Plasma Characteristics of Under-water Arc Discharge in Nanoparticle Fabrication

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***Abstract*— Synthetic nanoparticles are the process of making particles with a size of less than 100 nm and changing the properties of the material so that it can be improved to improve the usability of new products. One method that can be used is the arc discharge method in water, which is a synthetic method of nanoparticles, which is very simple because it does not require complicated equipment. This study uses graphene as an electrode, which is then immersed in water and mounted horizontally. Current and voltage monitoring is carried out during the arc discharge process using a Hall-based current sensor and the voltage is measured directly between the two electrodes. Variations in input current of 10A, 40A, 70A, and 100A affect the arc formed, current and voltage, and ionization energy. Monitoring with OES is also carried out to determine the shape of the plasma, and the wavelength when the arc occurs. The results obtained that the current has more effective and optimal results in synthesizing nanoparticles.**

Keywords—Plasma Arc Discharge, Nanoparticle, Current-voltage Monitoring, Ionization.

I. Introduction

Nowadays technological developments in the material field are leading to the nanoparticle revolution and there is an acceleration in the application of nanoscience and nanotechnology in the industrial world. This is because nanotechnology is very influential on the development of the times and the survival of life in the future. Some of the applications of nanotechnology are in the fields in material development, environmental science, electronics, optics, magnetism, energy storage, and electrochemistry [1].

The use of nano-based carbon materials is also very widely applied in the industrial field. The advantages of graphene in terms of optical properties, electrical properties, and mechanical properties make graphene interesting to study and develop further. Graphene can also be used as a good transistor because it has high mobility [2].

Carbon nanofiber is the most researched material in the twenty-first century to increase industrial quantities due to its unique properties such as good electrical/thermal conductivity, enhanced chemical/biocompatibility, and excellent corrosion resistance for various applications [3].

Graphene is a two-dimensional monolayer arrangement of carbon atoms that forms a hexagonal crystal structure resembling a honeycomb. Graphene has no band gap, the electron mobility of multilayer graphene is around 15000 $cm^2V^- s^{-1}$ at 300 K and about 60000 $cm^2V^{-1}s^{-1}$ at 4 K, while for few-layer graphene it is between 3000-10000 $cm^2V^{-1}s^{-1}$ [4]. The optical transmission of monolayer graphene reaches 97.7% [5] and the universal conductance is about $6.08x10\text{-}^{-5}\Omega^{-1}$ in the energy range of 0.1 eV to 0.6 eV [6]. Several advantages of graphene, namely optical, electrical and mechanical properties, make graphene interesting to study and have great potential for applications in the optoelectronic field.

Plasma can be made by utilizing an electric voltage, for example by exposing the electrodes horizontally in free air where the air is an insulator that cannot conduct electricity. Then the two electrodes are given an electric voltage so that the nature of the conductor will appear in the air between the electrodes and there will be an electric current flowing. This electric current indicates that there is ionization which results in the formation of ions and electrons between the two electrodes and the plasma [7].

Synthetic nanoparticles are a process of making particles with a size of less than 100 nm and changing the properties of material so that it can be improved to improve the usability of new products. Synthesis of nanoparticles can be carried out in vapor media (vapor/aerosol), liquid media (liquid), and solid media (solid).

The synthesis process can occur physically or chemically. Physically it does not involve chemical reactions, which occur only by breaking the material into nanometer-sized materials, or merging very small materials such as clusters, into nanometer-sized particles without changing the properties [8]. While the chemical synthesis process involves three chemical reactions from some starting materials so that other materials are nanometers in size. In chemical synthesis techniques, the growth of nanoparticles is controlled by optimizing the reaction parameters (eg, temperature, varying the reaction, reagent concentration, etc.) [9].

The method for producing a plasma arc discharge is through the evaporation of two carbon electrode rods. The two ends of the electrodes are separated by a distance of a few millimeters in a container filled with deionized water. Then an electric current of 10-100 A and a voltage of 60 V are applied to create a very high temperature change between the ends of the electrodes, so that evaporation will occur at the ends of the electrode rods. Two electrode rods connected by inverter arc welding are brought together so that an electric discharge occurs with a very high current density between the two electrodes. This current flow indicates ionization which results in the formation of ions and electrons between the two electrodes. Due to the influence of the high voltage between the electrodes (anode and cathode) there will be excitation of the filler gas. The ions will have high kinetic energy so that some of the negative ions will go to the cathode with large kinetic energy [10].

During the arc discharge process, electrons are discharged from the cathode to the anode, causing energy to be released in the gap between two electrodes. The energy is released in the form of plasma arc discharge at high temperatures, resulting in electrode surface erosion and the formation of carbon nanoparticles [11].

The method of synthesizing nanoparticles with arc discharge in water has the advantage of producing nanoparticles that crystallize by themselves due to the high temperature caused by joules heating [12]. The arc discharge method in water is a very simple synthetic method of nanoparticles because it does not require complicated equipment, so knowing and controlling the process of making nanoparticles is expected to increase the quantity and quality of production economically.

In 2016, Bin Qin [13] used a graphene layer with an arc discharge synthetic method and gas media in the form of helium, helium oxygen, and hydrogen helium. The arc discharge synthesis was carried out at pressures of 73 kPa and 169 kPa respectively with currents at 120 A and a voltage of 25-30 V. Then research was carried out by S. Yatom [14] who used a synthetic method with a laser with two graphite electrode cylinders. The electrodes are positioned vertically, with the cathode on top and the chamber filled with 500 Torr of helium gas. Further research on the synthetic method of gas in the form of argon and an argon/hydrogen mixture is used as plasma gas by Fengmei Su [15]. And Isya Fitri [16] conducted research using liquid media in the form of ethanol where ethanol can produce CNP quickly and more than distilled water liquid media. And Miftahul Anwar [17] Simultaneous I-t and V-t measurement methods have been demonstrated to be effective methods for observing the characteristics of plasma arc discharge for diagnostics of nanoparticle synthesis. The results of this I-t and V-t measurement proved to be accurate as a probing method for the ionization of plasma arc discharge that can amplify OES measurements, which are limited to visible light measurements.

Diagnostics for plasma arc discharge generally use optical emission spectroscopy (OES), which detects ionized emission species [18]. However, the Langmuir probe can also be used to determine the density of ions that occur, as well as plasma and electron temperatures (in energy) [19]. Thus far, some researchers have applied simultaneous current and voltage vs. time (I-t and V-t) data from the arc discharge to determine the current and voltage conditions when plasma ionization occurs [20-22], including investigating pressure wave propagation characteristics [23] and bubble expansion in water [24]. Nevertheless, the utilization of simultaneous I-t and V-t measurements as a probing method for the ionization energy of plasma arc discharge, which is crucial for understanding the arc shapes and ionization processes of plasma, has never been achieved.

In this research, liquid media was used in the form of distilled water. Variations of input current are also given, namely 10A, 40A, 70A, and 100A. The electrode used is graphene with a medium in the form of water. The current and voltage monitoring system is carried out simultaneously using the WCS1500 current sensor and the voltage is measured in parallel using 1:10 differential probes. The method used in this study is to vary the effect of different current variations so that it will affect the arc formed, current and voltage, wavelength, and the resulting nanoparticles.

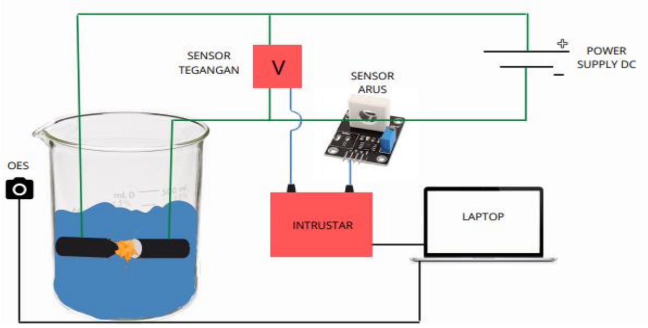

Fig 1. Schematic and Configuration of Arc Discharge Under-water system

II. Methods

A. Device Configuration

The design of the tool that will be made is the design of a tool for a plasma arc discharge system in water as shown in Figure 1. The electrode is made of 99.9% pure graphite which has the shape of a cylindrical rod with a diameter of 10 mm. The anode and cathode are immersed in a beaker containing a liquid medium. The anode and cathode are mounted horizontally on the welding clamp. The anode is made tapered so that electrons move from the anode to the cathode. The anode is moved manually via a lever. The electrodes are connected to an external DC power source.

Current is applied to the electrodes and the distance between the anode and cathode is adjusted to approximately 1 mm until a spark appears. The arc current is recorded by a digital oscilloscope which will then be processed using the Multi Analyzer Software and Origin Software. The soot produced by the arc discharge method causes the initially clear liquid medium to become cloudy and black. This soot is collected by separating the solid CNP from the liquid medium. The CNP was then poured into a petri dish and dried in a desiccator.

During the arc process, OES (Optical Emission Spectroscopy) is brought close to the measuring cup at the moment so that it can record and capture wavelengths and can determine the shape of the plasma that occurs. Then the data will be recorded with Ocean View Software.

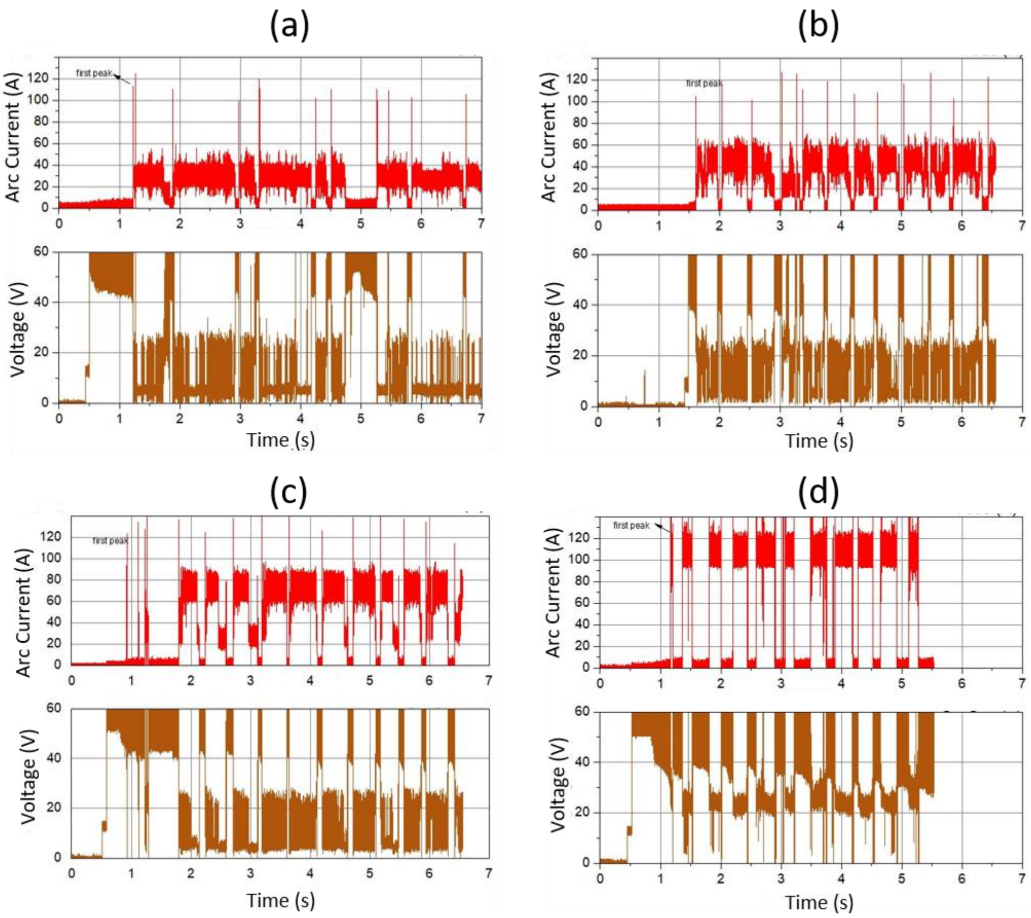

Fig 2. Current vs. voltage characteristics of arc discharge

B. DataProcessing Method

The data obtained is then processed using the origin software. The energy at the time of arc discharge is used to erode the anode. The energy produced by the arc discharge per unit time is as follows:

$$P = V * I \tag{1}$$

where:

P = Power (Watts)
V = Arc discharge voltage (V)
I = Arc discharge current (A)

$$W = \Delta P . \Delta t \tag{2}$$

where:

W = Energy (Joule)
P = Power (W)
T = Time (s)

$$N = \frac{\Delta I \times \Delta t}{1.6 \times 10^{-19}} \tag{3}$$

$$\text{Eionization} = \frac{P}{N} \tag{4}$$

where:

N = Number of charges
Eionization = Ionization Energy (Joule)

III. Results and Discussion

Analysis was focused on power consumption and energy ionization when the current is stable for each variation of applied current. Figure 2 shows voltage and current characteristics during the arc discharge events. Initially, before arc occurs, current and voltage values are 0 A and ~50 V respectively. The characteristics of the arc discharge are the current up and the voltage down. For an input current of 10 A, the current experiences several first peaks and the voltage drops to 29V.

Figure 2 shows that before the arc discharge occurred, the electrodes did not glow because the two electrodes had not been brought close to a distance of approximately 1 mm. After the arc occurs, the incandescence begins to appear and at the first peak, the current will increase and the voltage will decrease this is due to the condition of the maximum charge on the electrode then when the electrodes touch there will be a short circuit which causes the current to rise and then constant and the voltage drops to near zero. Then when the arc discharge takes place, the longer the glow will be very bright which lasts for a few seconds, this area is called the arc column.

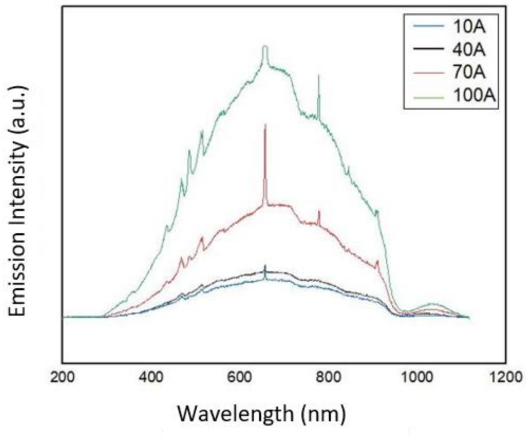

Fig 3. OES Spectra of arc discharge

The emission of light is caused by the absorption of light by the atom so that the atom is excited, that is, it returns to its original state by releasing energy in the form of light. From the graph above (Figure 3), there are three peaks with O_{II}, C_{II}, and H_{I} ions. This means that these ions participate in the reaction in the form of H and O from distilled water, and C from graphite carbon electrodes. In the graph above, it can be seen that the graph for the arc discharge of water media has the highest peak when the input current is 100 A, this is because more light is produced when there is an arc.

Ionization is a process in the formation of arc discharge where electrons move from the cathode to the anode and the electrons will collide with each other, resulting in a large electric field. During its journey, the electrons will accumulate molecules or gas atoms between the electrodes so that an ionization process occurs, where the electrons will be released from their shells due to the addition of energy. This collision process occurs continuously and will produce electronic avalanches and result in chain ionization. The amount of energy produced for the ionization process to occur is called ionization energy.

Figure 4 shows that at the peaks the ionization energy has the same value as the peaks in the OES method. However, there are several peaks in the ionization energy that are not present in the OES peak. If the value of ionization energy <2 x 10-19 J is in the infrared region, 2-7 x 10-19 J is in the visible light region, and >7 x 10-19 J is in the ultraviolet light region.

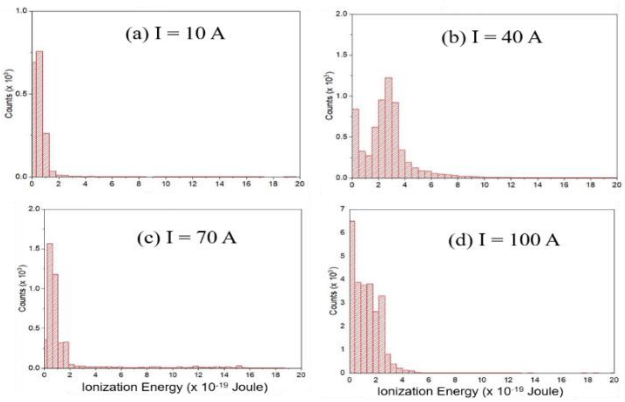

Fig 4. Ionization energy derived from current and voltage vs. time data for the different current variation

IV. Conclusion

We have successfully designed a plasma arc discharge system in water for the manufacture of nanoparticles. The electrode used is graphene with a medium in the form of water. The current and voltage monitoring system is carried out simultaneously using the WCS1500 current sensor and the voltage is measured in parallel using 1:10 differential probes. The effect of current variations on the arc formed, current and voltage, as well as ionization energy is that the greater the input current, the brighter the arc formed, the greater the current and the lower the voltage. And the distribution of ionization energy values will be more evenly distributed. The shape of the plasma and the wavelength produced during the arc discharge process are recorded through OES, that the larger the input current, the longer the wavelength will have a peak that varies.

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References

[1] I. Safarik and M. Safarikova. "Magnetic nano- and microparticles in biotechnology". Chemical Papers, Voulume 63, Issue 5, pp. 497–505, 25 August 2009. DOI: 10.2478/s11696-009-0054-2

[2] L. Kedzierski, J. M. Curtis, P. C. Doherty, E. Handman, and K. Kedzierska. "Decreased IL-10 and IL-13 production and increased CD44hi T cell recruitment contribute to Leishmania major immunity induced by non-persistent parasites". European Journal of Immunology, Volume 38, Issue 11, pp. 3090-3100, 7 November 2008. DOI: 10.1002/eji.200838423

[3] S. Sankararaman and M. S. Swapna. "Synthesis And Characterization Of Carbon Nanoparticles By Combustion Method". Thesis for M.Phil Degree, University of Kerala, Department of Opto-electronics, August 2018.

[4] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov. "Electric Field Effect in Atomically Thin Carbon Films". Science, Volume 306, Issue 5696, pp. 666-669, 22 October 2004. DOI: 10.1126/science.1102896

[5] P. K. R. Nair, B. M. Kumar, and V. D. Nair, "Agroforestry as a strategy for carbon sequestration", Journal of Plant Nutrition and Soil Science, Volume 172, Issue 1, pp. 10–23, February 2009. DOI: 10.1002/jpln.200800030

[6] A. B. Kuzmenko, E. V. Heumen, F. Carbone, and D. V. D. Marel. "Universal Optical Conductance of Graphite". Volume 100, Issue 11, pp. 117401-1-117401-4, 21 March 2008. DOI: 10.1103/PhysRevLett.100.117401

[7] E. Njatawidjaja, A. T. Sugiarto, T. Ohshima, M. Sato. "Decoloration of electrostatically atomized organic dye by the pulsed streamer corona discharge". Journal of Electrostatics, Volume 63, Issue 5, pp. 353-359, May 2005. DOI: 10.1016/j.elstat.2004.12.001

[8] M. Abdullah, Y. Virgus, Nirmin, dan Khairurrijal. "On the basic concept of nanotechnology". Jurnal Nanosains dan Nanoteknologi, Volume 1, Nomor 2, pp. 33-57, Juli 2008. ISSN 1979-0880

[9] S. Griffin, M. I. Masood, M. J. Nasim, M. Sarfraz, A. P. Ebokaiwe, K. H. Schäfer, C. M. Keck, and C. Jacob. "Natural Nanoparticles: A Particular Matter Inspired by Nature". Antioxidants, Volume 7, Issue 1, January 2018. DOI:10.3390/antiox7010003

[10] M. Loos. "Production of CNTs and Risks to Health". Carbon Nanotube Reinforced Composites, pp. 103–123, 2015. DOI:10.1016/b978-1-4557-3195-4.00004-7

[11] D.A. Mylnikov, A.A. Efimov, V.V. Ivanov, Investigation of the energy balance in the spark discharge generator for nanoparticles synthesis, J. Phys. Conf. Ser. 830 (2017), 012162, https://doi.org/10.1088/1742-6596/830/1/012162

[12] X. Gang, J. S.-li, and S. Z.-qian, "The production of carbon nano-materials by arc discharge under water or liquid nitrogen". New Carbon Materials, Volume 22, Issue 4, pp. 337–341, December 2007. DOI: 10.1016/S1872-5805(08)60005-0.

[13] B. Qin, T. Zhang, H. Chen, and Y. Ma. "The growth mechanism of few-layer graphene in the arc discharge process". Carbon, Volume 102, pp. 494-498, 2016. DOI: 10.1016/j.carbon.2016.02.074

[14] S. Yatom, J. Bak, A. Khrabryi, and Y. Raitses. "Detection of nanoparticles in carbon arc discharge with laser-induced incandescence". Carbon, Volume 117, pp. 154-162, 2017. DOI: 10.1016/j.carbon.2017.02.055

[15] F. Su, X. Qiu, F. Liang, M. Tanaka, T. Qu, Y. Yao, W. Ma, B. Yang, Y. Dai, K. Hayashi, and T. Watanabe. "Preparation of Nickel Nanoparticles by Direct Current Arc Discharge Method and Their Catalytic Application in Hybrid Na-Air Battery". Nanomaterials, Volume 8, Issue 9, September 2018. DOI: 10.3390/nano8090684.

[16] F. Andhika, S. Hastuti, and T. E. Saraswati. "The surface characteristics of carbon nanoparticles produced via submerged arc discharge in ethanol/water". AIP Conference Proceedings, Volume 2296, pp. 020069-1-020069-6, 16 November 2020. DOI: 10.1063/5.0031109

[17] A. Miftahul, T. E. Saraswati, L. Anjarwati, D. Moraru, A. Udhiarto, F. Adriyanto, H. Mghfiroh, and R. Nuryadi. "Probing Ionization Characteristics of Under and Voltage Versus Time Measurement In Carbon Nano Particle Synthesis". Journal Micro and Nano Engineering 14 (2022) 10009, 11 December 2021. https://doi.org/10.1016/j.mne.2021.100099

[18] J.W. Coburn, M. Chen, Optical emission spectroscopy of reactive plasmas: a method for correlating emission intensities to reactive particle density, J. Appl. Phys. 51 (6) (1980) 3134–3136, https://doi.org/10.1063/1.328060.

[19] G. Thakur, R. Khanal, B. Narayan, Characterization of arc plasma by movable single and double langmuir probes, Fusion Sci. Technol. 75 (4) (2019) 324–329, https://doi.org/10.1080/15361055.2019.1579623.

[20] S.-Y. Yoon, H. Jeon, C. Yi, S. Park, S. Ryu, S.B. Kim, Mutual interaction between plasma characteristics and liquid properties in AC driven pin-to-liquid discharge, Sci. Rep. 8 (1) (2018) 12037, https://doi.org/10.1038/s41598-018-30540-4.

[21] S. Gershman, A. Belkind, Electrical discharge in gas bubbles in gel, J. Appl. Phys. 128 (13) (2020), 133302, https://doi.org/10.1063/5.0016273.

[22] E. Corella Puertas, A. Dzafic, S. Coulombe, Investigation of the electrode erosion in pin-to-liquid discharges and its influence on reactive oxygen and nitrogen species in plasma-activated water, Plasma Chem. Plasma Process. 40 (1) (2020) 145–167, https://doi.org/10.1007/s11090-019-10036-3.

[23] S. Basnet, R.R. Pokhrel, R. Khanal, Characteristics of magnetized dusty plasma sheath with two ion species and *q*-nonextensive electrons, IEEE T. Plasma Sci. 49 (4) (2021) 1268–1277, https://doi.org/10.1109/TPS.2021.3066888.

[24] Y. Han, Y. Liu, F. Lin, Z. Li, Q. Luo, Experimental investigation of arc formation and bubble expansion initiated by pulse discharge in water, in: 2015 IEEE Pulsed Power Conference (PPC), IEEE Explore, 2015, pp. 1–5, https://doi.org/10.1109/ PPC.2015.7296930. https://ieeexplore.ieee.org/document/7296930.