Characteristics of a Novel Water Plasma Torch

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Relying on heat generated by plasma arc heating liquid water into steam as a swirl gas, a water plasma torch has the distinctive steam generation structure, which has various applications such as in the treatment of organic waste and hydrogen production for fuel cells in future vehicles. The operational features of the water plasma torch and water phase change process in the discharge chamber are investigated based on the temporal evolution of the voltage and current. The optical emission spectrum measurement shows that the water molecule in the plasma is decomposed into H, OH and O radicals. As the electrodes do not require water-cooling, the thermal efficiency of the torch is very high, which is confirmed by analytical calculation and experimental measurement.

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Steam thermal plasma has characteristics of high enthalpy and high activity.[1] It is a promising method for hydrogen production[2] and carbonized waste treatment.[3] However, previous studies[4] of water plasma torches have been carried out in which the working gas was a mixture of steam and carrier gases such as nitrogen, argon or other gases. These water torches are not practically useful due to low efficiency of water disintegration and low thermal efficiency. Uhm *et al.*[5] developed a microwave steam torch to generate a pure steam plasma that does not require other carrier gas. However, a commercial steam generator must be used, and additional heating is also required to prevent condensation in the microwave steam torch, which results in lower thermal efficiency and complexity. In this Letter, we present a novel water plasma torch and discuss its characteristics, including its configuration, water phase change process, thermal efficiency, and the optical emission spectrum of the water plasma.

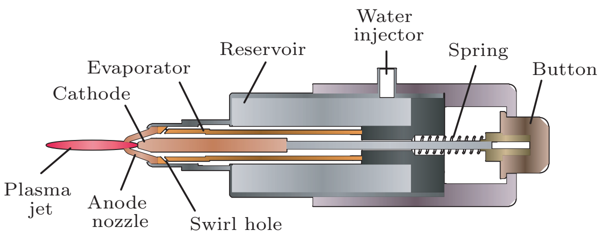

Fig. 1. The configuration of the water plasma torch.

The water plasma torch is a dc thermal plasma generator[6,7] of coaxial design with a cathode of zirconium or hafnium with 2 mm diameter embedded into a copper rod in the center and a nozzle-type anode of copper. The configuration of the water plasma torch is presented in Fig. 1. The features of the torch results from the ingenious design that the steam generator unit is integrated into the structure of the torch. The plasma arc is initiated by pushing the cathode till contacting the anode nozzle. The heat energy is released by the arc on the nozzle and the evaporator evaporates the water held in the reservoir. The resultant steam passes through the swirl hole in the evaporator and enters the discharge chamber as a vortex gas. The steam is then heated to a high temperature due to the arc discharge, and thus forms a plasma jet at the nozzle. The electrodes does not require any additional water-cooling system. The distinctive design of the pure steam torch provides a portable thermal plasma generation system, which does not require a special steam generator unit, and the thermal efficiency of this torch is high.

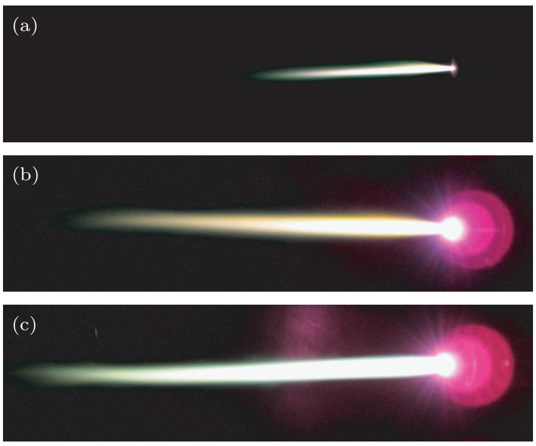

Fig. 2. The water plasma torch in operation with nozzle diameter of (a) 1 mm, (b) 2 mm, (c) 3 mm and 6 A current.

Typical pictures of the water plasma torch which was operated with different nozzles at the fixed water feed rate (6 ml/min) are shown in Fig. 2. When arc is ignited, the length of the plasma jet is very long. As the time goes by, the length of the plasma jet is gradually shortened and eventually stabilized. It is most

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likely that the torch is at the "laminar jet" working state in the initial stage, as the low flow rate of the plasma-forming steam weakens the vortex effect because of a little amount of steam production.[8] Once the torch has reached a steady state, the high flow rate of the plasma-forming steam enhances the vortex effect due to much steam production, and the torch is at the turbulent plasma jet working state. For the same reason, with the diameter of the nozzle exit increasing, the length of the plasma jet increases, just as shown in Fig. 2. However, when the diameter of the nozzle exit is more than 2.5 mm, the plasma jet becomes instable.

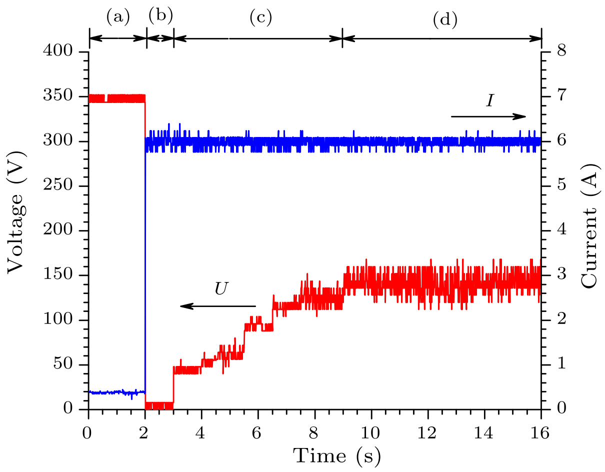

Fig. 3. Temporal evolution of the arc voltage U and current I for different periods: (a) before discharge, (b) at the time when the cathode contacts with the anode, (c) during the amount of steam increasing, (d) when the amount of steam is stabilized.

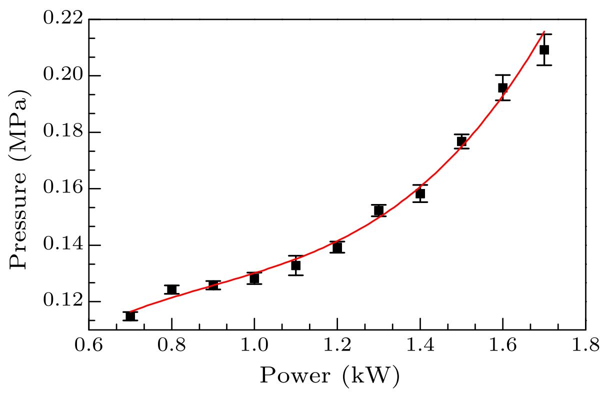

Fig. 4. The steam absolute pressure in the discharge chamber at different input powers.

The arc voltage and current wave forms before and during discharge, as shown in Fig. 3, were recorded by an oscilloscope (Tektronix TDS2024). A dc power (350 V, 6 A) was used for the arc discharge. From the temporal evolution of the arc voltage and current, we can see water phase change process and the working gas (steam) formation process. At the beginning, the presence of liquid water in discharge chamber cannot be broken down under the applied dc voltage, whereas there is a tiny current between the cathode and the anode, as shown in region a of Fig. 3, therefore, it can be inferred that water is heated into water vapor caused by joule heat to form vapor-water two-phase coexistence in the discharge chamber. In period b, there is a short-circuit current because of the cathode contacting the anode. Once the cathode is separated from the anode, the water plasma arc is ignited, as shown in region c of Fig. 3. There may be plasma-vapor-water three-phase coexistence in the discharge chamber at the beginning of period c. During this process, with the increase of heat, the liquid water soon evaporates completely in the discharge chamber. As the amount of steam increases, the cross section of the arc column becomes smaller because the higher steam flow rate enhances the vortex effect that cold steam can force the arc column to be constricted around the axis. Accordingly, the increase of arc resistance results in the rise of arc voltage, as shown in Fig. 3(c). When thermal equilibrium is established in the discharge chamber, the arc voltage is stabilized, as shown in period d in Fig. 3, which means that the steady steam flows into the discharge chamber and then is excited into steam thermal plasma.

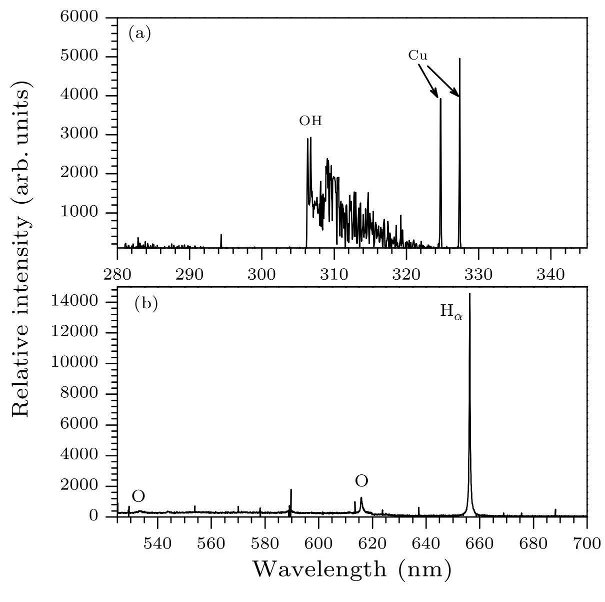

Fig. 5. Optical emission spectrum of the water plasma.

A steady steam pressure in the discharge chamber generated at different input powers is shown in Fig. 4, which was measured by a high temperature pressure transmitter (model: PT421). It can be seen that the steam pressure increases with the input power. It is noted that, although the power supply seems to provide constant current, the actual arc current fluctuates with time as shown in Fig. 3(d). Consequently, the pressure of steam production also has the temporal fluctuations. Such changes finally result in the temporal evolution of the arc voltage characterized by the saw-tooth signals as shown in Fig. 3(d).

The evaluation of the main intermediate species generated in the plasma discharge has been carried out by in situ optical emission spectroscopy (OES) measurements. The OES spectrum in Fig. 5 shows the main emission lines including OH (306.4 nm), H_α(656.3 nm) and O (533.07 nm and 615.8 nm), and the emissions from H_α and OH are prominent. This means that the water molecules are decomposed into H, OH and O radicals in the plasma.[5]

Generally, for a non-transferred gas-stabilized dc plasma torch, thermal efficiency η is defined as[9]

$$\eta = \frac{E_{\text{input}} - Q_{\text{cooling}}}{E_{\text{input}}}, \quad (1)$$

where E_{input} is the input power, Q_{cooling} is the heat losses in the cooling water. For this torch, Q_{cooling} can be written as

$$Q_{\text{cooling}} = Q_{\text{rad}} + Q_{\text{conv}}, \quad (2)$$

with Q_{rad} being the energy loss due to heat radiation by the anode surface to the ambient air, and Q_{conv} the energy loss due to convection between anode surface and the ambient air. Therefore, the thermal efficiency η of the torch reads

$$\eta = \frac{E_{\text{input}} - (Q_{\text{rad}} + Q_{\text{conv}})}{E_{\text{input}}} = \frac{VI - [A\varepsilon\sigma(T_s^4 - T_{\text{sur}}^4) + Ah(T_s - T_\infty)]}{VI}, \quad (3)$$

where V is the arc voltage, I is the arc current, A is the outer surface area of the anode, ε is the emissivity of the anode surface, σ is the Stephan–Boltzmann constant, h is the anode-environment convective heat transfer coefficient, $T_{\text{sur}} = T_\infty = 300$ K is the ambient temperature and T_s is the temperature of the anode outer surface, which is measured by a thermocouple. This energy efficiency is calculated to be about 96% from Eq. (2). The high efficiency is attributed to the distinctive steam generation as explained above.

In conclusion, a water plasma torch, which does not need any additional water cooling system, carrier gas and special steam supply system, is presented. The torch operational features, especially the water phase change and the pure steam plasma formation process were investigated. The OES measurenent shows the water molecules in the plasma are mainly decomposed into H, OH and O reactive radicals who are beneficial for chemical reaction, which is very useful in industrial applications such as carbonized waste treatment, hydrogen-rich gas production etc. An analytical calculation shows that the water torch is a high energy-efficiency device.

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