A novel 2.45 GHz/200 W Microwave Plasma Jet for High Temperature Applications above 3600 K

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Abstract. State of the art atmosphere plasma sources are operated with frequencies in kHz/MHz regions and all high power plasma jets make use of tungsten electrodes [1]. A microwave plasma torch has been developed at FH Aachen for the application in various fields. The advantages over other plasma jet technologies are the high efficiency combined with a maintenance-free compact design and non-tungsten electrodes. In this paper the development of a 200 W torch is described. Argon is used as the primary plasma gas and a second gas can be applied for additional purposes. For the plasma generation a microwave at 2.45 GHz is sent through the torch. The special internal topology causes a high electric field that ignites the plasma at the tip and leads to the ionization of the passing Argon atoms which are emitted as a jet. By designing the copper electrode as a cannula it is possible to gain plasma temperatures higher than the electrode’s melting point. The electric field simulations are made with Ansoft HFSS. Experiments were carried out to verify the simulations. The upcoming steps in the development will be the scale-up to higher power levels of several kW with a magnetron as power source.

1. Introduction
State of the art AC plasma sources are operated with frequencies in kHz/MHz regions and mostly contain tungsten electrodes [1]. By increasing the frequency the minimum voltage for ignition is reduced.

In this paper a novel microwave plasma torch is described which makes use of a bi-static matching in addition to an inner topology that allows a single frequency ignition and operation. This makes it possible to apply fixed frequency power supplies, such as magnetrons, which is an important step to achieve high power levels.

2. Development of the microwave plasma jet
For the development of a plasma jet the two different states, ignition and operation (bi-static), need to be considered.
The ignition state requires a maximum electric field strength at the tip of the electrode exceeding the avalanche voltage of the process gas [2]. In contrast to this the operation state demands getting as much power as possible into the plasma after it has been ignited.

2.1. First plasma jets
The first plasma jet designed enabled the tuning of both states for their optimal performance [3]. The torch was able to generate a plasma with a constant input power of 200 W. The drawback of this concept was the presence of two different frequencies for the respective states. Therefore this plasma jet could not be used with a magnetron. To amend this, a new topology is developed which is shown in Figure 1.

![Figure 1. Inner topology of the new plasma jet with ignition and operation path](image)

Figure 1 displays the inner structure of the so-called two-way plasma jet whose development can be found in [3].

The two-way plasma jet includes two separate electrodes for ignition and operation, which are ideally independent. Argon is flooded into the setting. Inner conductors are solid brass wire.

Ignition is realized by the help of the electrode creating a high electric field at the tip of the torch. After ignition the electrical properties are changed due to the presence of the plasma stream, which forms a conducting body itself. This behavior can be explained by comparing the plasma with a transistor switching from the off to the on state.

First tests showed successful ignition and operation at a single frequency so that proof of concept was achieved.

2.2. Cannula-electrode plasma jet
To improve the system performance the operating electrode was replaced with a cannula carrying a process gas, allowing a better cooling and a centric exit of the gas flow. In Figure 2 the new configuration for the head can be seen.

A second stream can be applied to flood the torch with another gas to streamline the plasma and add additional cooling to the case.

3. Electric field simulations
The electrical properties of the plasma jet can be simulated and described in detail [4]. Simulations are performed with Agilent ADS by designing the equivalent circuit that gives a principle idea of the torch's dimensions. These dimensions serve as the starting point for an EM-simulation in Ansoft HFSS and the final simulation results are illustrated in the next figure with an input power of 50 W.
Figure 2. 3D simulation of ignition at 2.45 GHz with Ansoft HFSS (left) and operation simulation (right)

Figure 2 shows the 3D-EM-simulation of the new configuration. On the left the ignition state with a maximum electric field strength of about $1 \times 10^6$ V/m is illustrated. The right part of Figure 2 presents the operation state including an approximated plasma jet which is represented by four cylindrical bodies with different electrical conductivity. In the next figures the results of the HFSS simulation are plotted.

Figure 3. Achieved simulated ignition voltage at tip (approx. 2500 V) (left) and simulated operation power in plasma (min. power efficiency 93%) (right)

On the left side of Figure 3 the resulting ignition voltage of the bottom electrode against the outer case is presented with a maximum value of 2500 V. The right plot shows the operation power with a minimum efficiency of about 93%. This value is retrieved by calculating the volume density loss inside the cylindrical bodies.

The characterization of the plasma in terms of ion and electron temperature and density is being performed. Temperatures must be above 3700 K, since it is possible to melt tungsten wire (melting point 3695 K) which is shown in Figure 4. Located in the center of the plasma is the peak temperature with a high gradient. The plasma works in an atmospheric environment and runs with an Argon flow.

Figure 4. Cutting tungsten wire with a 200 W plasma torch
4. Applications

Figure 5. Self-ignited Argon plasma of first prototype (200 W input power), ignition electrode does not influence the plasma stream, experiments confirm simulation results.

In Figure 5 a prototype with a self-ignited Argon plasma is shown with 200 W CW input power. An Argon stream of 0.1 l/min is run through the cannula and the torch also has an outer air stream of 1 l/min. The shown plasma consists only of the ionized Argon atoms and is additionally focused by the second gas. Experiments show a plasma ignition at about 60 W of input power.

Tests are performed on raw surfaces with different results and effects on different materials. Input power is yet too low to melt down larger metal bulks, however thin foils of metal can be treated as intended. Organic materials combust instantly and non-organics melt. In Figure 6 the melting of a metal plate can be seen. In addition melting of non-metal solids like various salt crystals was possible, where the thermal conductivity is sufficiently low to prevent heat dissipation. A local melting of the material on the treatment spot is the result.

An oven is set-up with a 200W plasma torch as combustion source for demonstrating the principal possibility of treating low-level radioactive wastes [5]. Typical waste components and compositions are treated and results show an intended combined combustion and melting of organics and non-organics, respectively. One result is that the power is still too low to melt larger specimen, but the temperature is sufficient to treat all kinds of material. When applying the plasma on a mixture of typical low-level waste and glass particles, all substances melt together to form an amorphous substance, proving the possibility to vitrify material with this plasma application.
5. Outlook

A second and bigger prototype is built and connected to a magnetron. Air is used as process gas and the resulting plasma with 850 W is shown in Figure 7. This proofs the ability of the new topology to endure high power and supports the intention to further scale up the input power to several kW allowing improvements and further applications like welding, cutting, air cleaning, surface treatment, and also melting.

6. Summary

In this paper the development of a 2.45 GHz microwave plasma torch is described. Changes in topology for single-frequency operation, simulation and test results of the first prototype are presented. The 200 W torch is successfully tested by melting and burning of different substances. Various applications needing a high temperature in an atmospheric environment can be carried out. A second, magnetron-driven prototype for high power applications was successfully built and tested.

References

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