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BRIEF REVIEW: COLD PLASMA

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Graphical abstract

Abstract

Plasma is energetically the fourth state of matter, apart from solid, liquid, and gas states. Cold plasma discharges can be generated by stationary and pulsed (DC) and alternating (AC) electrical fields. It can be used to improve mechanical properties, adhesion and treatment. Nowadays, plasma technology has been used in many fields such as bio medic, automotive, printing and textile. In this brief review paper, cold plasma will be explained pertaining to how it works, the mathematical equations involved and its applications as produced by researchers.

Keywords: Cold plasma, plasma generation, plasma discharge, plasma modelling, plasma application

Abstrak

Plasma adalah penuh semangat negeri keempat perkara, selain daripada keadaan pepejal, cecair dan gas. Luahan plasma sejuk boleh dihasilkan dengan bergerak dan berdenyut (DC) dan ulang-alik (AC) bidang elektrik. Ia boleh digunakan untuk meningkatkan sifat mekanik, lekatan dan rawatan. Pada masa kini, teknologi plasma telah digunakan dalam pelbagai bidang seperti pegawai perubatan bio, automotif, percetakan dan tekstil. Dalam kertas kajian ringkas ini, plasma sejuk akan diterangkan mengenai bagaimana ia berfungsi, persamaan matematik yang terlibat dan aplikasi sebagai yang dihasilkan oleh penyelidik.

Kata kunci: Plasma sejuk, generasi plasma, cecair plasma, pemodelan plasma, aplikasi plasma

1.0 INTRODUCTION

The term "plasma" was first introduced by Irving Langmuir (1881-1957) in 1923 to describe the jellylike behavior of those regions of an electrical discharge that is capable of showing a certain periodic variation or movement of the free electrons. Plasma is the fourth state of matter [1]. It consists of neutral electrons, molecules and positive and negative ions [1]. Plasmas can be generated by applying energy to a gas, thus producing excited species and ions [2]. When the positive and negative ions combine with each other, the energy is released as visible and UV light [3-4]. Forms of energy that is needed to produce plasma from gas are such as electricity, heat, laser light, extremely rapid compression and radiation. There are two categories of plasmas i.e., cold and hot (thermal) plasmas. Figure 1.1 shows the characteristics of Cold and Hot Plasmas.

Plasma can be differentiated by the temperature it generates, either hot or cold plasmas. Hot plasmas can exist under two circumstances—when the heavy particles are very energetic; at temperatures in the order of 10^6-10^8 °K (10^2-10^4 eV) or when the pressure is atmospheric, even at temperatures as low as 6000°K. Whereas, cold plasmas can also exist under two circumstances—when the temperature of the electrons is much higher than that of the heavy particles, as the electrons can reach temperatures of 10^4-10^5 °K (1-10eV) or when the temperature of the gas can be low as room temperature. The cold plasmas will become the main focus in this paper. Cold plasmas have been developed specifically and purposefully based on their non-equilibrium properties and their capability to cause physical and chemical reactions with the gas at relatively low temperatures.

Cold plasma is a plasma type of that has non-uniform distribution of energy i.e. known as none equilibrium [1]. It gains reactivity from the high energy electrons, while the ions and neutral species remain cold [5]. Cold plasma application is for surface modifications by using a glow discharge technique. There are many types of surface modifications such as surface cleaning, cross-linking, degradation, surface oxidation, ion implantation and polymerization [6].

	LTE Plasmas	**Non-LTE Plasmas**
Current Name	Thermal Plasmas	Cold Plasmas
Properties	$T_e = T_h$ High electron density; $10^{21} - 10^{26}\ m^{-3}$ Inelastic collisions between electrons and heavy particles create the plasma reactive species whereas elastic collisions heat the heavy particles (the electrons energy is thus consumed)	$T_e > T_h$ High electron density; $<10^{19} m^{-3}$ Inelastic collisions between electrons and heavy particles induce the plasma chemistry. Heavy particles are slightly heated by a few elastic collisions (that is why the electron energy remains very high)
	Arc plasma (core) $T_e = T_h$=10 000K	Glow discharges $T_e \approx 10\ 000 - 100\ 000\ K$ $T_h \approx 300 - 1\ 000\ K$

Figure 1.1 Characteristics of cold and hot (thermal) plasmas [2]

2.0 GENERATION OF COLD PLASMA

Generally, cold plasma discharges can be generated with stationary and pulsed (DC) and alternating (AC) electrical fields. Various electrical power supplies can be used to generate the cold plasma discharges such as pulsed (DC), Inductively Coupled Plasma (ICP) and Capacitive Coupled Plasma (CCP). Besides, nowadays, many researchers are attempting to develop the configuration of atmospheric pressure plasma discharges such as Arc Discharge, Corona Discharge, Dielectric Barrier Discharge (DBD), Uniform DBD, and Atmospheric Pressure Plasma Jet (APPJ). Table 2.1 shows the description and characteristics for each cold plasma generator.

Table 2.1 The characteristics of various cold plasma generators

Generator	Characteristics
Pulsed (DC)	Plasma generated within fluorescent light tubes. It is used in material processing and manufacturing to modify ion energies, in sputter sources like magnetrons, and for physical mechanism of surface modification. It is simple in geometry, easy to generate, complex in structure and also has a voltage-current characteristics.
Capacitively Coupled Plasma (CCP)	Similar to glow discharge plasmas, but instead of a DC or low frequency electric fields, it is generated with high frequency RF electric fields, typically 13.56 MHz. It is widely used in micro fabrication and integrated circuit (IC) manufacturing industries.
Inductively Coupled Plasma (ICP)	Similar to CCP and has similar applications, but the electrodes consist of a coil wrapped around the discharge volume, which inductively excites the plasma. ICP has slightly more advantages compared to CCP, as CCP is less intense (low ion density and low ion energy).
Arc Discharge	High power thermal discharges, having very high gas temperature of approximately 10 000 K. The discharge is sustained by thermionic emissions, which can be generated by various power supplies. Commonly used in metallurgical application.
Corona Discharge	Non-thermal discharge generated by the application of high voltage to sharp

	electrode tips. The sharp tip creates an electric field sufficient for breakdown only in the vicinity of the tip, the remaining region of discharge gap remain dark. Coronas are very weak discharges, having very low electron and ion densities and are commonly used in ozone generators and particle precipitators.
Dielectric Barrier Discharge (DBD)	Dielectric barrier discharge is non-thermal in nature and is generated by the application of high voltages across small gaps wherein a non-conducting coating prevents the transition of the plasma discharge into a self-sustained glow or arc. Breakdown occurs in the form of streamers and charges build up on the electrodes during the discharge. A low frequency AC field <100 kHz is used to cycle the discharge and maintain it. They are widely used in the treatment of fabrics in roll to roll configuration.
Atmospheric Pressure Plasma Jet (APPJ)	The atmospheric pressure plasma jet (APPJ) is a type of RF CCP plasma discharge operated at atmospheric pressure. In the APPJ the systems are stabilized by operation in helium or argon gases. The atomic noble gas operation makes it significantly easier to maintain the non-equilibrium system. Such systems can be stably operated in '*normal*' and '*abnormal*' modes in pure helium. However, only a very minor faction of precursor gases can be added.

3.0 MATHEMATICAL EQUATION

Plasma particles are subjected to electric and magnetic forces. They also need to follow the basic laws of fluids. Depending on the level of interest, plasma can be studied at different levels of accuracy, by following trajectories of individual particles, trajectories of "small parcels" of plasma, or evolution of velocity distributions. In this paper, two approaches are being considered; single particle motion approach and fluid approach.

The single particle approach is the lowest level description of plasma. It is useful for determining the trajectories (orbits) of individual particles in external forces. Usually in this approach, the focus is on a single or several particles, and it is difficult to say that this approach fulfils the plasma definition as it usually does not include the collective effects. However, it is a useful way of understanding the plasma dynamics in strong external fields. Each plasma particle is subjected to the Lorentz force:

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \qquad (3.1)$$

where

$\mathbf{E} = \mathbf{E}(\mathbf{r}, \mathbf{t})$ is the electric field,
$\mathbf{u} = \mathbf{u}(\mathbf{t})$ is the velocity of a single particle,
$\mathbf{B} = \mathbf{B}(\mathbf{r}, \mathbf{t})$ is the magnetic field,
$\mathbf{a} \times \mathbf{b}$ is the cross product for vectors a and b.

The consequence of Equation (3.1) and the cross product is that the particle will rotate in the plane perpendicular to the magnetic field and that a time stationary magnetic field will not change the energy of the particle.

In the fluid approach, we are interested in the behavior of a small volume/parcel of plasma, in which we have defined the temperature, density, and net velocity. This parcel contains a sufficient number of plasma particles, so that the temperature and density are well defined. The fluid element follows basic fluid dynamics, but it also needs to account for Maxwell equations. Thus the following set of equations needs to be considered:

$$\partial n/\partial t+\nabla.\,(n\,\mathbf{u})=0 \qquad (3.2)$$

$$mn[\partial \mathbf{u}/\partial t+(\mathbf{u}.\nabla)\mathbf{u}]=qn(\mathbf{E}+\mathbf{u}\times\mathbf{B})-\nabla.\boldsymbol{P}+\boldsymbol{P}ij \qquad (3.3)$$

$$\partial/\partial t[n/2.m\upsilon^2]+\nabla.[n/2.m\langle\upsilon^2\mathbf{u}\rangle]-nq\langle\mathbf{E}.\mathbf{u}\rangle =m/2\int\upsilon^2\;(\partial f/\partial t)d\mathbf{u} \qquad (3.4)$$

The velocity $\mathbf{u}$ refers to the fluid element and can thus be position and time dependent; $\mathbf{u} = \mathbf{u}(\mathbf{r}, \mathbf{t})$. Equation (3.2) is just an ordinary continuity equation; indeed plasma, just as any other fluid, needs to conserve mass (continuity of mass or charge transport). Equation (3.3) is the Navier-Stokes equation that relates the force density acting on the plasma fluid element to the pressure gradient force, the Lorentz force in its density equivalent, momentum exchange between different plasma species. The momentum equation is coupled to the Maxwell equations, but the fields are, on the other hand, related to density and velocity of the plasma, thus they need to be solved together. Whereas, Equation (3.4) is the energy transfer equation due to momentum exchange between different plasma species.

For cold plasma model analysis, two assumptions can be made in order to simplify the analysis. These assumptions are; the thermal motion of particles is neglected and the collision term, **P**ij can be approximated by an "effective" collision frequency, assuming that collisions cause a rate of decrease in momentum:

$$\boldsymbol{P}ij=-mn\nu_{eff}\,\boldsymbol{U} \qquad (3.5)$$

Therefore, from Equation 3.3, the cold plasma can be modelled as:

$$mn[\partial \mathbf{u}/\partial t+(\mathbf{u}.\nabla)\mathbf{u}]=qn(\mathbf{E}+\mathbf{u}\times\mathbf{B})+\boldsymbol{P}ij \qquad (3.6)$$

4.0 COLD PLASMA APPLICATION

There are many uses of plasma technology. Figure 4.1 shows the application of plasma technology in many industrial application areas. Plasmas are also used in electrical engineering—optics printing technology and many more. Figure 4.2 shows the increment of plasma applications in the industry for the next 10 years, which indicate the importance of a continuous development of plasma technology.

Figure 4.1 Uses of plasma technology in various industrial areas [5]

Generally, cold plasma can enhance mechanical properties, electrical properties, wetting, dyeing and printing, treatment, metal-coated organic polymers, improve adhesion in composite and laminates, used in biology and medicine and also in membrane and environmental technology [7]. Table 4.1 shows the applications of plasma that have been developed by researchers.

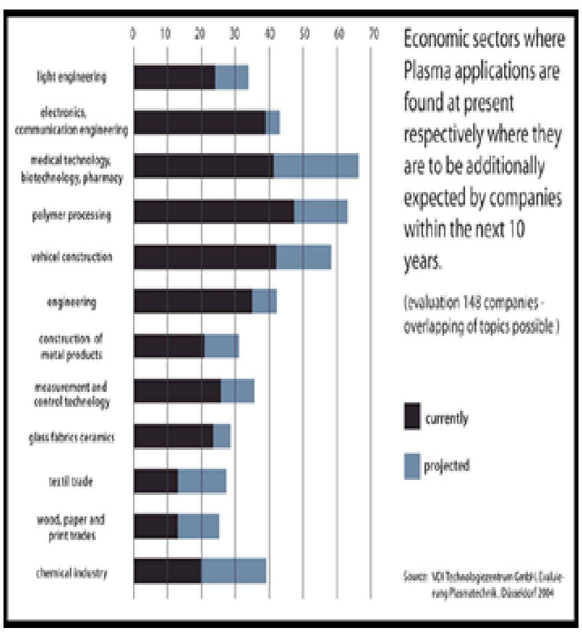

Figure 4.2 Industrial plasma applications in the next 10 years [5]

Table 4.1 Applications of plasma

Application		Reference
Enhance Mechanical Properties	1) Improve mechanical properties of ceramic fibres – Tensile Strength	[8]
	2) Improve Tensile strength, stress of jute fibre/ poly (lactic acid) biodegradable composites	[9,10]
Improve Adhesion	1) Improve adhesion of Polymer - Polyethylene, Polypropylene, Polystyrene and Poly(ethylene terephthalate)	[11,12]
	2) Packaging Surface Treatments on Wetting and Adhesion	[13]
	3) Improve adhesion of polymers for food packaging.	[14]
Treatment	1) Decontamination of Strawberries	[15]
	2) Treatment on recycle paper – hydrophobic to hydrophilic.	[16]
	3) Improve fertilization and irrigation of Germination	[17]
	4) Increase viscoelasticity, strength of the dough	[18]
	5) Softening Cotton and reduce felting of wool.	[7]
	6) Create water repellent on wood	[6]
	7) water, air, food and drink treatment	[1, 19, 20]
Biology and Medicine	1) Can Ablate some cancer cells (Lung, melanoma, head and neck, brain and bladder)	[21]
	2) Clean and sterilize infected tissue in a dental cavity or on root channel.	[22]
	3) Treatment of Infectious skin diseases and wound healing.	[23]
	4) Deactivation of Biofilms – S-Mutans bacteria – E. Coli	[24]
	5) Tooth Bleaching	
	6) Instrument Sterilization – Dental Instruments	
	7) Activation of p23 protein	
	8) Activation of p21 CDK inhibitor	
	9) Treatment of Chronic Venous Leg Ulcers.	[25]
	10) Reducing bacterial and Fungal Species	[26]

From the tables above, many applications of plasma that have been created by researchers in the medical field can improve adhesion for polymers. In the medical field, plasma can be used for sterilization and treatment. While for the adhesion improvement of materials, more research has been done on polymers. This shows that more research can be done to improve adhesion for other materials such as composites. The research on cold plasma is very significant, especially in order to provide better material treatments, thus improving the material properties such as durability, toughness and corrosion resistances. Therefore, in the future, the authors will need to focus on adhesion improvement treatments on materials such as composites and cable wire.

5.0 CONCLUSION

There are many uses of plasma technology in various fields such as electrical, medical, mechanical and automotive. This shows that plasma is important in many fields. It can be used for sterilization, enhancing mechanical properties and improving adhesion. All enhancements and improvements on the applied materials by using cold plasma are expected to produce better materials properties for example in terms of its strength, toughness, electrical resistivity, corrosion resistivity, durability, etc.

The cold plasma field has a lot of research potential to explore. However, researchers need to overcome a lot of challenges such as the limited reference from text books to journal papers, lack of components to build or design ideal experimental rigs, the risks of research especially those that involve high voltage power supplies. Based on existing applications of plasma, some research can be done to create new application of plasma, which can be used to improve daily life.

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