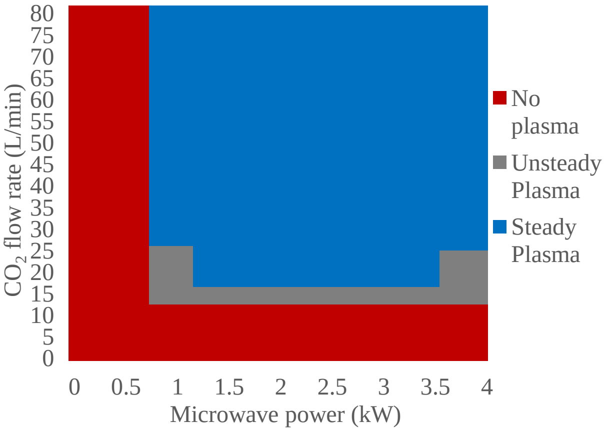

Fig. 3: Carbon dioxide operation conditions

Secondly, the average temperature in the gas collection chamber was determined varying the forward microwave power and the carbon dioxide flow rate. The results of those experiments are presented in Fig. 4. The bottom chimney is designed to be cooled by injecting air which is then flowing along the quartz tube and exiting at the end of the chimney. It was decided to keep the standard air cooling of the chimney resulting in the injection of cold air inside the chamber. In fact, preventing the air from entering the chamber could result in the chimney pressurization or its insufficient cooling. This is important to remember that this cold air causes considerable cooling of the inside of the collection chamber.

According to Fig.4, the temperature recorded in the chamber ranges from 250˚C up to 800˚C.Those results show the overall trends of the influence of the operating conditions on the temperature recorded in the chamber. In fact, higher temperatures are generated for lower carbon dioxide flow that can be explained by a dilution effect. As expected, an increase in microwave power results in a temperature increase in the collection chamber. Those temperatures are actually quite high considering that 40 L/min of cold air are also injected in the chamber. In addition, Heat transfer calculations have been carried out in order to estimate the heat losses from the chamber. Considering convection at the outside surface and the conduction in the 1.5 cm fibre wool insulation layer around the chamber, it is determined that heat losses are varying between 0.6 and 3 kW for inside temperature varying between 250˚C and 800˚C. It is thus estimated that 50% to 80% of the heat energy entering in the chamber is currently lost through heat losses. It was shown in the literature that a furnace chamber could be maintained at a temperature of 1,200°C using a similar steam plasma torch [10]. However that chamber has a volume of 2 L whereas the chamber in our current experiments is about 24 L. It is expected that a temperature of 850°C could be maintained in a smaller well insulated chamber with operating conditions of 20 L/min carbon dioxide and 1.5 kW forward microwave power. Heat management is a major challenge in order to use the energy generated from the plasma torch in an efficient manner. The first experiments pointed the need to modify the bottom chimney and its cooling system in order to prevent the air from entering the chamber while protecting the equipment. This is a promising result regarding the integration of the plasma torch with a gasifier as it shows that high temperature suitable for gasification can be maintained.

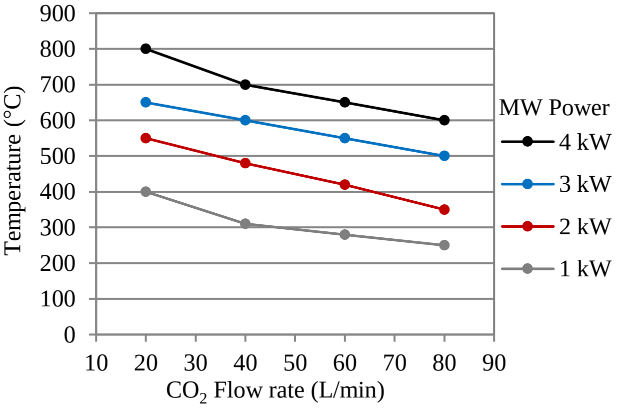

Fig. 5: Chamber temperature varying operating conditions

A preliminary analysis of the plasma chemistry has been carried out using optical emission spectroscopy measurements. Fig. 5 presents the plasma spectrum for pure carbon dioxide plasma (operating conditions are 20 L/min carbon dioxide at 1.5 kW microwave power) and for a mixture of steam and carbon dioxide (addition of 2 g/min steam). Addition of steam was only carried out for short periods as it is difficult to achieve stable steam plasma operation mainly due to condensation issues that will be solved by using hot carbon dioxide as a carrier gas. Those spectrums have been measured in the centre of the downstream source where the highest plasma temperature is expected.

Carbon dioxide and steam dissociate at high temperature into carbon monoxide and hydrogen respectively through the following reactions:

$$CO_2 \rightarrow CO + \frac{1}{2}O_2 \tag{1}$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{2}$$

Those reactions can be decomposed in numerous step reactions involving C, O, CO, C_2, O_2 and CO_2 for the carbon dioxide dissociation [11] and involving H, O, OH, H_2, O_2 and H_2O for steam dissociation [12]. In Fig. 5, the presence of the C_2 Swan band as well as the O and C peaks prove the dissociation of carbon dioxide molecules [13]. When steam is added to the working gas, the OH peak can then be detected proving the dissociation of H_2O molecules [12]. The dissociation of CO_2 and H_2O occurs through numerous processes such as the shift of thermodynamic equilibrium happening for temperatures above 2,500K and is also enhanced by the exceptional properties of plasma through electrons impact for example [2]. Similar spectrums have been obtained in the literature and the analysis of the peaks showed temperatures above 6,000K in the heart of the plasma [11, 14].

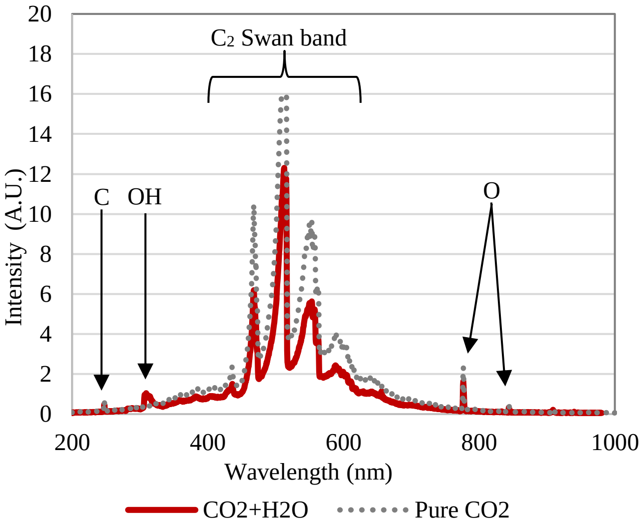

Fig. 4: Pure CO_2 and CO_2/H_2O plasmas spectrum

Carbon dioxide and steam plasma are generating various active chemical species such as singlet oxygen O and hydroxide radical OH as well as excited species, electrons and photons. However, those species are only present in the hottest part of the plasma as they tend to react backward to form carbon dioxide and steam again when the temperature is decreasing [14]. However, if hydrocarbons are in contact with the plasma, they could react with the produced oxygen preventing the CO_2 recombination while decomposing hydrocarbons. In addition, steam and carbon dioxide are very actives molecules for the conversion of solid and gaseous hydrocarbons through respectively steam and dry reforming reactions at high temperature. The plasma gasification thus combine the benefits of CO_2 and H_2O

dissociation into useful fuel (CO and H_2) while making a perfect medium for solid feedstock conversion into syngas.

4. Conclusion

A microwave-induced plasma torch has been tested in order to evaluate its potential for biomass and waste gasification application. The plasma torch is a robust system able to generate stable carbon dioxide plasma for a wide range of operating conditions included carbon dioxide flowrate between 20 and 80 L/min and applied microwave power between 1 and 4 kW. Addition of steam is also possible as long as there is no condensation in the stream lines. The plasma torch is able to maintain high temperature when connected to a chamber proving its capacity to be used as a heat source in an integrated gasifier. However, heat management is a major challenge in order to make an efficient integrated system. Optical emission spectroscopy measurements show the dissociation of CO_2 and H_2O molecules in the plasma while generating very chemically active species. This study demonstrates that the plasma torch is able to generate an ideal environment for gasification reactions with high temperature and high chemical activity. Microwave steam and carbon dioxide plasma is thus a very promising technology that could be combined with solid oxide fuel cells in order to maximise the energy recovery from biomass and waste.

5. Acknowledgement

This work was supported by the European Regional Development Fund (ERDF) through the Centre for Global Eco-Innovation (CGE) in partnership between Lancaster University and Stopford Energy & Environment. This research was also supported by Innovate UK through the grant number 133710.

6. References

[1] C. Lupa, L. Ricketts, A. Sweetman, B. Herbert, Waste Management 31 (2011) 1759-1764.

[2] A. Fridman, Plasma Chemistry, Cambridge University Press (2008).

[3] G.S. Ho, H.M. Faizal, F.N. Ani, Waste Management 69 (2017) 423-430.

[4] D.H. Shin, Y.C. Hong, S.J. Lee, Y.J. Kim, C.H. Cho, S.H. Ma, S.M. Chun, B.J. Lee, H.S. Uhm, Surface & Coatings Technology 228 (2013) 520-523.

[5] H.S. Uhm, Y.H. Na, Y.C. Hong, D.H. Shin, C.H. Cho, Internation Journal of Hydrogen Energy 39 (2014) 4351-4355.

[6] P.V. Aravind, W. Jong, Progress in Energy and Combustion Science 38 (2012) 737-764.

[7] D.H. Choi, S.M. Chun, S.H. Ma, Y.C. Hong, Journal of Industrial and engineering Chemistry 34 (2016) 286-291

[8] S.M. Chun, Y.C. Hong, D.H. Choi, Journal of CO_2 Utilization 19 (2017) 221-229.

[9] R.Ø. Gadsbøll, J. Thomsen, C. Bang-Møller, J. Ahrenfeldt, U.B. Henriksen, Energy 131 (2017) 198-206

[10] S. Kim, H. Sekiguchi, Y. Doba, Applied Thermal Engineering 52 (2013) 1-7.

[11] H.S. Uhm, H.S. Kwak, Y.C. Hong, Environmental Pollution 211 (2016) 191-197.

[12] H.S. Uhm, J.H. Kim, Y.C. Hong, Physics of plasma 14 (2007) 073502.

[14] H. Sun, J. Lee, H. Do, S.K. Im, M.S. Bak, Journal of Applied Physics 122 (2017) 033303.