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**New technology for hydrogen and geopolymer composites
production from post-mining waste**

Deliverable 4.1

**Evaluation of Data from Operational Tests of the
Plasma Gasifier**

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Deliverable 4.1 Evaluation of Data from Operational Tests of the Plasma Gasifier

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1. Introduction

The sub-task focused on plasma gasification of the carbonaceous fraction from a mine dump contributes to the main objective of the project, which is the use of waste materials for environmentally friendly and cost-effective technologies. Given the uncertainties in the fuel market, plasma gasification is a promising method for the production of synthesis gas containing a high proportion of hydrogen and carbon monoxide, making it a suitable source for energy applications. The experiments were conducted under stable conditions with similar temperature and pressure profiles, confirming the consistency of the process. In particular, the composition and quality of the synthesis gas were monitored, with the high quality of the output product confirming the efficiency of plasma gasification for obtaining value-added raw materials.

2. Goal of the work

The aim of the experimental activities was to investigate the plasma gasification of a sorted coal fraction using a high-temperature plasma reactor located at CEETe, VSB–Technical University of Ostrava. The tests focused on evaluating the effect of key process parameters, particularly the steam-to-fuel ratio and fuel feed rate, on the composition and yield of the produced syngas.

Gasification was conducted at a constant temperature of 1600 °C, with varying steam/fuel ratios (0.6, 1.0, 1.3) and fuel feed rates (15 and 20 kg/h). Each test ran for one hour using a fixed amount of feedstock

In parallel, current-voltage characteristics of the plasma torches were measured under three nitrogen flow rates (148, 195, and 250 L/min) to assess the electrical behavior of the plasma arc under different gas conditions.

3. Plasma Gasification

The basic principle of plasma gasification is as follows. A plasma torch is used in the gasification reactor to maintain a high temperature of around 1 800 °C. The burners are of different designs. The most commonly used are arc independent burners. These burners are integrated into the reactor. The actual gasification process then takes place in the reactor. The fuel is converted into synthesis gas and vitrified gas in the presence of an oxidising medium and high temperature. The gasification medium may be air, water vapour or other suitable medium. A schematic of such a gasifier is shown in Fig. 1. [1]

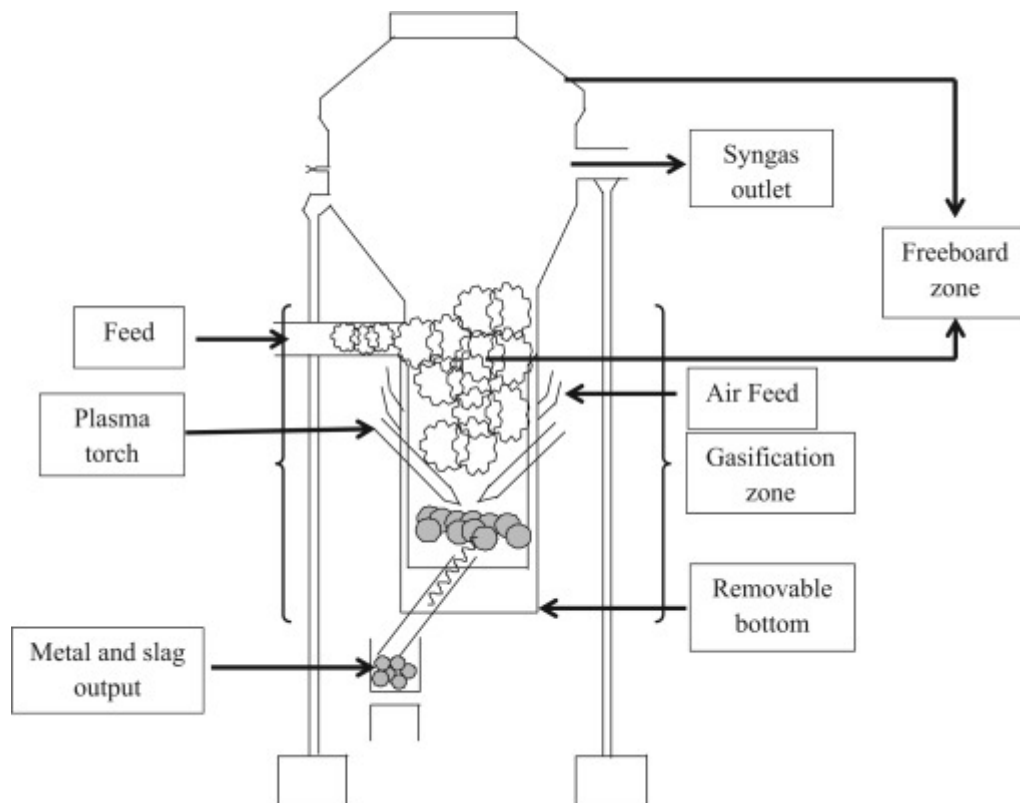


Fig. 1 Scheme of Plasma Gasifier [1]

4. Design of Plasma Torches

In plasma reactors, arc independent DC burners are most often used. Their design is shown in Fig. 2. The ionization gas enters the chamber in the burner and flows through the boiler around the cathode. An electrical discharge occurs between



the cathode and the anode, thus igniting the arc. Argon, nitrogen, or helium is most commonly used as the ionization gas. This arc is then blown out of the burner by the ionization gas. The burners used in the CEETe gasifier are of similar design. [2]

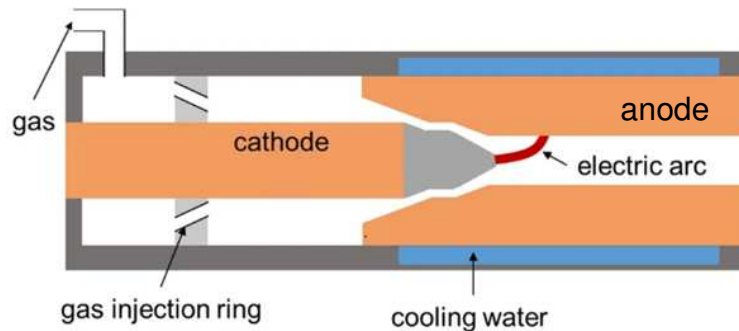


Fig. 2 Schematic of an Arc Independent Burner [2]

A modified version of the arc burner is the hybrid stabilized electric burner with rotating anode, see Fig. 3. Similar to the previous case, the arc is ignited in the ionized gas between the cathode and the anode. The hybrid stabilized electric arc, developed several years ago at the Institute of Plasma Physics of the CAS in Prague, combines gas and vortex stabilization. In the hybrid argon-water plasma torch, the arc chamber is divided into two parts: a short cathode region where the arc is stabilized by tangential argon flow, and a longer part stabilized by a water vortex. This arrangement not only provides better stabilization of the cathode region and protection of the cathode tip, but also allows a wider control of the plasma beam characteristics than is possible with arcs stabilized solely by gas or liquid. [3]

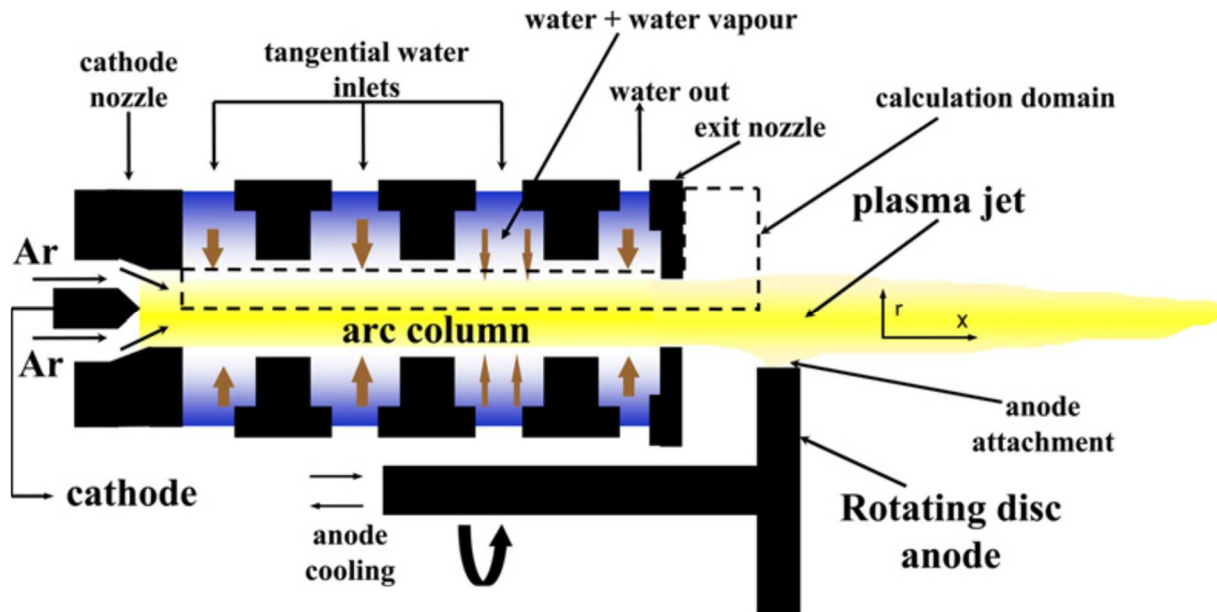


Fig. 3 Principle of Hybrid Plasma Torch with Combined Gas (Ar) and Vortex (water) Stabilizations [3]

Another design of burners used in plasma gasification is the microwave burner. A microwave plasma torch is a device that uses microwave radiation to create plasma, which is an ionized gas composed of positive ions and free electrons. Unlike conventional flames, which use a chemical reaction to ignite the fuel, a microwave plasma torch generates plasma using electromagnetic waves with frequencies in the microwave range, typically around 2.45 GHz. The microwaves generate an electric field that causes the gas particles to gain energy and become ionized, producing plasma. This environment reaches very high temperatures, often up to several thousand degrees Celsius, and has the ability to rapidly decompose or melt various materials. [4]

Microwave plasma torches are widely used in industry and science for materials processing such as metal melting, waste gasification, flue gas cleaning and chemical synthesis. The high temperatures and clean plasma environment (free of impurities and combustion gases) make them ideal for applications where high purity and precision are required. In addition, their flexibility to use different types of gases as plasma sources, such as argon or nitrogen, is an advantage, allowing the plasma properties to be controlled according to the specific needs of the process. [4]



5. Plasma Gasifier Installed in CEETe

The plasma gasification unit installed at CEET is used to convert organic materials (biomass, fossil fuels) and alternative fuels into gas using high temperature plasma in a plasma reactor. The fuel is thermochemically converted into so-called "energy gas" at temperatures of several thousand degrees in the absence of air. The resulting energy gas consists of low molecular weight substances, with hydrogen (H_2) and carbon monoxide (CO) predominating. In addition, the energy gas contains water vapour, carbon dioxide (CO_2) and small amounts of nitrogen (N_2), methane (CH_4), sulphur dioxide (SO_2) and hydrogen chloride (HCl). A by-product of the reaction is a melt (slag), which is formed from inorganic substances present in the starting biomass. Cooling of the melt produces a slag, in whose crystalline lattice contaminants may be bound. Tests show that the leachability of slag is lower than that of glass and can therefore be used, for example, as a building material. The advantage of plasma gasification technology is that it does not produce harmful emissions.

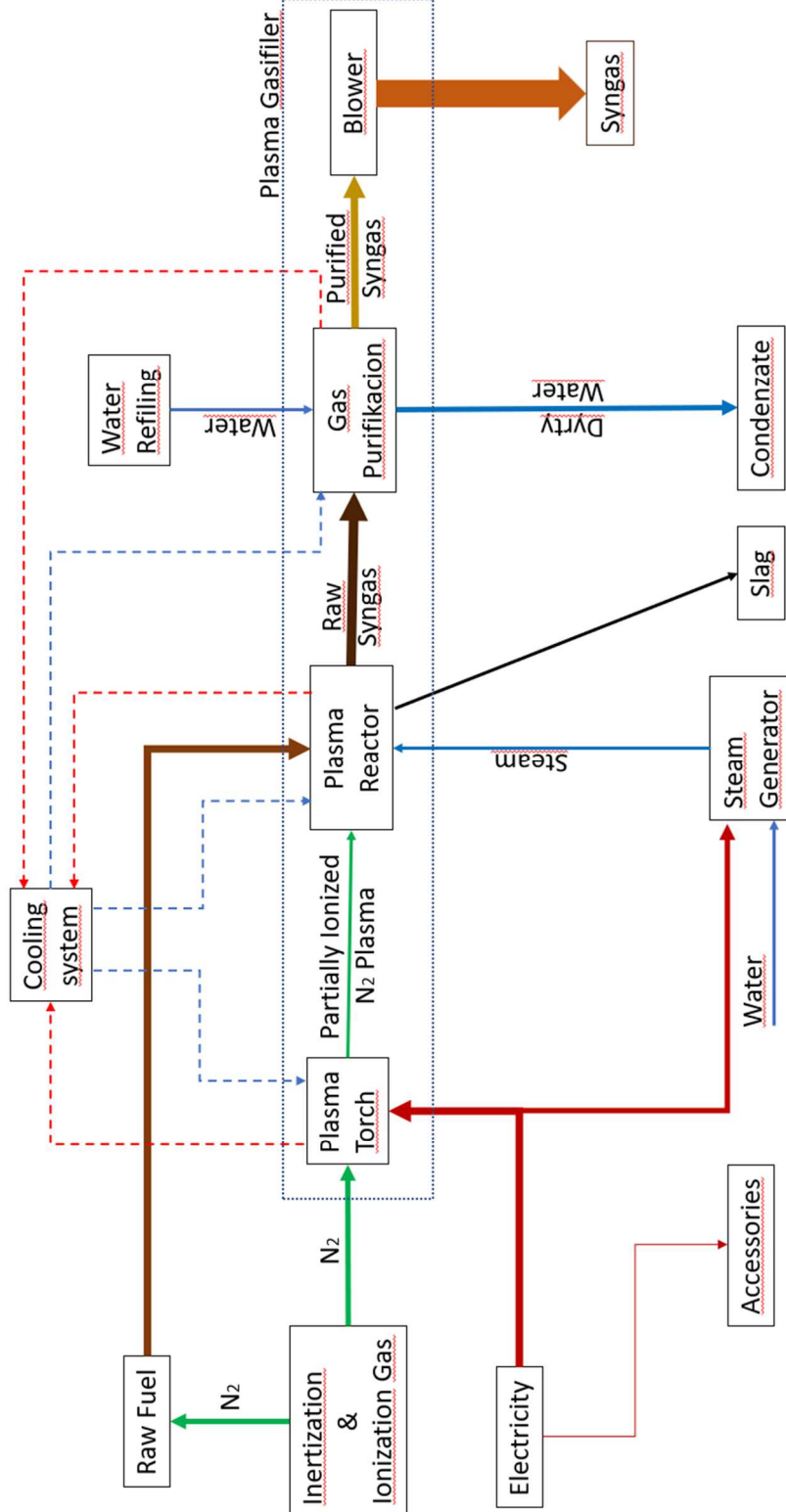
It is a laboratory facility designed for research purposes. The technology is designed so that it can be gradually expanded with additional modular elements. The schematic diagram of the technology includes individual apparatuses, the basic parameters of which are given in Tab. 1

These are the following technological blocks:

1. **Material handling.** This block contains the material stack and its transport to the reactor.
2. **The plasma reactor** is the main technological apparatus where gasification is carried out by the action of plasma. The reactor includes a plasma torch with carrier gas.
3. **Direct cooler.** This unit provides direct cooling of the gas produced in the reactor by water.
4. **The blower** provides transport of the produced gas either for subsequent use in CEETe technology or for disposal in the afterburner.
5. **Cooling system.** This system is used to cool the plasma gasifier.



Fig. 4 Technology Block Diagram





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Fig. 5 Picture of Plasma Gasifier in CEETe



Tab. 1 Basic Parameters of the Technology

Item	Unit	Value
Quantity of fuel processed	kg/h	20–60
Permitted moisture content in fuel	% _{mass}	max. 20
Burner power	kW	50–150
Steam - temperature	°C	250
Steam - pressure	bar	4.5
Steam flow rate	kg/h	4,1 – 8,1
Cooling water - flow rate	l/min	16–25
Cooling water - cooling capacity	kW	25–50

The raw material is poured into a hopper which is placed on strain gauges. A vault breaker is installed in the hopper. Two gate valves are located under the hopper to hermetically seal the reactor inlet. To remove air naturally contained in the fuel, the hopper is equipped with a regulated supply of inerting medium.

After the fuel has passed through the open gate valves, it continues to the reactor by means of a screw conveyor. The flow of fuel into the reactor is regulated by changing the speed of this conveyor. In the reactor, the fuel comes into contact with the plasma cone. Due to the high temperature and flow velocity, the material is converted very quickly into syngas and Slag.

The reactor itself is implemented as a welded steel reactor, which can be split in several planes by means of flanges. To protect the steel part from the effects of heat and abrasion, the reactor is lined on the inside with a multi-layer lining. The reactor is equipped with a duplicator jacket to prevent unwanted heat transfer to the reactor surroundings. The reactor is equipped with several process openings for the burner and thermocouple inlets, fuel supply, slag and gas venting.



The reactor is equipped with three plasma burners with a total maximum power input of up to 150 kW (50kW each). These are DC arc burners with independent arc, see Fig. 6. Nitrogen is used as ionization gas after the initial arc ignition.



Fig. 6 Plasma Torch

In addition to the fuel, gasification medium is also fed into the reactor. In this particular case it is water vapour. The water vapour is prepared in an electric steam generator and, after it has been superheated, is fed into the reactor. Its flow rate is monitored by means of a differential pressure gauge and, if necessary, regulated by means of a control valve. The temperature of the steam at the inlet to the reactor can vary from 150 to 300 °C.

The Slag is drained from the bottom of the reactor. The outflow is regulated via a plug and is subsequently captured in a lined vessel.

The resulting syngas leaves the reactor through a pipe in the centre of the reactor and continues to the gas cooling and cleaning system. The first step of gas cooling is a direct cooler in which water is sprayed into the syngas. Here, the cooling water evaporates, cooling the syngas to a temperature of around 200 °C. After cooling in the 1st stage of the cooler, the gas continues to the 2nd stage. The 2nd stage is designed



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as a charge absorber. The gas is further cooled with ice water to an outlet temperature of 10 °C. The outlet gas has 100% humidity at a given temperature and pressure.

The transport of synthesis gas throughout the system is provided by a roots blower. The speed of this blower is controlled according to the reactor pressure to maintain a pressure of -2 to 2 kPa. This blower is located downstream of the 2nd cooling stage.

The synthesis gas is subsequently used for the technologies located in the CEETe building. For its on-line analysis, part of the gas is extracted and subsequently analyzed.

6 Fuel

Sorted coal fraction was used as fuel for the plasma gasifier. The sample was labeled "Coal-bearing fraction HALDEX VSB" supplied by HALDEX, see Fig. 7. It was a mechanically sorted coal-rich fraction from a stockpile that was produced after the treatment of raw coal. ITPE carried out a series of analyses to determine some of the properties of the feed fuel. These analyses are shown in Tables 2 to 5 The data were converted to a fuel moisture content of 2.67%mass. This moisture content was determined in the VSB using a RADWAG MA 110.R thermal balance.



Fig. 7 Raw Material



Tab. 2 Ultimate, Approximate and Calorimetric Analysis of Fuel

W^r	A^r	C^r	H^r	N^r	S^r	Cl^r	O^r	Q_i^r	Q_s^r
%mass	%mass	%mass	%mass	%mass	%mass	%mass	%mass	MJ/kg	MJ/kg
2,67	15,83	67,58	4,52	1,00	0,08	0,08	8,27	27,58	28,64

Tab. 3 Elemental Content in Dry Fuel (from calculations)

Substance	Concentration (%mass)
Si^d	3,437
Al^d	2,578
Na^d	0,091
K^d	0,342
Mg^d	0,226
Ti^d	0,119
Sr^d	0,024

Tab. 4 Chemical Composition of Ash in Terms of Oxides

Substance	Concentration (%mass)	Substance	Concentration (%mass)
SiO₂	45,22	TiO₂	1,22
Al₂O₃	29,96	Mn₃O₄	0,07
Fe₂O₃	5,71	P₂O₅	1,27
CaO	3,51	SO₃	2,87
MgO	2,30	BaO	0,20
Na₂O	0,76	SrO	0,18
K₂O	2,54		



Tab. 5 Ash Fusion Temperature ISO 540:1995 IDT

Atmosphere	Temperature		°C
Oxidizing	Initial Deformation	DT	1310
	Softening	ST	1480
	Hemispherical	HT	1510
	Fluid	FT	1530
Reducing	Initial deformation	DT	1260
	Softening	ST	1420
	Hemispherical	HT	1470
	Fluid	FT	1490

Another parameter that is important mainly for the transport of the fuel itself and also its distribution in the reactor is the sieve analysis. Sieve analysis is used to determine the size distribution of individual particles using a system of sieves. This analysis was carried out at VŠB using a set of sieves from the manufacturer PRECISELEKT with the following sizes of circular holes: 50 mm; 28.4 mm; 16 mm; 9.5 mm; 4.73 mm; 0.85 mm; 0.25 mm and 0 mm. The results from this analysis are presented in Fig. 8. The smallest interception was on the 50 mm grids, through which all particles fell. The largest number of particles is in the interval <4.73 mm and >0.85 mm. There are 29% of such particles by mass. A positive aspect is that the sample contained a very small amount of fine particles (<0.25 mm) and specifically 1.2 wt%. As a result, there will be no more intense dust drift during gasification.

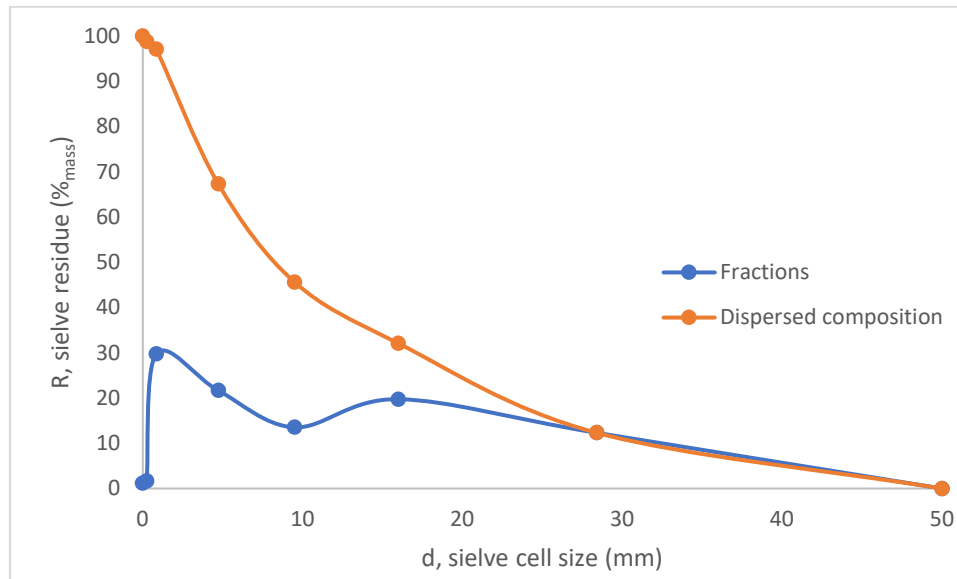


Fig. 8 Sieve Analysis of Raw Fuel

7 Experimental Description

7.1 Preparation of the Gasifier

Before the experiment, the reactor must be heated according to the temperature ramp. This is mainly due to the heavy lining that is placed in the inner part of the reactor and serves mainly as thermal insulation and abrasion protection for the steel parts of the reactor. Heating is carried out at a rate of 100 °C/h until the operating temperature of the reactor is reached. The heating process took approximately 16 hours. Plasma burners with a total power of 60 kW were used for the heating. Based on the results from the Ash fusion temperature, see Table 5, the operating temperature must be higher than the FT temperature. For this reason, the temperature was chosen to be 1600 ± 100 °C. This ensures that the temperature at the bottom of the reactor chamber will also be higher than the ash flow temperature and the ash will be able to flow as liquid slag from the reactor into the containment.

Once the operating temperature is reached, the next step is to verify the inert atmosphere inside the reactor. Since nitrogen is used as the ionization medium, which is inert, the total removal of air will already occur during heating. The check is carried



out using an on-line process analyzer with an electrochemical cell. This step is very important for safety reasons.

7.2 Gasification Process

The gasification process itself begins with the injection of fuel into the reactor. The weighed fuel is first put into a storage tank. From there, it is conveyed by a screw conveyor to the reactor. Water vapour is injected into the reactor at the same time as the fuel. The water vapour to fuel ratio and the fuel flow rate are shown in Table 6. The temperature of the water vapour was maintained in the range of 150 to 200 °C. During gasification, the temperature in the reactor is continuously monitored so that it is continuously controlled by changing the flow at each burner. The actual gasification of the fuel always took about one hour and the entire plant is always used.

Tab. 6 Steam/Fuel Rate and Fuel Flow Rate

Test	Steam/Fuel Ratio	Fuel Flow Rate
	(kg/kg)	(kg/h)
0,6_20	0,6	20
1_20	1	20
1,3_20	1,3	20
0,6_15	0,6	15

The end of the fuel dosing, i.e. the gasification process, was determined by monitoring the composition of the outlet gas, by decreasing the concentrations of Carbon monoxide (CO), carbon dioxide (CO₂), and hydrogen (H₂) gases while increasing the concentration of nitrogen (N₂), which served as the ionization gas.

The vitrified gas was collected after the experiment was completed and its quantity was subsequently weighed to determine the mass balance.



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7.3 On-line Analysis of Syngas

Syngas composition was determined using an on-line Syngas Analyzer Gasboard 3100P, which measures the concentrations of carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), hydrogen (H₂), oxygen (O₂). The gas was purged of contaminants that could compromise the analyzer or bias the entire measurement before entering the analyzer. CO, CO₂, CH₄, are determined by the analyser using non-dispersive infrared absorption. H₂ is measured by a thermal conductivity sensor. O₂ is measured by an electrochemical sensor. N₂ is determined as 100% without the sum of all gases measured. Gas for analysis was collected downstream of a roots blower integrated in the plasma gasifier system.

Since the raw syngas exits the reactor directly through a quench cooler, where dust particles, hydrocarbons, and H₂S are adsorbed, these components were not analyzed in the gas. Moreover, due to the low sulfur content in the feedstock, the concentration of H₂S in the syngas is expected to be very low.

The amount of synthesis gas was determined by a KIMO 12975 pitot tubes with a KIMO MP210. This probe was placed downstream of the blower during the entire measurement. The gas pressure and temperature were further determined at this point.

7.4 Mass Balance

The mass balance of the whole process was designed according to Fig. 9. The input to the process is: gasification medium - steam, fuel, ionization gas - nitrogen, cooling water. The output of the process is: slag, output water from the gas treatment, syngas and condensate. This balance can be described using eq. 1.

$$\text{Inputs} = \text{Outputs}$$

$$\dot{m}_{\text{Steam}} + \dot{m}_{\text{Fuel}} + \dot{m}_{\text{I.G.}} + \dot{m}_{\text{C1}} + \dot{m}_{\text{C2}} = \dot{m}_{\text{Slag}} + \dot{m}_{\text{Syngas}} + \dot{m}_{\text{Conden.}}$$

eq. 1

Where:



$\dot{m}_{Steam}$ – Gasification medium flow rate, (kg/h)

$\dot{m}_{Fuel}$ – Fuel flow, (kg/h)

$\dot{m}_{I.G.}$ – Ionization gas flow, (kg/h)

$\dot{m}_{C1}$ – Flow of cooling water to the 1st stage of cleaning, (kg/h)

$\dot{m}_{C2}$ – Flow of cooling water to the 1st stage of cleaning, (kg/h)

$\dot{m}_{Slage}$ – Slag flow rate, (kg/h)

$\dot{m}_{Syngas}$ – Synthesis gas flow, (kg/h)

$\dot{m}_{Conden.}$ – Condensate flow after the 2nd cleaning stage, (kg/h)

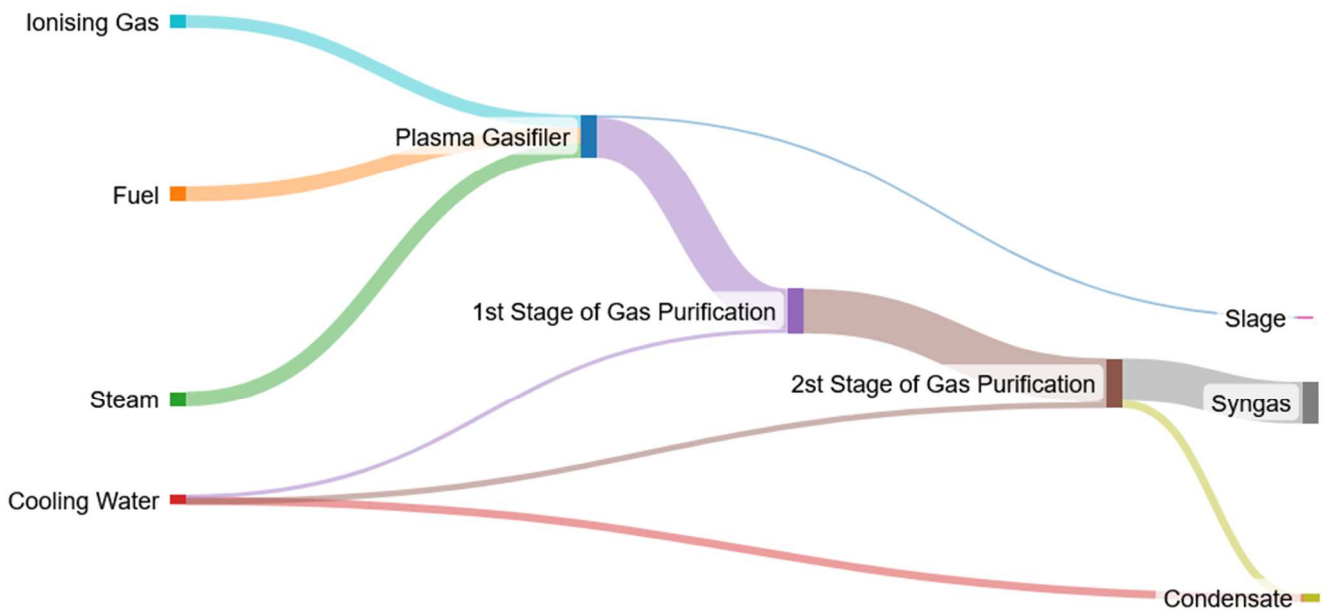


Fig. 9 Sankey Diagram Mass Balance of Gasification



The flows or quantities of individual streams were determined in the following ways:

Mass flow	Measurement method
Flow rate of gasification medium	Measuring orifice: SIEMENS FPS200 + differential manometer: SITRANS P320
Fuel flow rate	Weighed + length of dosing
Ionization gas flow rate	Measuring orifice: SIEMENS FPS200 + differential manometer: SITRANS P320
Slag flow rate	Weighed after experiment
Synthesis gas flow	Pitot tube: KIMO 12975 with KIMO MP210

Due to the technological design of the entire gasification plant, it was not possible to accurately determine the flow rate of cooling water entering the 1st and 2nd treatment stages. For this reason, the product yield from the gasifier was determined based on eq. 2 and 3.

$$X_{Syn gas} = \frac{\dot{m}_{Syn gas}}{\dot{m}_{Steam} + \dot{m}_{Fuel} + \dot{m}_{I.G.}} \cdot 100 \quad \text{eq. 2}$$

$$X_{Slage} = \frac{\dot{m}_{Slage}}{\dot{m}_{Steam} + \dot{m}_{Fuel} + \dot{m}_{I.G.}} \cdot 100 \quad \text{eq. 3}$$

Where:

$X_{Syn gas}$ – Yield of synthesis gas, (%_{mass})

X_{Slage} – Yield of slag, (%_{mass})



7.5 VA Characteristics of Plasma Torch

During the experiments, the temperature in the reactor was controlled by adjusting the power supply current of the individual plasma torches. The current and voltage were continuously measured using FLUKE 374 FC and FLUKE 117, and the measurement circuit diagram is shown in Fig. 10. To obtain the voltammogram characteristics at higher flow rates (195 and 250 l/min), further measurements were taken after the main experiment, this time at these set flow rates.

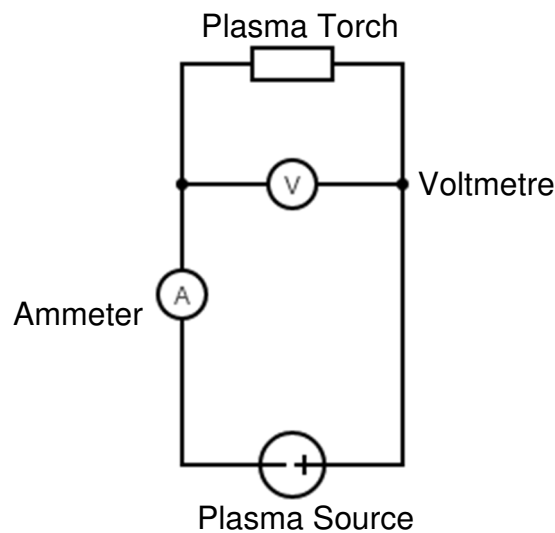


Fig. 10 Circuit Diagram for Measuring VA Characteristics of Plasma Torch.



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8. Experimental Results

8.1 Parameters of the Gasification Process

The temperature and pressure dynamics were similar in all four tests performed. Therefore, only a representative result from test 20_1 is presented in this report, which illustrates well the overall behaviour of the system during the experiment. This selection allows to simplify the presentation of the data and to focus on typical waveforms without the need to detail the results of all individual tests.

Fig. 11 shows the average temperature waveform in the reactor throughout the experiment. Fuel entry into the reactor occurred at exactly 00:00:00, which is the beginning of the recorded graph. As can be seen from the graph, the temperature increased rapidly to a level of approximately 1 600 °C, where it then stabilized. After a short period of oscillation around this value, the temperature remained in a stable range, with no significant fluctuations. Towards the end of the experiment there was a slight drop in temperature, which may be due to a change in reactor conditions or to the consumption of some of the fuel. The temperature history shows the stability of the system, indicating that the reactor effectively maintained the specified operating temperature for most of the experiment.

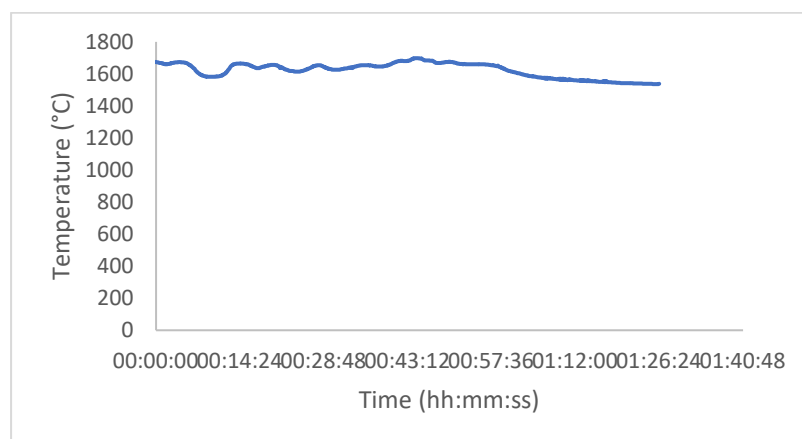


Fig. 11 Average Reactor Temperature



Fig. 12 shows the pressure evolution in the reactor during the experiment. The pressure values vary from approximately -5 kPa to 5 kPa, indicating dynamic changes inside the reactor during the experiment. At the beginning (time 00:00:00), short-term pressure increases are observed, which may be related to the fuel entering the reactor. Frequent fluctuations occur over time, with the pressure oscillating around zero with periodic peaks and troughs. Significant pressure changes at certain intervals may be due to changes in the reactor process or fuel reactions. Towards the end of the experiment, the pressure dropped slightly and stabilized closer to the lower values, which may indicate a stabilization of the reactor conditions. This pressure pattern indicates the dynamic nature of the experiment and the need for careful monitoring of the pressure profile.

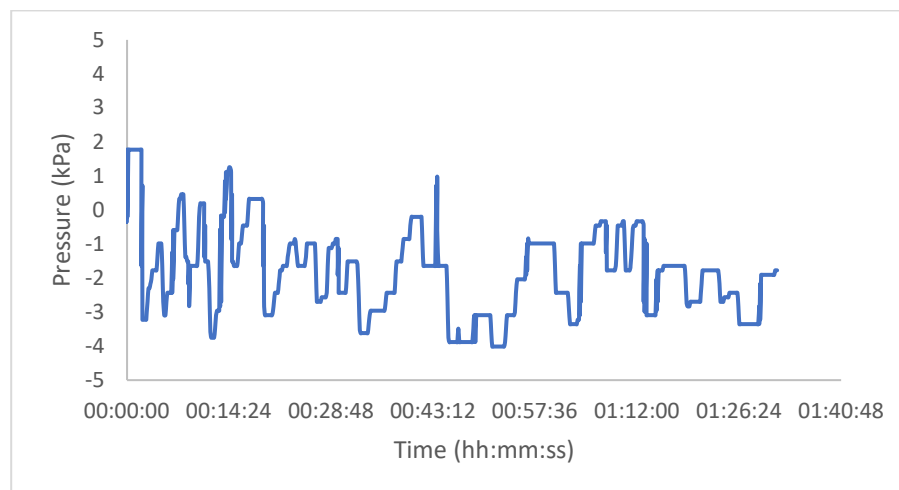


Fig. 12 Pressure in the Reactor

8.2 Syngas Composition

Due to the relatively short time for individual experiments, which was given by the limited amount of fuel supplied and the large volume of the reactor, the stabilization of the synthesis gas composition occurred very slowly. In our experience, the gas coming out of the gasifier after approximately 40 min of experimentation can be considered as a reliable synthesis gas composition that is already stabilized. The entire fuel is fed into the reactor during 60 min. From the 50th minute onwards we can assume that the



screw conveyor is not fully filled. For these reasons, the gas composition for each test is set as the average of the composition from the 40th to the 50th minute of the experiment. The results of the composition of the individual tests are shown in Fig. 13

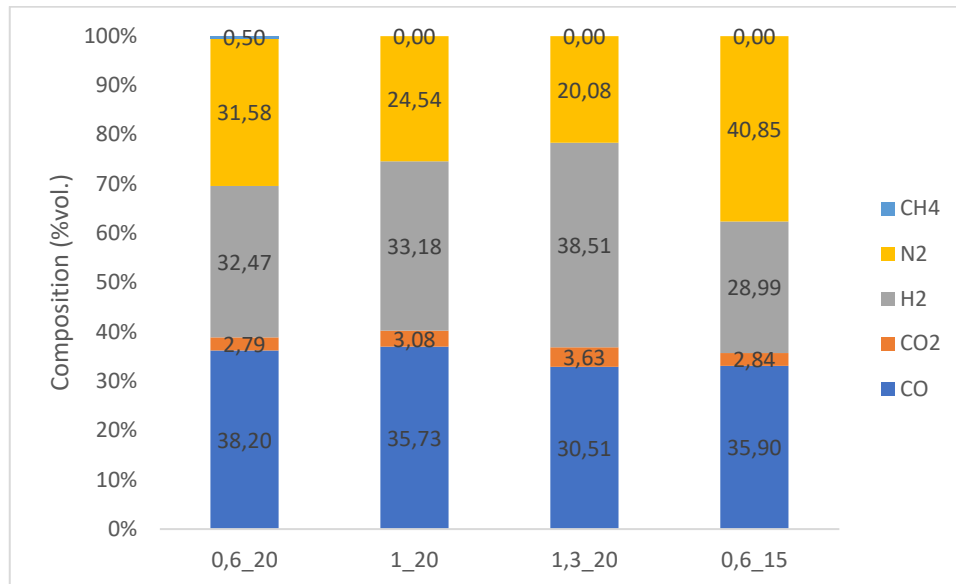


Fig. 13 Composition of Syngas

In Fig. 13, we can see that the synthesis gas composition was approximately constant throughout all 4 experiments. The proportion of N₂ ionization gas ranged from 20,08 %vol. to 40,85 %vol. The presence of N₂ is due to the fact that it is used as an ionization gas for the operation of plasma torches. The maximum N₂ for the 0.6_15 test is due to the reduction in the flow rate of the fuel with the gasification medium, whereas the flow rate of the ionization gas remained the same.

For clarity, Fig. 14 shows the synthesis gas composition converted to a nitrogen-free (N₂) composition. It can be seen from the graph that the main factor affecting the amount of hydrogen (H₂) in the resulting synthesis gas is the Steam/Fuel ratio.

At lower values of this ratio (e.g. 0.6) the water vapour content is limited, which favours reactions that produce mainly carbon monoxide (CO) and small amounts of methane (CH₄). This results in a higher calorific value of the gas, which is advantageous for applications where a higher proportion of CO is desired. The lower

amount of steam also limits the reaction (Water-Gas Shift) and therefore less H_2 and CO_2 are formed. [5; 6; 7]

Conversely, an increase in the Steam/Fuel ratio results in an increase in hydrogen (H_2) and carbon dioxide (CO_2) production at the expense of CO . The high steam content activates the water shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$), which increases the production of H_2 while converting CO to CO_2 [6; 7; 8]. Therefore, a higher Steam/Fuel ratio is advantageous in applications that require a higher proportion of hydrogen, such as fuel cells or pure hydrogen production.

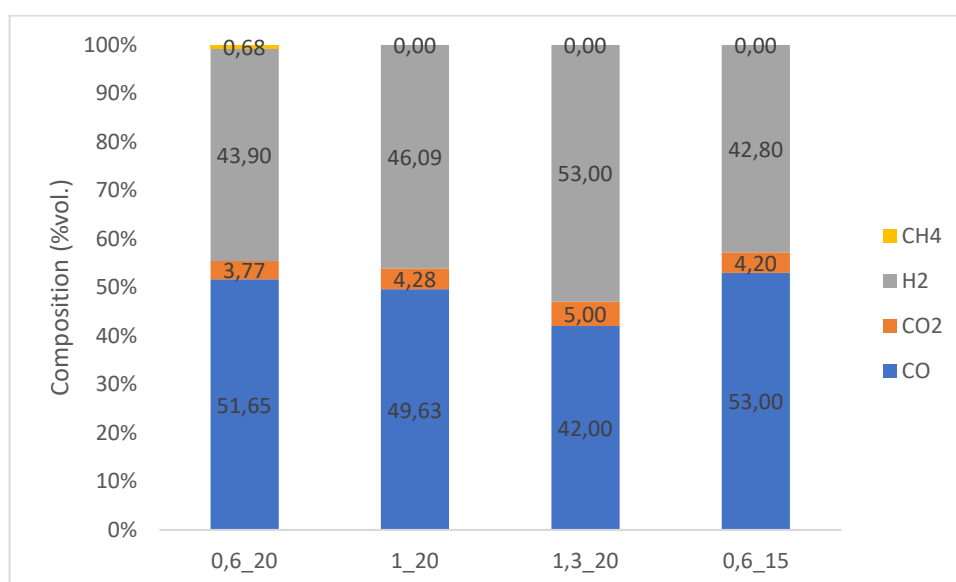


Fig. 14 Composition of Syngas without N_2



8.3 Mass Balance

Based on the determined mass flow rates of the inlet and outlet streams, a mass balance was performed. Fig. 15 shows the contribution of each inlet to the reactor. The Steam/Fuel ratio was determined according to the experimental parameters. The amount of ionization gas was dependent on the design of the plasma torch. From the results, it can be seen that the highest ionization gas fraction was obtained in the 0.6_15 test, which is mainly due to the reduction of the fuel or steam flow rate.

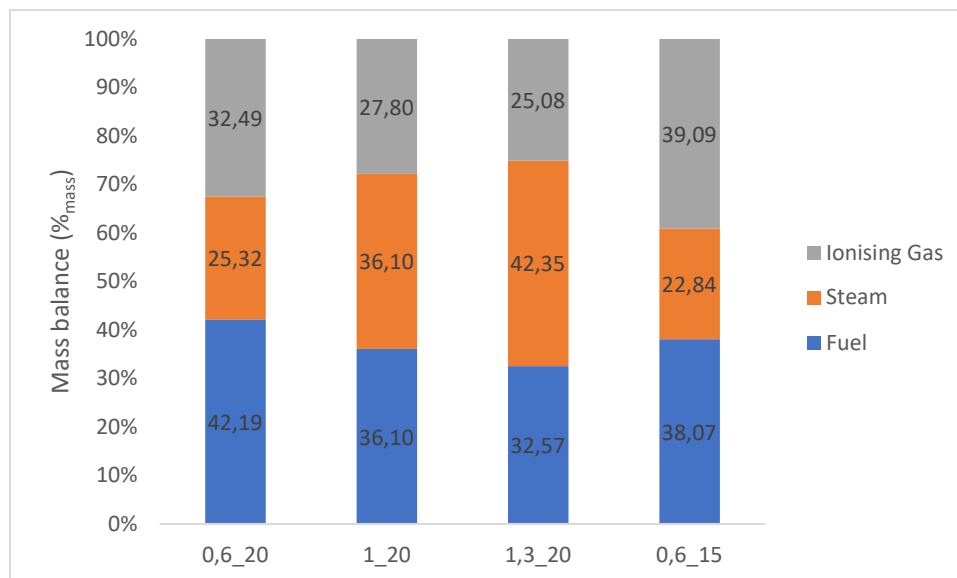


Fig. 15 Mass Balance Feedstock of Gasification

The results of the bar chart, in Fig. 16, of the mass balance of the plasma gasification products show that the highest gas yield was obtained in the 1.3_20 test, which can be attributed to the highest amount of water vapor at the inlet of the gasifier. On the other hand, the lowest yield was recorded in the 0.6_20 test, when the steam/fuel ratio was the lowest. Changing the fuel rate also affected the amount of synthesis gas produced: when the fuel flow rate was reduced from 20 to 15 kg/h, the flow rate of the inlet ionization medium remained approximately the same. The syngas/fuel mass ratio was also approximately maintained, but the ionization gas caused a dilution of the resulting syngas, which is also consistent with the results of its composition shown in Fig. 14.

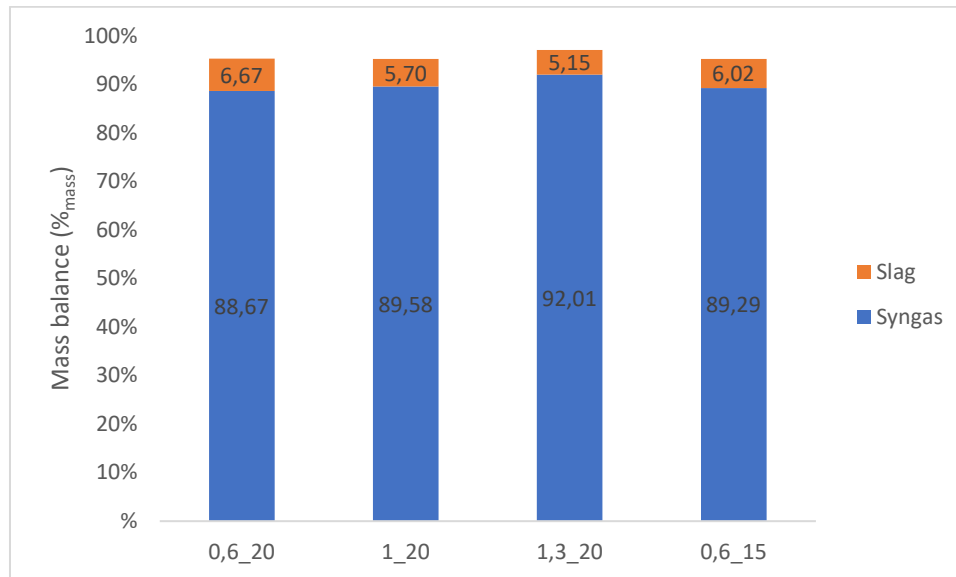


Fig. 16 Mass Balance Yields of Gasification

8.4 VA characteristics of plasma torch

Fig. 17 shows the measured voltammogram characteristics of the plasma arc torch at three different ionization gas (nitrogen) flow rates of 148, 195 and 250 l/min. It can be seen from the graph that the voltage increases with increasing nitrogen flow rate at the same current values.

At the lowest flow rate (148 l/min) the voltage reaches the lowest values, while at the highest flow rate (250 l/min) the voltage is the highest. The characteristics of all three curves show a decrease in voltage with increasing current up to a certain value, after which the voltage stabilizes and remains almost constant or only slightly fluctuates. This voltage drop at higher current values may be due to the increase in the temperature of the arc, which affects its electrical conductivity. [9; 10; 11]

The results show that a higher nitrogen flow rate leads to an increase in voltage, which may be due to a larger volume of ionization gas in the arc region. It has been shown in a number of studies that an increase in the flow rate of ionization gas (nitrogen) generally leads to an increase in voltage at the same current. This phenomenon is explained by the fact that a higher gas flow rate increases the bulk



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density of ions and atoms in the arc, which requires a higher voltage to maintain a stable arc. [10; 12]

A voltage drop with increasing current over a certain range is also commonly observed in the literature, which is related to the increase in temperature and electrical conductivity of the plasma. However, after a certain value of current is reached, the voltage often remains relatively stable, as in your graph, or may even increase slightly if ionization and heat generation increase. [9]

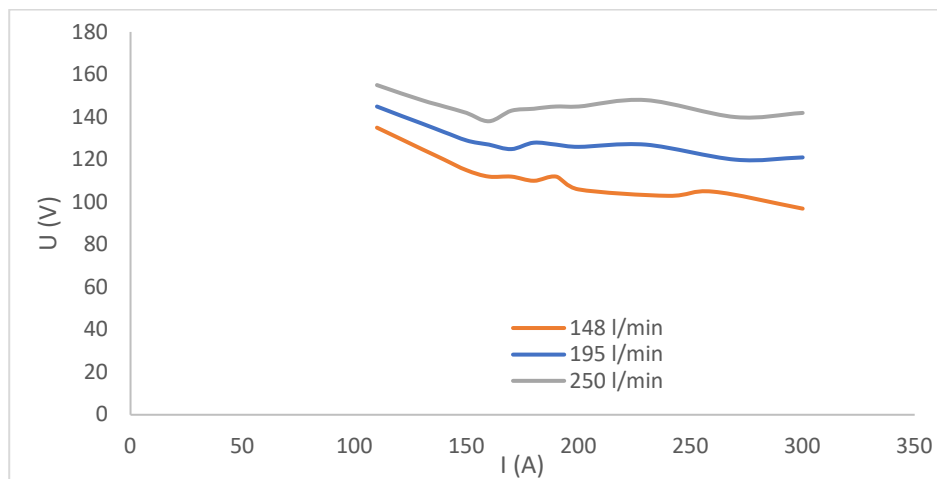


Fig. 17 VA Characteristic of Plasma Torch



9. Conclusion

Four plasma gasification experiments of a sorted coal fraction were carried out in a plasma gasifier located in the CEETe building at VSB – Technical University of Ostrava. The experiments were conducted at a temperature of 1 600 °C, each lasting one hour. Due to the limited amount of available feedstock, the tests were performed with a batch size of 20 kg in three experiments and 15 kg in one. The main objective of the experiments was to evaluate the effect of the steam-to-fuel ratio on syngas yield and composition. Three different steam/fuel ratios were tested: 0.6, 1.0, and 1.3. The fuel feed rate was set to 20 and 15 kg/h.

The mass balance of input materials and resulting products showed a high syngas yield, reaching up to 92 % by volume. With increasing steam/fuel ratio, the syngas yield slightly increased – specifically from 88.67 % at a ratio of 0.6 to 92.01 % at a ratio of 1.3. A higher steam/fuel ratio also led to an increase in hydrogen (H₂) content in the syngas, accompanied by a slight increase in carbon dioxide (CO₂) and a decrease in carbon monoxide (CO) content. Conversely, at lower steam/fuel ratios, higher CO production and trace amounts of methane (CH₄) were observed. A lower fuel flow rate (15 kg/h) caused dilution of the syngas by the ionization gas (N₂), resulting in an increased nitrogen content in the gas.

The results indicated that the optimal conditions for plasma gasification of the sorted coal fraction were achieved at a fuel flow rate of 20 kg/h or higher, a temperature of 1600 °C, and a steam/fuel ratio of 1.3. With increasing steam-to-fuel ratio, an increase in syngas volume was observed, but so was an increase in water vapor content, which may appear to reduce the heating value. However, a significant portion of the steam reacts at high temperatures with the raw fuel in reactions such as the water–gas shift ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$) and in the oxidation of carbon and hydrogen. Therefore, it is not correct to assume that a higher amount of steam necessarily lowers the heating value of the produced syngas.

The experiments also included the determination of the current-voltage (I-V) characteristics of the plasma torches at three different nitrogen flow rates (used as the ionization gas): 148, 195, and 250 L/min. The I-V curves show that with increasing



nitrogen flow, the voltage increases at the same current values. At the lowest nitrogen flow (148 L/min), the voltage reached its minimum values, while at the highest flow (250 L/min), it reached the maximum. For all three flow rates, the curves show a voltage drop with increasing current up to a certain point, after which the voltage stabilizes and remains almost constant or only slightly fluctuates. This voltage drop at higher currents may be attributed to an increase in arc temperature, which affects its electrical conductivity. A higher nitrogen flow results in a greater volumetric density of ions and atoms in the arc region, requiring higher voltage to maintain a stable arc. This phenomenon, also confirmed in other studies, demonstrates that increasing the ionizing gas (nitrogen) flow rate generally leads to higher voltage at a given current.

Regarding the composition of the syngas, the concentration of H_2S was not monitored. This is due to the method of gas handling – the raw syngas exits the reactor directly through a quench cooler, where dust particles, hydrocarbons, and H_2S are adsorbed. Subsequently, the gas passes through a packed column designed for significantly higher flow rates than those used in these experiments. As a result, substantial removal of these components occurs. Moreover, due to the low sulfur content in the feedstock, the concentration of H_2S in the produced gas is presumed to be very low.

The results table does not include condensate formed after gas cooling. Due to the use of a direct-contact cooler and an absorption column, it is not possible to quantify how much of the collected moisture originates from the syngas itself and how much comes from the cooling water, which represents the predominant share.



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