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Arc Discharge Device Working at Atmospheric Pressure

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Abstract

Arc in vacuum is one of the important methods used to prepare carbon materials. However, the use of vacuum increases the cost of the arc method. This paper introduces an arc discharge device working at atmospheric pressure. The current-limiting resistor, capacitor and inductor make the discharge gentle. The electrode temperature can be adjusted from 2040 K to 3673 K. Carbon nanofibres were prepared at the electrode temperature of 3645 K by using this device.

Keywords

Arc, Carbon Nanofibers, Chemical Vapor Deposition, Atmospheric Pressure

1. Introduction

Electric arc is widely used to prepare carbon materials, such as large-area diamond film [1], single crystal diamond [2], graphene [3], carbon nanofibres [4] and carbon nanotubes [5]. The general growth process is as follows: the electric arc furnace needs to be evacuated before operation, and then a certain amount of arc ignition gas is injected. After voltage is applied, a stable electric arc can be obtained by opening the distance between the two poles. The high temperature and ion bombardment generated by the electric arc will evaporate the graphite anode. During the process of moving to the furnace wall the evaporated atoms will recrystallize to form carbon nanotubes or other carbon nanomaterials as the temperature drops rapidly. The most commonly used arcing gases are hydrogen, nitrogen, helium and argon. Ando *et al.* [6] found that hydrogen can etch amorphous carbon impurities, so as to obtain carbon nanotubes with clean surfaces. Given that the arc discharge becomes severe with increased air pressure,

the stable operation of these devices needs a vacuum environment, thereby increasing the cost of equipment and complicating the process. This paper introduces a mild discharge device working at atmospheric pressure.

2. Experimental

2.1. The Discharge Device

The structure of the discharge device is shown in Figure 1. The mixed gas of hydrogen and ethanol is sprayed between two discharge electrodes through a thin tube, the arc discharge heats the gas flow and ethanol is decomposed to generate active particles. Then, the gas enters the circular pipe and flows through the substrate 1 cm away from the electrode, and the carbon material grows on the substrate. The diameters of the tubule, tungsten needle and circular pipe are 1 mm, 1.6 mm and 8 mm, respectively. The mixed gas of hydrogen and ethanol is prepared by flowing hydrogen through anhydrous ethanol.

In the circuit shown in Figure 1, the direct current power supply is connected to both ends of the capacitor through a current-limiting resistor. One end of the capacitor is connected to one electrode through an inductor, and the other end of the capacitor is connected to the other electrode. The power supply, capacitance and inductance are 550 V, 1 μF and 400 μH, respectively. Current-limiting resistors, *i.e.* 200, 350, 650, 1250 and 2450 Ω, are used in accordance with the required power.

The arc ignition process is as follows. First, the two electrodes come into contact and are connected to the circuit. Then, the distance between the electrodes is slowly opened, and a stable and continuous arc is generated between the two electrodes. By finely adjusting the electrode spacing through the one-dimensional sliding table, the circuit current continues to decrease with the opening of the spacing until the arc is finally broken. The pitch of the one-dimensional sliding table is 1 mm, and the stepping angle is 1.8˚ with 400 subdivisions. The pulse frequency is 659 Hz. An oscilloscope is connected to the discharge through 100 times of attenuation, and the voltage change at both ends of the electrode is monitored.

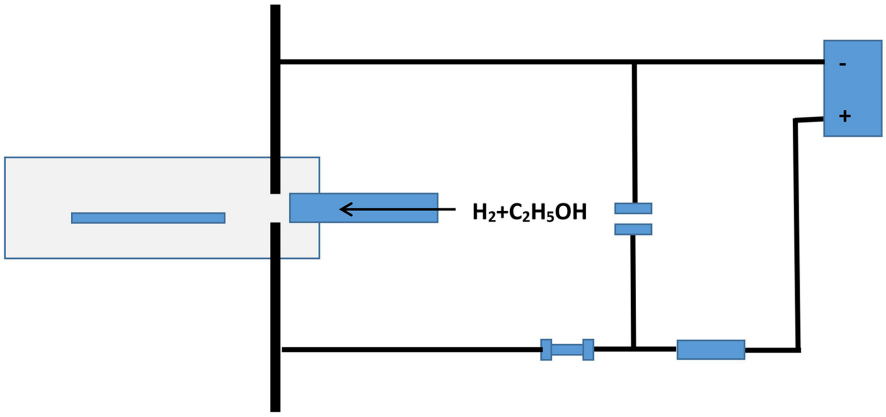

Figure 1. Structure of the discharge device working at atmospheric pressure.

2.2. Carbon Nanofibres

Carbon nanofibres were prepared using this device. The power of 300 W corresponds to the source temperature of about 3645 K, and the growth last for 2 h. The prepared materials were characterized by scanning electron microscopy (SEM).

3. Results

The temperature of the electrode is estimated by calculation. A cooling part is not present in this device. If all the power generated by the arc discharge is converted into thermal radiation in accordance with the white bright area of about 5 mm in the electrode at high temperature, the calculated emission area is about 30 mm^2. The relationship between electrode temperature and discharge power can be determined using the formula: $P = 5.67 \times 10^{-12} ST^4$.

Figure 2 shows the relationship between electrode temperature and power. In the low-temperature region less than 2000 K, the temperature changes remarkably with power, and a power change of 6 W can change the electrode temperature from 2000 K to 2100 K, increasing by 100 K. In the high-temperature region, the change in the electrode temperature with power is not evident from 3400 K to 3500 K. About 28 W of power is needed to increase the temperature by 100 K. The electrode temperature is stable at high temperature.

The discharge power between the electrodes can be calculated in accordance with the current of the circuit:

$$P = UI - RI^2$$

U is the power supply voltage; I is the current in the circuit; R is the current-limiting resistance; and P is the electrode discharge power.

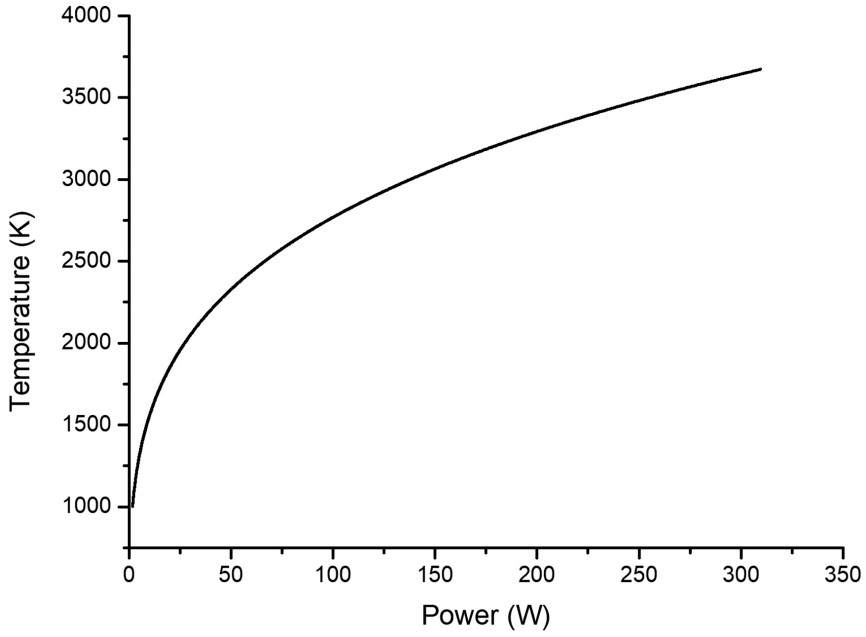

Figure 2. Temperature of the electrode at different powers.

Figure 3(a) shows the power current relationship curve when R is 350 Ω. When I is 1.57 A, the two electrodes are on, and the P of the electrodes is zero. With decreased I, P first increases and then decreases. The maximum power is U2/(4R). At R = 350 Ω, P_{max} = 216 W.

Theoretically, all P below 216 W can be generated by using R of 350 Ω. However, when the two electrodes are close or far apart, the actual discharge is unstable and not suitable for long-term growth. As shown in Figure 3(a), areas I and III are unstable, and area II is stable. Figure 3(b) shows the waveform diagram of the voltage on the two electrodes of area II. A uniform discharge with a frequency of about 294 Hz can be seen. Glow discharge and arc discharge quickly switch. Figure 3(c) shows the enlarged waveform diagram of the voltage on the two electrodes of area II. The oscillation waveform with a frequency of about 44 KHz corresponding to the frequency of LC oscillation circuit when L = 400 μH and C = 1 μf is observed. Figure 3(d) shows the waveform diagram of the voltage on the two electrodes in area I and shows two parts, *i.e.* uniform discharge and messy discharge with a frequency of about 23 Hz. Corresponding to

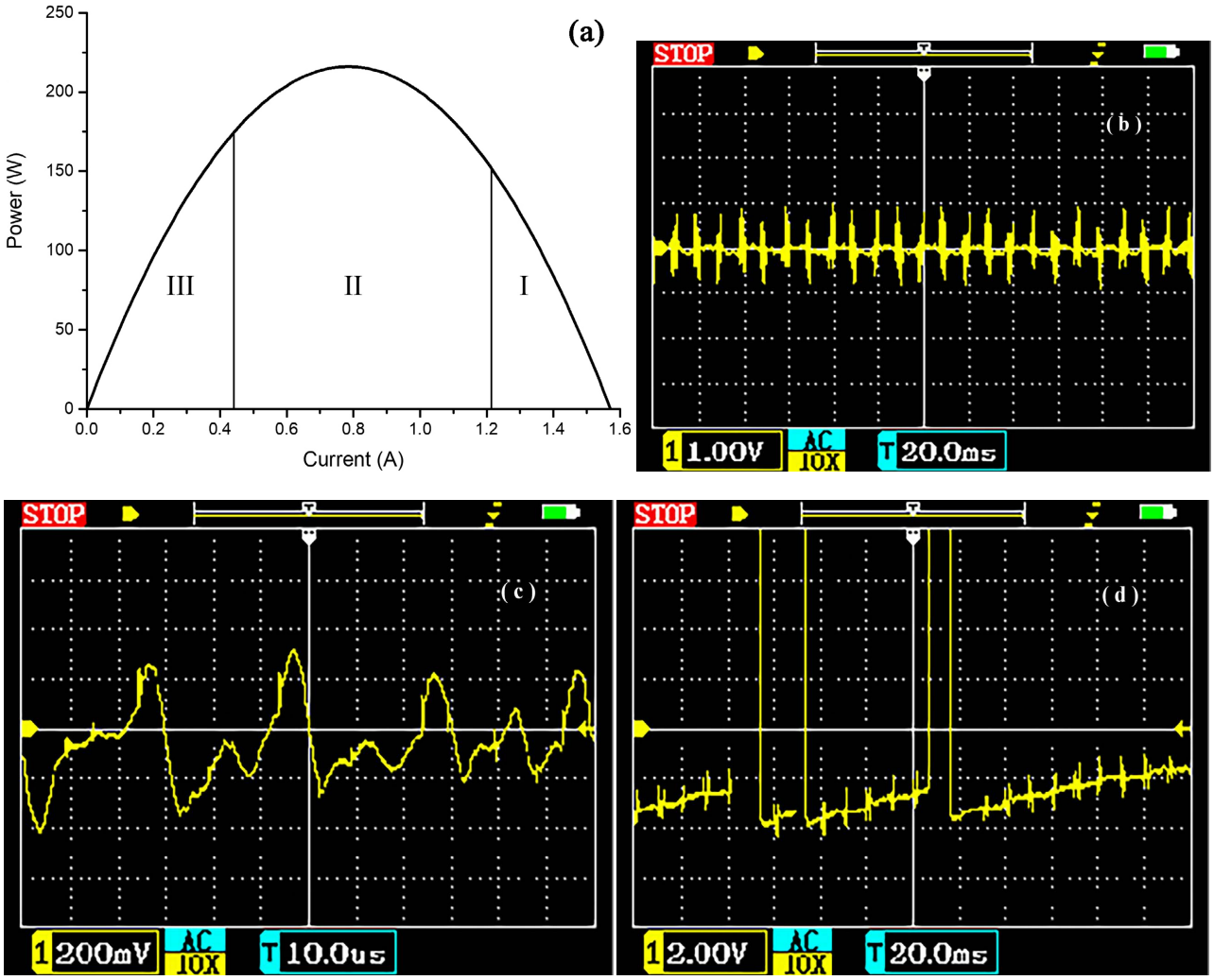

Figure 3. Arc discharge at the resistance of 350 Ω.

the arc breaks and discharges again. In area III, once broken, the arc will not discharge again and will be extinguished directly. Therefore, only the arc discharge power in zone II is stable and controllable.

Under a certain resistance, a stable discharge in a certain power range can be realised. Through different combinations of resistors, the output power of tens to hundreds of watts can be realised. Figure 4(a) shows the power curves of 378, 216, 116, 60.5 and 30.9 W with current-limiting resistance values of 200, 350, 650, 1250 and 2450 Ω, respectively.

Figure 4(b) shows the electrode morphology at a certain stable power with different current-limiting resistance values. Amongst the photos of different resistance values, the one of 2450 Ω is taken directly, and others are taken through sunglasses. At current-limiting resistance of 2450 Ω, the power of 29 W corresponds to the electrode temperature of 2040 K. At current-limiting resistance of 1250 Ω, the power of 39 W corresponds to the electrode temperature of 2200 K. At current-limiting resistance of 650 Ω, the power of 105 W corresponds to the electrode temperature of 2800 K. At current-limiting resistance of 350 Ω, the power of 187 W corresponds to the electrode temperature of 3240 K. At current-limiting resistance of 200 Ω, the power of 266 W corresponds to the electrode temperature of 3540 K. By adjusting the discharge gap electrode temperature at a current-limiting resistance of 200 Ω, the temperature can exceed the melting point of tungsten by 3673 K, which shows that the electrode burns, the current in the circuit automatically decreases and the arc increasingly brightens. After a few minutes, the electrode gap becomes large, the arc cannot last, and the arc goes out.

Carbon nanofibres were prepared using this device. Figure 5 shows the morphology of carbon nanofibres, which are predominantly composed of a wire

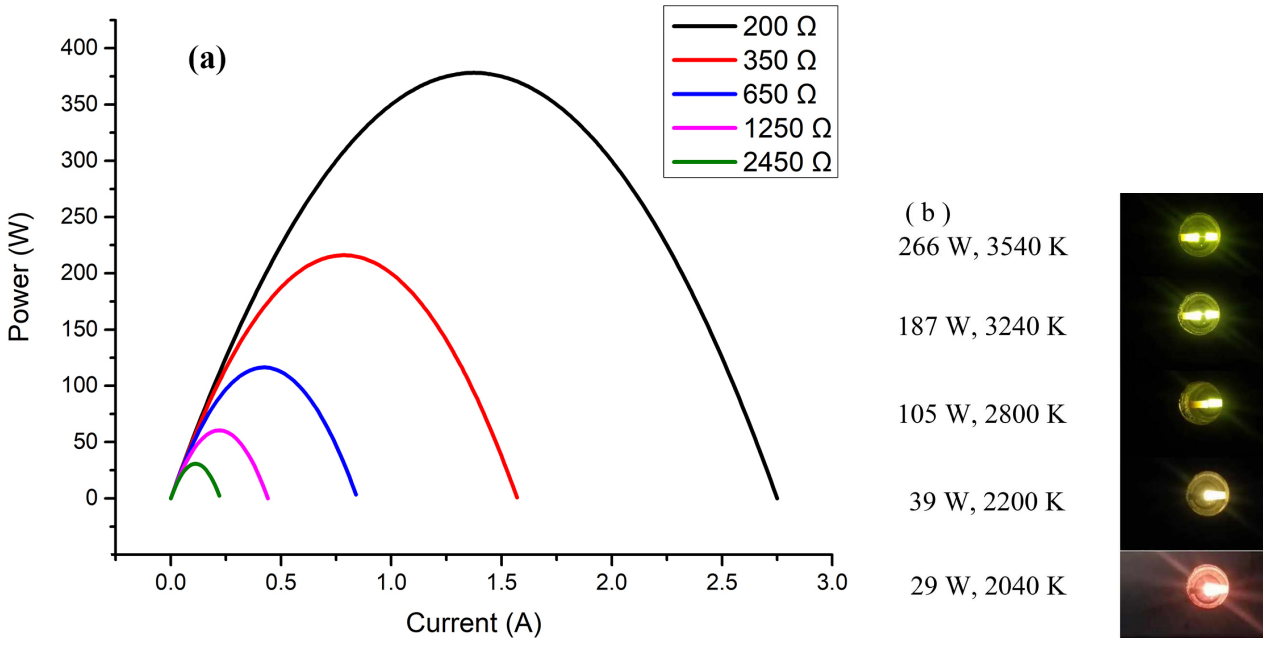

Figure 4. Electrode morphology with current-limiting resistance values of 200, 350, 650, 1250 and 2450 Ω.

Figure 5. Morphology of carbon nanofibres.

body with a diameter of about 0.5 μm. These fibres have a curved shape and are uniformly curved into a ring-shaped body. On the surface of these thick lines, some thin lines have small diameters. The formation of carbon nanofibres shows that this arc discharge device can crack ethanol well and meet the growth conditions of carbon materials.

Graphite electrode is used in literature. At high temperature, the electrode volatilizes rapidly, releasing a large amount of carbon, which makes the product contain more impurities. In this paper, we use tungsten needle electrode to prepare carbon nanofibers by electric discharge pyrolysis of ethanol, which is a chemical vapor deposition method. It can better control the carbon concentration in growth and improve the product quality.

4. Conclusion

In summary, this paper introduces a mild and controllable arc discharge device working at atmospheric pressure. Through the combination of current-limiting resistors, stable and continuous arc discharge in the power range of tens to hundreds of watts can be realised. The electrode temperature can be adjusted within the range of 3673 K or less. Carbon nanofibres are prepared by this device, showing that carbon fibre materials can be prepared by the arc at atmospheric pressure. This device will reduce the cost of carbon material preparation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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