A Brief Review on Atmospheric Air Plasma

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Abstract. Atmospheric pressure air plasma is an attractive technology because it is easy to set up and handle, cheap, and safe. In this paper, a brief review on air plasma configuration and the results of air plasma is presented. One of the important properties of any plasma treatment is the generation of reactive atom species such as oxygen(O), nitrogen(N) also known as RONS, and other ions molecules particles. Air plasma has been found to have the same effect when treating surfaces. Surface modification, hydrophilicity, and decontamination effect were observed when materials are exposed to air plasma. The advancement of air plasma technology will improve the surface processing technology by reducing its operating cost.

1. Introduction

Generally, plasma is known as the fourth state of matter in a form of ionized gas [1]. Plasma is ignited by the interaction of gas, heat, and a strong electromagnetic field. Typically, reactive oxygen and nitrogen species play a major role in atmospheric pressure plasma formation (RONS) [2]. As the main components of air are nitrogen and oxygen, reactive oxygen species (ROS) include ozone and hydroxide radicals, while reactive nitrogen species (RNS) include nitrogen oxides [3].

The interaction of plasma produces free electron, neutral reactive species atom such as oxygen (O) and nitrogen oxide (NO), molecules, and radicals [4-6]. The plasma effect is very selective and different. It is could be oxygen (O) as plasma killing and nitrogen oxide (NO) as plasma healing [5]. Some examples of applications of plasma are: sterilization [6], surface modification [7], food safety [8], water purification [9], textiles [10], medical [11] and others. Compared with the conventional sterilization method, plasma technology is advantageous to decontaminate surfaces such as lower cost, easy to build and operate [12]. In addition, the process is conducted is at a low temperature, has no toxic residue, and harmless to people [13]. For exposures to polymers, reports showed that plasma causes minimal damage to polymer surfaces [14]. In comparison with chemical processes, utilization of atmospheric plasma is cheaper, more convenient, and eco-friendly. However, there are some disadvantages to the use of plasma due to the consumption of expensive discharge gasses, costly maintenance for vacuum bulky equipment.
2. Air Plasma

Air plasma attracted researchers due to its advantages for example; its high-end performance in sterilization, low cost, and eco-friendly. Thus, the interest in the production of air plasma has increased [15-17]. Air plasma has been shown effective in tissue engineering and drug delivery [18-19]. Meanwhile traditional low-pressure plasma device has costly and assimilation problems because of difficulty resulting from the need for vacuum [20-22].

Voltage, frequency, and electrode are parameters that play an important role to generate the plasma. Burt reported that air plasma was generated using two planar, 120 V, and 60Hz effective in disinfection methicillin-resistant *Staphylococcus aureus* (S.aureus)[23]. M Kuchenbecker used dielectric barrier discharge (DBD) configuration in ambient air, high voltage pulses approximately 13 kV, 100 kHz to prepare the application of the DBD device in dermatology [24]. Figure 1 and Figure 2 show an example of DBD air plasma and jet plasma respectively.

![Figure 1. An example of DBD air plasma](image1.png)  ![Figure 2. An example of air plasma jet](image2.png)

3. Chemical Interaction in Air Plasma

An air plasma process produces other molecule atoms including oxygen and nitrogen or also known as RONS. Anatoly B Shekhter describes that air plasma produced nitric oxide (NO) proved to induce effects during wound remedial and tissue reproduction [27]. Other studies have also shown that NO may affect the immune system and promote the proliferation of cells, angiogenesis, and synthesis of collagen, then resulting in damaged skin being healed [28-33].

M. Ito et al studied the complex process for transporting the RONS from gas form to liquid form in ambient air, which can be a cause to restrict enhancement in the treatment time [34]. Concurrently, a study by S. Kuo et al stated that reactive atomic oxygen (O) can kill a wide range of microbes for sterilization by chemical reactions by creating H2O2 and oxidant hydroxyl radicals (OH) in blood [35]. This is because of interactions between platelets or red blood cells (RBC) and white blood cells (WBC) by oxidants formed during blood and abundant reactive atomic oxygen (RAO) interactions. The contribution of O2, NO, OH, O3, and other reactive molecules are very important and their presence is important to the application.

4. The Effect of Air Plasma Applications

The progress in using air reduced the need for noble gases to be used as working gas to generate plasma without compromising the plasma treatment effect. The effect of its air plasma treatment can be seen in its application on hydrophilic purposes [36], hydrophobic surface [37] and modify physical properties [38]. Report describes that air plasma processing is an advance and successful method to improve the biocompatibility of Ti alloys. For bactericidal effect, air plasma treatment were efficient and time exposure dependant for inactivating bacteria such *Pseudomonas aeruginosa* (*P.aeruginosa*), *Staphylococcus aureus* (*S.aureus*), and methicillin-resistant *S. aureus* (MRSA)[39]. Table 1 shows the atmospheric air plasma device configuration and its application.
Table 1. Atmospheric air plasma device configuration and application

| Device Type | Device Configuration | Properties | Effect | Application |
|-------------|----------------------|------------|--------|-------------|
| Jet [26]    | copper electrode, DC pulse, 2.52kV, 2 kHz. | Bactericidal | • inactivate S. aureus, P. aeruginosa, and MRSA • reduction of water contact angle | Chronic wound bacteria inactivation |
| DBD\textsuperscript{a} [40] | aluminum electrodes, DC 3kV, 50 kHz. | Surface modification | • improving the antimicrobial property of the banana fabric | Banana fabric treatment |
| DBD\textsuperscript{a} [41] | aluminium and metal electrodes, DC pulse, 9 kV, 500 Hz | Wettability, Surface modification | • enhance water contact angle • inactivate bacteria | Bacteria inactivation |
| DCSBD\textsuperscript{b} [42] | parallel strapline electrodes, AC, voltage up to 20 kV, 14 kHz to 18 kHz | Bactericidal | • decrease in the carbon surface concentration • no significant effect of plasma on ITO morphology | ITO surface cleansing |
| DBD\textsuperscript{a} [43] | aluminium electrodes AC, 15kV, | Wettability, Morphology change | • increased roughness and wettability | Clean cotton fibre |
| Jet\textsuperscript{[44]} | aluminium electrode, coaxial DC pulse- adjustable kHz | Bactericidal | • effective in eliminate bacteria • no morphology changes | Bacteria inactivation |
| DBD\textsuperscript{a} [45] | 100W, 13.65MHz | Biocompatibility | • enhanced both the biocompatibility and osteogenic | Orthopaedic biomaterial development |

\textsuperscript{a}DBD Dielectric Barrier Discharge
\textsuperscript{b}DCSBD Diffuse Coplanar Surface Barrier Discharge

5. Conclusion
Generating plasma using air as its working gas has shown a comparable effect with plasma generated using gasses such as helium, argon, and others. Due to the simplicity of the design and gas usage, the air plasma device will benefit in reducing operational costs. This brief review has discussed examples of air plasma device configuration, the comparison of chemical processes, and the treatment effect of air plasma. On the other hand, this paper also describes the results of air plasma application through its latest studies, for example, in textile, biomedical, and material. In conclusion, air plasma is an effective and safe tool to use for treatment. The effect of air plasma treatments is at par with other types of atmospheric plasma. The future aspect of air plasma device is that it could be industrial recommendation for setting plasma process. Current atmospheric plasma technologies have higher operational cost because of the working gas used to generate plasma. Air plasma offers lower operational cost and produces similar outcomes to traditional atmospheric plasma treatment. However, some areas such as the device size and plasma stability still need to be investigated to ensure air plasma could be adapted in an industrial setting.

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