Optimizing a Plasma Burner by Implementing Additive Manufacturing in the Spinner Design

Leandri Kriek, Izak J. van der Walt, Albertus J. Viljoen and Abraham F. van der Merwe

Abstract—Waste management is becoming increasingly difficult as the waste in countries is continuously increasing. Due to this crucial issue the demand for engineering processes, to not only manage waste but also to reduce waste, is increasing. Plasma gasification as solid waste treatment is one of the most effective and environmentally friendly methods to manage waste as it does not only reduce the waste but also converts the waste into synthesis gas that can be converted into fuel or energy.

In this investigation a non-transferred arc plasma is used to generate an arc inside the plasma torch, creating a tail flame which in turn processes the waste material. Electrodes (anode and cathode) are used to generate the arc inside the burner by supplying electricity to the electrodes. The efficiency of the burner is therefore directly related to the energy loss inside the burner. Vortex stabilisation is used as a method to shield the plasma burner anode wall against heat transfer from the arc to the wall. The vortex stabilisation method makes use of a spinner which swirls a swirling gas (mainly argon or nitrogen) down the anode wall, creating a gas vortex.

Additive manufacturing is a growing field of interest as it allows the designer to break away from the conventional manufacturing methods, where complexity is an issue. Additive manufacturing will be used to manufacture newly designed spinners, where curved gas flow pathways are introduced into the design of the spinner. Additive manufacturing will be used to manufacture newly designed spinners, where curved gas flow pathways are introduced into the design of the spinner (a technique that is not possible in conventional manufacturing methods). To verify the quality of the titanium additive manufactured spinners, x-ray tomography technology will be used.

The objectives of this investigation are to improve the holistic function of the burner by minimising the energy loss to the walls of the anode by introducing curvatures in the spinners by means of additive manufacturing. Variations in the (i) curvature of the spinner as well as (ii) the number of gas flow pathways and their effect on the efficiency of the burner will be investigated. Experiments will be carried out with variations in (i) the power supply to the burner as well as (ii) the gas flow rate of the swirling gas.

Index Terms—Additive Manufacturing, Plasma Gasification, Plasma Burner, Spinner, Vortex Stabilisation, X-Ray Tomography.

I. INTRODUCTION

Plasma can be seen as a distinct fourth state of matter [4] and can be defined as an ionized gas. It mainly consists of free electrons and positively charged ions mixed together [4]. Ionization is the process where a molecule gains a positive or negative charge by either losing or gaining electrons to form ions. This in turn yields a molecule with an electrical charge - either positive or negative. It is important to take note that to be classified as plasma the negative and positive charges should balance each other, therefore plasma should be electrically neutral; this is called a quasi-neutrality property [2]. The electrical charge that an ion possesses provides the molecule with the ability to conduct electricity [2] and to produce and respond to magnetic fields. As the temperature of the molecules increase over time the molecule gains energy and transitions takes place from solid to liquid, liquid to gas, and gas to plasma, depending on the original state of matter [4]. The properties of plasma are very similar to that of gases as it has no specific shape or constant volume.

Plasmas can occur naturally or man-made, of which natural plasmas contribute to about 99% of the optical universe [4]. There are numerous methods that can be used to induce a plasma, of which exposing a gas to a high temperature or a high electrical discharge are two of the most commonly used techniques in the industry [2]. Plasmas provide three main advantages in the field of chemistry [4]:

- The ability of some plasma components to exceed the temperature and energy densities of the traditional chemical technologies.
- Plasmas have the ability to create large quantities of energetic and chemical active species.
- Plasmas possess the ability to be nowhere near thermodynamic equilibrium; this result in high quantities of energetic and chemical active species with bulk temperatures ranging as low as room temperature.

Man-made plasmas consist of a wide range of temperatures, densities and pressures. The temperature range of man-made plasmas is phenomenal; it can range from as low as room temperature to as high as the average interior star temperature (ranging from a few thousand Kelvin to 50, 000 Kelvin) [4]. Plasmas in general can be divided into two basic categories namely: (i) completely ionised plasmas and (ii) weakly ionised plasmas [4]. As the latter implies, plasmas are therefore not compelled to be fully ionised to be categorized as plasma.

Numerous methods can be used to induce man-made plasma of which the main methods of interest in industry include:

1. Electrical discharge
2. Chemical decomposition
3. Photodissociation
4. Laser plasmas
5. Coaxial plasma torch
6. Plasma jet
7. Inductive plasma
8. Induction plasma

The only true disadvantage of plasma gasification is that it uses electricity as a source of energy, but seeing that energy is one of the products that can be obtained in this process, this can be used as an option to partially supply power to the system, with the remainder of the power supplied by an external source [6].

Plasma gasification convert carbon containing waste including materials such as ordinary tyres, paper, medical waste and even low level radio-active waste into synthesis gas (syngas). Syngas consist mainly of carbon monoxide (CO) and hydrogen (H₂) with relatively small quantities of carbon dioxide (CO₂) and methane (CH₄) [8].

The plasma gasification processes are directly dependent on plasma torch technology. A plasma torch supplies the heat which convert the waste into syngas. Electric arc generated plasmas can be subdivided into two types namely (i) transferred arc plasmas and (ii) non-transferred arc plasmas [6] The difference between the two arc plasmas lies in the electrode design. The electrode of the transferred arc plasma is the processing material in contradiction with the function of the non-transferred arc plasma where an arc is generated inside the plasma torch creating a tail flame which in turn processes the material. This means that a tail flame is used to put the process of gasification into action [8].

Non-transferred arc plasmas have numerous applications in industry of which plasma waste treatment is included. The execution of the material processing by non-transferred torches conventionally takes place at the outside of the torch; this is the region where the thermal plasma is exposed to ambient gas. The majority of existing plasma generating methods use a vacuum to induce the plasma. A major disadvantage of this method is that it is economically unfeasible as well as inefficient in productivity [5].

To stabilise a plasma the flow characteristics and behaviour are important parameters to take into account. Another parameter that should be taken into account in stabilising the plasma would be to focus the induced plasma at the centre of the occurring flow; this is predominantly to obtain constant surface treatment. This can be done in two conventional ways namely (i) wall stabilisation and (ii) vortex stabilisation. The former refers to stabilisation that is induced by lowering the electrical conductivity whilst simultaneously cooling the outer wall. The result is not only the stabilisation of the tail flame but also minimisation of heat loss. The latter includes a swirling gas which is tangentially injected into the plasma torch to serve as insulation between the wall of the burner and the arc. This minimises the heat loss [5].

Vortex flow is one of the most common methods used in plasma wall-isolation to prevent heat transfer to occur. Two known apposing methods have been used to stabilise the gas vortex used to insulate the plasma wall. The Forward Vortex Stabilisation (FVS) method, although most commonly used, seems to be the more inefficient method when compared with the Reversed Vortex Stabilisation (RVS) method. Forward Vortex Stabilisation refers to the configuration where the spinner is placed upstream relative to the electric discharge and the outlet of the plasma jet is faced to the opposing side. The problem occurring in this method, when intense fluid flow is present, include the pressure minimum at the spinner side axis to be deeper than that of the downstream axis, resulting in central reverse flow. This transfers the energy from the centre to a more upstream location, causing a significant amount of heat to be transferred to the plasma walls resulting in unnecessary heat loss [3]. The idea behind the RVS method is to direct the outlet of the plasma jet towards the axis of the spinner; therefore the gas comes into the discharge zone from all angles excluding the outlet side and no immense recirculation zone will form [3].

In this investigation a non-transferred arc plasma is used to generate an arc inside the plasma torch, creating a tail flame which in turn then processes the waste material. Electrodes (anode and cathode) are used to generate the arc inside the burner by supplying electricity to the electrodes. The efficiency of the burner is therefore directly related to the energy loss inside the burner. Vortex stabilisation is used as a method to shield the plasma burner anode wall against heat transfer from the arc to the wall. This is measured by means of thermocouples indicating heat loss to the cooling water. Three thermocouples are used during this experiment: one to measure the temperature of the inlet cooling water stream and two other thermocouples used to measure the anode and cathode outlet cooling water. The vortex stabilisation method makes use of a spinner which swirls a swirling gas (mainly argon or nitrogen) down the anode wall, creating a gas vortex.

Additive manufacturing will be used to manufacture newly designed titanium spinners, where curved gas flow pathways are being introduced into the design of the spinner. To verify the quality of the titanium additive manufactured spinners, x-ray tomography technology will be used

II. EXPERIMENTAL SETUP AND APPARATUS USED

A. Burner Assembly

The configuration of the burner can be seen in Fig. 1. The positions of the spinner as well as the anode and cathode are clearly indicated in Fig 1.
then cooled and circulated back to the cooling water inlet of the burner. The thermocouples are attached to the inlet of the cooling water, used to cool the burner, as well as the anode and cathode cooling water outlets respectively. The thermocouples serve as an indication of the heat loss to the wall of the anode and cathode. With this information the efficiency of the gas vortex, and therefore the spinner can be determined.

### B. Dimensions of Newly Designed Spinners

Five Spinners were tested (including the standard spinner) to determine if any observations can be made regarding the influence on the efficiency of the burner. The dimensions of the different spinners’ gas-flow holes are indicated in Table I.

<table>
<thead>
<tr>
<th>Spinner</th>
<th>Number of holes</th>
<th>Size of holes [mm]</th>
<th>Curvature Radius [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Spinner 1</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Spinner 2</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Spinner 3</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Spinner 4</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

All the newly designed spinners that are mentioned in Table 1 is shown in Fig. 2 and 3.

![Fig. 2 Spinner 1 (left) and Spinner 2 (right)](image)

![Fig. 3 Spinner 3 (left) and Spinner 4 (right)](image)

A sectional view of the standard spinner that is conventionally used is observed in Fig. 4.

![Fig. 4 Sectional view of a Standard Spinner](image)

A sectional view of a spinner with curved pathways is shown in Fig. 5.

![Fig. 5: Sectional view of a spinner with Curved Pathways](image)

### III. METHODOLOGY

The experimentation process is started by first disassembling the burner. The gap between the cathode and the anode is then set to 2 mm. This is a very important step as the gap between the cathode and the spinner should not be smaller than the gap between the anode and the cathode. A smaller gap between the cathode and the spinner can cause the arc that is generated to attach itself to the spinner rather than the anode as the arc attaches itself to nearest contact point. This may result in either short circuiting of the burner or melting of the spinner if the experiments are carried out for a long enough time period. Both cases results in ineffective operation of the burner.

All of the spinners were designed using Solid works Software and then exported to be additive manufactured. The newly designed additive manufactured spinners are inserted individually into the disassembled burner, where two o-rings are used, at the top and the bottom of the spinner, to keep the spinner in place. The burner is then reassembled with the spinner inserted.

The experiments were carried out at different electrical currents: 100, 150, 170, 190, 200 and 220 amperes and different gas flow rates: 1.55, 2.07, 2.59 and 3.10 g/s. Each individual
spinner is tested under these variable operating conditions. The experiments were started by first using argon as swirling gas at 100 amperes. Once the plasma has started and reaches a steady state the argon swirling gas is replaced with nitrogen and the first experiment is carried out, starting at the lowest current and flow rate. The current is held constant whilst the flow rate of the gas is varied. Once the highest flow rate is reached the current is raised to the next setting. The gas flow rate is then varied again from the lowest gas flow rate to the highest. This procedure is repeated until all the experiments are carried out for each spinner.

The burner is allowed to stabilise after each new operating condition that is introduced to the burner before taking the readings from the thermocouples. After a few experiments it was observed that one minute was sufficient for the burner to stabilise. Therefore each experiment was carried out for one minute before taking the necessary readings. For each different flow and current settings the temperature measurements on the thermocouples are observed and registered. Calculations follow to determine the power supplied to the burner as well as the heat loss to the wall of the anode and cathode. The heat loss is then subtracted from the power supplied resulting in the actual power achieved by the burner, which is used in the determination of the efficiency of the spinner.

IV. CALCULATIONS

The Spinner efficiencies were calculated by first calculating the applied power to the burner by means of equation (1):

$$ P = IV $$

Where;
- $P$ = power in kW
- $I$ = Current in Amps
- $V$ = Voltage in Volts

The heat loss of the burner is calculated by determining the heat loss to the cooling water used to cool the anode and the cathode. The equation for heat loss is reported in equation (2):

$$ Q = \dot{m}c_p(T_2 - T_1) $$

Where;
- $Q$ = heat loss [kW]
- $\dot{m}$ = mass flow rate of water [kg/s]
- $c_p$ = specific heat capacity of water [kJ/kg(°C)]
- $T$ = temperature [°C]

The specific heat capacity of water is independent of temperature and has a constant value of ~ 4.188 kJ/kg(°C). Therefore equation (2) can be reduced to:

$$ Q = \dot{m}c_p(T_2 - T_1) $$

Equation (3) is then used to calculate the heat loss to the anode and the cathode separately. A total heat loss value is then calculated using equation (4).

$$ Q_{\text{total}} = Q_{\text{anode}} + Q_{\text{cathode}} $$

The efficiencies of the spinners at the set operating conditions can then calculated by means of equation (5):

$$ \eta_{\text{spinner}} = \frac{P - Q_{\text{total}}}{P} \times 100 $$

Average efficiencies for the spinners was obtained by taking the various gas flow rates and currents supplied to the spinners, into account for each individual spinner.

V. RESULTS AND DISCUSSIONS

The power-current plots for all the different spinners can be observed in Fig. 7-10. In all of these figures it can be seen that the power values increase with an increase in applied current.
The power values also increase with an increase in gas flow rates. The standard spinner can be seen as an outlier in all these figures with much lower power values obtained at the different applied currents.

From Fig. 7 it can be seen that at a nitrogen flow rated of 1.55 g/s all spinners behave more or less in the same way with the exception of the Standard spinner which yields lower power values for all currents applied. The newly designed spinners seem to have an almost linear increase in power with an increase in current. All spinners have an increase in power values when the current is increased.

In Fig. 8 the standard spinner behaves as an outlier with much lower power values acquired than all other spinners for the applied currents. Spinners 1-3 behave almost exactly the same throughout all the applied currents. A linear increase in power can be seen with spinner 4, as the current applied is increased. All spinners, excluding the standard spinner, shows an increase in power when the applied current is increased.

From Fig. 9 an almost linear increase in the power can be observed for all spinners from 100-170 amperes. The standard spinner behaves as an outlier and is seen to almost reach a steady state applied power value of roughly 13-14 kW. The stand spinner yield much lower applied power values than the spinners with curved gas flow pathways. Spinner 4 shows a sudden decrease in power at 190 amperes after which the power starts increasing again at 200 amperes. Spinners 1-3 behaves similarly for all applied currents throughout.

Fig. 10 shows linear increases in power when the current is increased. All spinners behave the same with an exception of the standard spinner, which can be seen as an outlier. The standard spinner yields much lower power values than all other spinners for the same applied currents. From Fig. 10 it can also be observed that spinner 2 and 4 yields slightly higher power values than all the other spinners. For all current increases the power of the different spinners also increases, with an exception of the standard spinner, which shows a decrease in power at 200 amperes.

The applied power and the heat loss that is calculated is used in equation (5) to determine the efficiencies of the spinners at the different operating conditions. These efficiencies are used to calculate an average efficiency for each spinner.

The heat loss-current plots for all spinners at the different gas flow rates are reported in Fig. 11-14. From these figures it can be observed that the total heat loss to the anode and cathode increase with increasing gas flow rates. The power for most of the spinner also appears to increase as the currents are increased.

From Fig. 11 it is seen that all spinners behave more or less the same for applied currents between 100 and 170 amperes. At 190 amperes spinner 1 and the standard spinner show outlying behaviour with lower heat loss values when compared with the other spinners. An overall observation can be made that it the heat loss values appear to increase with an increase in applied current to the burner.

From Fig. 12 it can be seen that spinner 4 starts with the lowest heat loss at 100 amperes but as the current increases the heat loss value for this spinner also increase. At 220 amperes spinner 4 has the highest heat loss value. Spinner 2 and there show similar behaviour throughout the entire graph. From 170 amperes the standard spinner starts behaving like an outlier as
lower heat loss values can be observed for this spinner when compared to all other spinners.

From Fig. 13 it can be observed that spinners 1, 2 and 4 behave similarly throughout all applied current values. Spinner 3, can be seen to yield higher heat loss values overall. The standard spinner shows to have much less heat loss occurring at the same applied currents when compared to the other spinners. Further an overall observation can be made that the heat loss values increase with an increase in current, with an exception of spinner 4 and the standard spinner at 190 amperes.

From Fig. 14 it can be observed that the standard spinner behaves as an outlier with lower heat loss values than all other spinners. Almost linear behaviour can be seen with increases in heat loss as the applied currents increase, for all spinners excluding the standard spinner.

The average efficiencies of the spinners are reported in Fig. 15.

Fig. 15 Calculated Spinner efficiencies

From Fig. 15 it can be observed that all of the newly designed spinners can be concluded more efficient than the standard spinner, which has an efficiency of 32.65%. Therefore introducing a curvature to the gas flow pathways does have a positive effect on the burner efficiency and the burner can therefore be optimized by implementing curved gas flow pathways into the spinner design.

Further observation of Fig. 15 indicates that a curvature radius of 48 mm is more efficient than a curvature radius of 96 mm, as spinner 1 and 2 has a radius of 48 mm and yielded efficiencies of 47.99 and 47.40 % respectively. This is higher when compared to spinners 3 and 4, with efficiencies of 42.70 and 44.90 % respectively. This shows that a smaller curvature radius is more efficient than a larger curvature radius.

Lastly it can be observed that a curvature radius of 48mm is more efficient when 4 gas flow pathways are introduced to the spinner design. This is different to the efficiencies of the 96mm curvature radius where 6 gas flow pathways are more efficient than 4 gas flow pathways. The difference in the efficiencies can be ascribed to the quality of the additive manufactured spinners. The qualitative representations of the spinners are done by means of x-ray tomography and the sectional views of the newly designed spinners are shown in Fig. 15 and Fig. 16.

VI. CONCLUSION

From Fig. 15 it can be seen that all of the newly designed spinners can be concluded more efficient than the standard spinner. Therefore introducing a curvature to the gas flow pathways does have a positive effect on the burner efficiency and the burner can therefore be optimised by implementing curved gas flow pathways into the spinner design.

A smaller curvature radius was seen as more effective than a larger curvature radius, and it was also concluded with the x-ray tomography pictures that spinner 2 was not printed effectively.

Conclusions regarding the applied power and heat loss were that the power and heat loss values increase with an increase in current. The power and heat loss values also increase with an increase in the nitrogen gas flow rates.

VII. RECOMMENDATIONS

A recommendation that can be made out of the data obtained, is that the standard spinner should be replaced by a newly designed spinner, where curved pathways are introduced for the gas to flow through.

If the spinner is replaced by a spinner with curved pathways the recommendation is that a smaller curvature should be implemented rather than a larger curvature radius.

The curvature radius can be optimised with further studies using computational fluid dynamics (CFD) to obtain the most efficient curvature radius.

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REFERENCES


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Izak J. van der Walt was born on 1974/09/27 in Pretoria, Gauteng. He matriculated from the Hoër Skool Staats President CR Swart and studied a National Diploma in Analytical Chemistry (‘93 - ‘95) at TUT, then known as the Technikon Pretoria. After graduating he received his B-Tech degree in Chemistry in the following year and his Masters Degree in Science Chemistry (’02) from the University of the Witwatersrand, Johannesburg. In 2008 he was awarded a PhD Chemistry from NWU for a thesis titled “Recovery of valuable products from polytetrafluoroethylene (PTFE) waste”

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