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TOWARDS PLASMA-ENHANCED GASIFICATION: INVESTIGATING FREE-BURNING CARBON ARCS IN MOLECULAR GAS MIXTURES

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Abstract. A pre-study of free burning arcs between carbon electrodes for potential use in gasification processes is presented. Free-burning arcs offer the potential to be used without additional gas feed or significant changes to gas flows in established gasification systems as well as with minimal cooling requirements for improved energy efficiency. Direct current (DC) arcs with currents up to 200 A and power levels up to 40 kW have been operated in molecular gas mixtures of H_2, CO and CO_2. The electrical characteristics and dynamic behaviour of the arcs under various electrode configurations have been analysed, along with an assessment of electrode erosion. Finally, concepts for the power sources have been deduced and tested.

Keywords: Free-burning arc, graphite electrodes, molecular gas, gasification.

1. Introduction

Thermochemical conversion processes play a key role in establishing material cycles, for example in the recycling of waste materials or the use of biogenic residues. The mostly endothermic reactions, such as those for the production of synthesis gas, require the supply of energy, which is achieved, for example, in gasification processes through the combustion of carbon carriers. The latter releases CO_2. Replacing combustion processes with electrical energy in the form of thermal plasmas has the potential to significantly reduce CO_2 emissions while increasing the quality of the synthesis gas [1, 2]. Research to date has focused on the use of plasma burners (see e.g. [3]). Disadvantages include the necessary supply of plasma gas to the process and limited energy efficiency due to burner cooling. When using free-burning arcs, it is possible to couple not only the arc energy but also larger proportions of the energy in the electrodes into the process gas (see e.g. [4]).

This paper reports on a preliminary study on the use of a DC free-burning arc between graphite electrodes in typical gas mixtures as found in gasification processes. An arc operation system including an electrode feeding unit and a power sources was designed, constructed and tested, which will subsequently be installed in a test reactor for the gasification of carbonaceous solids.

2. Experimental Setup

With the aim of testing free-burning arcs in the range of several tens of kilowatts, two experimental setups were used.

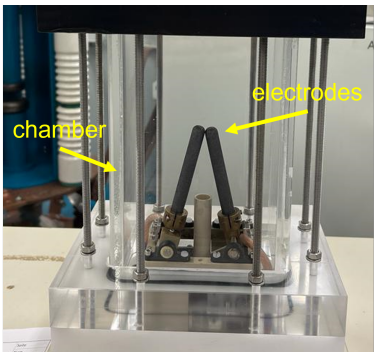

Figure 1. Setup A; Graphite electrode arrangement in a PMMA chamber for short time arc tests.

Setup A was adapted to perform first experiments more flexible in a larger current range and with a high voltage supply to operate arcs of varying arc length. Therefore, a pulse DC current source based on a capacitor bank as described in [5] was used providing approximately rectangular pulses with nearly constant current over up to 20 ms. Thus, the limitation was the short arc operating time. Pulses with current maxima between 70 and 200 A were generated with capacity charging voltages between 500 and 1500 V. Two graphite rod electrodes with a diameter of 9 mm and a lenght of 85 mm were mounted in vertical direction in a transparent plastic gas chamber made of polymethyl methacrylate (PMMA) as shown in Fig. 1. The electrodes were positioned so that their tips were in contact. For arc ignition, the electrodes were quickly separated by tilting them sideways with electromagnetic drives. The maximum gap distance of 16 mm was reached after about 10 ms. The cham-

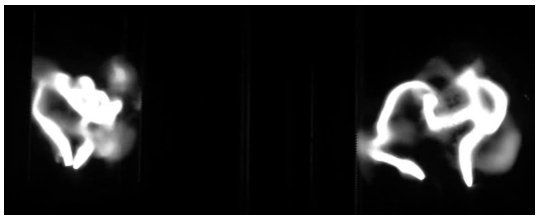

Figure 2. Example of arc images in setup A; side and front view of an elongated arc at 200 A.

ber with inner dimensions of 110 × 170 × 65 mm^3 (W×H×D) can also withstand higher pressures, but was used here at atmospheric pressure. The chamber was flushed for 20 s and filled with gas with a slight overpressure before each experiment. The arc current was measured by a Pearson current monitor (Model 1423). For measuring the arc voltage, a voltage probe (Tektronix 6015A) was applied, and the signals were registered by an oscilloscope Yokogawa DLM3000. Arc images were recorded with a high speed camera with 1024×1024 pixel matrix (IDT-MotionPro Y4), typically 10000 frames per second and 1 μs exposure time. In some experiments, a mirror was used to capture two images of the arc simultanerously, the front view and a side view, to make complex arc elongations visible. An example of the arc at 200 A is shown in Fig. 2

Based on initial experience from the measurements with setup A, a next setup B was developed for arc tests with longer operation times. The setup was designed so that it can later be installed in an experimental gasification reactor. A reaction chamber made of steel of inner dimensions of 500 × 400 × 510 mm^3 (W×H×D) with a side flange for the feed of one electrode and a front flange with a window for optical access was used to simulate the gasification reactor volume. An electrode feeding unit was constructed with a linear actuator CTC-060. Graphite rod electrodes with a length of 800 mm and a diameter of 30 mm were held with a massive copper clamp as shown in Fig. 3. The copper clamp can be cooled and was mounted on the actuator via an insulator. The electrode feeding unit is covered by another gas-tight steel chamber, since it is intended to be mounted to a gasification reactor subsequently. In setup B, the feeding unit was mounted to the reaction chamber on the side flange. A conical tip rod electrode with a diameter of 9 mm was fitted to the end of the 30 mm electrode to operate the cathode. Another short graphite rod with a diameter of 30 mm was mounted to the chamber wall and operated as a fixed anode. Both electrodes were positioned in the chamber on a common axis so that their tips are in contact. The cathode can be moved for electrode separation and arc ignition. Gap distances up to 100 mm have been studied.

Notice, that for later use in the gasification reactor, two identical electrode feeding units are planned for anode and cathode operation that will face each other and provide larger gap distances. The electrodes in

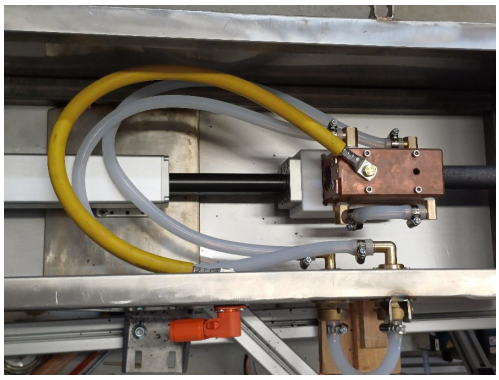

Figure 3. Electrode feeding unit of setup B with the actuator, the insulator, the copper clamp and the graphite rod electrode.

setup B were connected to a DC power source Trumpf-Hüttinger DC 3050 which delivers currents up to 125 A, power up to 50 kW, and voltages up to 800 V. A coil of 15 μH was placed in series to stabilise the arc current by supplying additonal voltage during transient arc fluctuation. The steel chamber was flushed for 20 s and filled with either nitrogen or CO_2 gas with a slight overpressure before each experiment. Arc current and voltage was measured using a 26 mΩ shunt and a Teledyne LeCroy PPE6kV Oscilloscope Probe respectively, and recorded with a Yokogawa DLM2054 digital oscilloscope. The arc was observed through the front window with a Photron FASTCAM NOVA R3, Modell 150K-M-16GB, high-speed camera at a typical frame rate and exposure time of 1000 fps and 2 μs respectively.

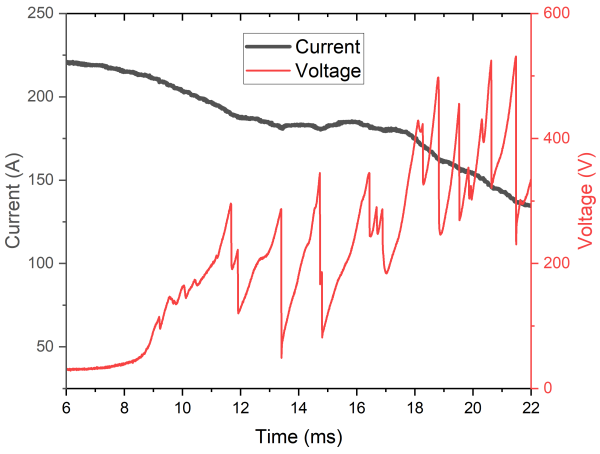

Figure 4. Example of the voltage and current course over time for the arc in setup A, gas (b) and at a set current of 200 A.

3. Results and discussion

With setup A, arcs in pure CO_2 (a) and three gas mixtures 30% H_2+ 70% CO_2 (b), 30% H_2+ 70% CO (c), and 33% H_2+ 33% CO_2+ 33% CO (d) have been studied at nearly atmospheric pressure. The gas mixtures were selected so that their composition of gaseous elements simulates a range of typical conditions in a gasification process of solid carbonaceous fuels.

An example of the voltage and current course over time in a pulse of approximately 25 ms is shown in Fig. 4. The contact separation started here at 5 ms. For a set current of 200 A, the current over the pulse is not exactly constant and falls slightly from 230 to 150 A without larger fluctuations in the example. In contrast, the voltage shows typical fluctuations which become larger with increasing time because of the increase of the gap distance. A sawtooth-like structure results from the irregular elongation of the arc, as illustrated by the high-speed images in Fig. 2. The local voltage maxima correspond to maximum elongations of the current path followed by a sudden decrease because of the transition to a short current path. Analysis of the frequency spectrum of the voltage fluctuations did not result in any specific frequency values. It is expected, that the arc extensions mainly result from the inner magnetic field of the current path. They are considered advantageous because they allow a larger arc–gas ineraction volume for the electrical power transfer.

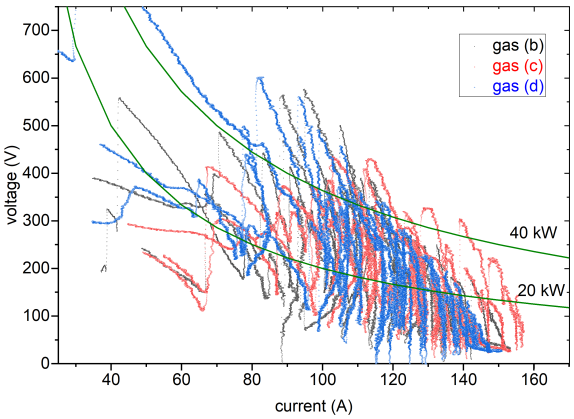

Figure 5. Instantaneous values of the arc voltage and current (symbols) for the set current of 150 A for three gas mixtures (b), (c), and (d). The green solid lines indicate the coresponding voltage for two fixed power values.

Fig. 5 shows voltage over current values obtained for the three gas mixtures (b), (c), and (d) for a set current of 150 A in setup A. As the values lay in the same region, no significant differences were found between the gas mixtures, neither in terms of arc dynamics nor voltage and power range.

As expected, the power that can be transferred through the arc scales with the current. Fig. 6 illustrates the scaling for the case of gas mixture (b). At the set current of 200 A, a power of more than 60 kW can be obtained in maximum. A statistic evaluation of the data from Fig. 6 is presented for completeness in Fig. 7. However, the average values are of less importance here as the experiments have been performed with moving electrodes and increasing gap length over the current pulse. The aim of the investigations with setup A was to determine typical peak values of the electric power that can be achieved with longer arcs.

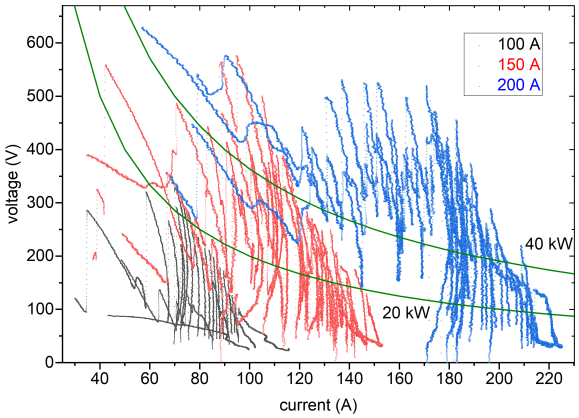

Figure 6. Instantaneous values of the arc voltage and current (symbols) for gas mixture (b) for three different set currents.

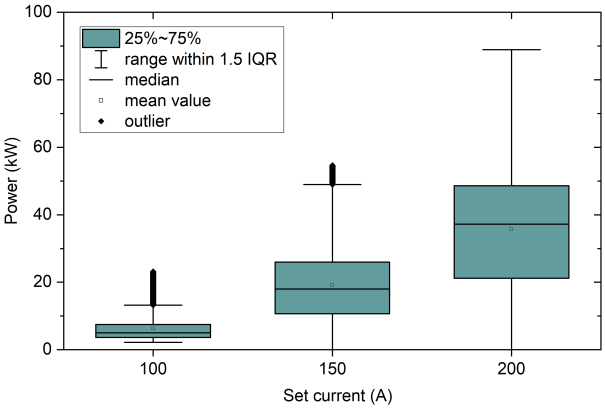

Figure 7. Boxplot of the electric power over the set current related to the voltage current characteristics in Fig. 6 for gas mixture (b).

Experiments with setup B have been focused after initial tests with N_2 on arcs in pure CO_2 with the aim to study the long-term behaviour at enhanced electrode distances. In most of the experiments the tip of the graphite cathode was a rod with a diameter of only 9 mm and conically shaped. This was used to reach a more stable behaviour of the arc. In addition, a specific procedure was applied to start the long-term arc operation. After the first electrode separation and arc ignition the electrode distance was maintained at 10 mm for 5 s. Then the distance was increased with a typical speed of 0.5 m/s to the final value, typically up to 100 mm.

Typical images of the arc in setup B are shown in Fig. 8. The heating of the cathode in the beginning of each experiment results in an almost stable behaviour of the arc cathode attachment. The cathode erosion leads to a rounding of the conically shaped tip, as expected. The anode attachment is typically more unstable and causes a stronger erosion which was acceptable, and the length reduction was limited because of the large electrode diameter. It should be noted that for the results presented here, the electrodes were

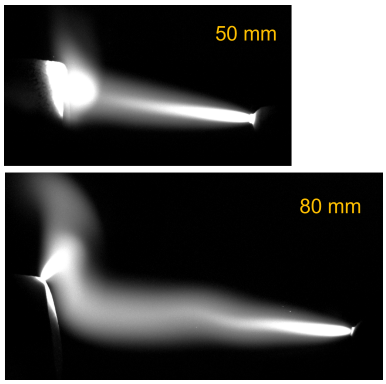

Figure 8. Examples of arc images in setup B at 100 A for final electrode distances of 50 and 80 mm.

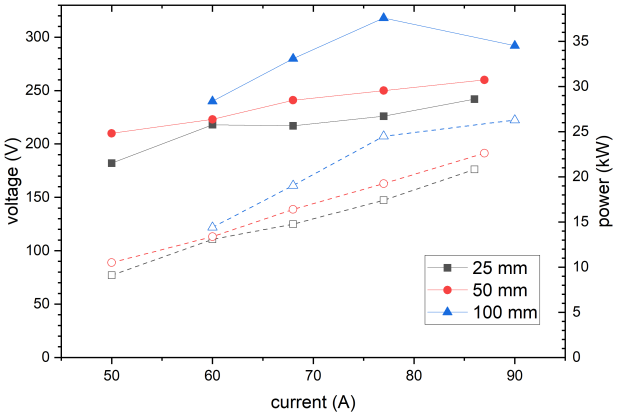

Figure 9. Mean values of voltage (filled symbols connected by solid lines) and power (open symbols connected with dashed lines) for arcs in setup B in gas (a) (CO_2) for three different electrode distances.

not actively cooled, apart from cooling via the holders in the reactor or in the feeding unit.

Over a total arc time of 500 s in several tests at approx. 100 A, a reduction of the cathode length (with the diameter of 9 mm) of 9 mm was measured, resulting in an erosion rate of about 9.3 g/h and about 26 μg/C. The erosion of the anode was determined by weighing to 3 g resulting in a rate of about 22 g/h and 60 μg/C. These values present first rough estimates and have been evaluated as relatively high. This may be also due to the morphology of the graphite material used, which was not specifically selected.

Corresponding to the more stable behaviour of the arcs in setup B, much lower voltage and current fluctuations have been typically measured here. However, sudden higher voltage fluctuations occasionally occurred, which in extreme cases led to arc extinction. Arc experiments have been performed for several final electrode distances over several minutes. The voltage values measured over time ranges after reaching the final electrode distance were averaged. Corresponding mean values together with the mean values of the power are shown in Fig. 9 for three electrode distances for illustration. Small arc elongations and the dynamics of the anode attachment explain deviations from a linear correlation of voltage and electrode distance and non monotonous increase of the voltage with current.

4. Conclusions and outlook

Arcs between carbon electrodes have been tested in gas mixtures of H_2, CO and CO_2 which are relevant for gasification processes of solid fuels. Arc elongations can be used to achieve higher arc voltages and couple higher amounts of electrical power into the gas. For example, average powers up to 40 kW can be easily obtained at currents of about 200 A for gap distances of only 10 mm, when erratic arc elongations are caused by gas stream and/or magnetic forces.

A graphite electrode system including an electrode feeding unit and an adapted DC power source have been developed. The arc operation with the system was tested in CO_2 at atmospheric pressure. Almost stable arc operation over minutes was obtained for electrode distances of up to 100 mm and currents up to 90 A. The system is ready for the implementation in a gasification test reactor, and corresponding experiments are planned for the near future.

Additional work is required to further increase the time during which stable arc operation without any arc extinction can be guaranteed. Furthermore, the test of different graphite materials is planned to study the electrode erosion and the required speed of electrode feeding for long-term operation.

Data availability statement The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.34711/INPTDAT.933.

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