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Industrial Applications of Plasma and Plasma Jets: A Systematic Review

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Abstract
Purpose: This paper reviews the existing literature on plasma and plasma jets and attempts to describe the current and future applications of the same.
Design/methodology/approach: A systematic literature review methodology was used. Keywords were used to search for relevant papers from scientific research databases and after an initial review, 42 papers were used for the literature review.
Findings: The literature review reveals that different types of plasma (thermal and non-thermal) as well as plasma jets (atmospheric pressure plasma jets and low-pressure plasma jets) have a wide range of applications in various industries such as production of bio-diesel fuel, materials processing, biomedicine including dentistry, and most notably, space travel.
Implications/Originality/Value: This review paper adds to the existing literature on applications of plasma and plasma jets and is a valuable resource to beginner students and researchers in the field.
Keywords: *plasma, plasma jets, industrial applications, plasma propulsion, systematic review*

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I. Introduction

Plasma is the fourth state of matter, the phase beyond the gaseous one (Kash, 1961). Plasma is generated by ionization, which takes place when sufficient amount of the electrical energy is supplied to a gas (Hessel, Cravotto& Fitzpatrick, 2013).

Plasma is broadly classified into thermal and non-thermal plasma. Non-Thermalplasma can further be divided into atmospheric pressure plasma and low-pressure plasma.

Atmospheric pressure plasma can essentially be classified by the type of discharge used for the generation of plasma such asdielectric barrier discharge (DBD), corona discharge and glow discharge (Penkov, Khadem, Lim& Kim, 2015).

In low pressure plasma, the temperature of the gas is usually below 150 degrees C so that thermally sensitive substrates are not damaged. It is widely used in semiconductor industries (Schutze, Jeong, Babayan, Park, Selwyn& Hicks, 1998).

Thermal plasma, which is a source of concentrated energy, positive and negative ions, highly active radicals and intense radiation make it ideal for welding, melting and spraying operations.The high temperatures of thermal plasma together with the high reactivity due to the presence of free ions and radicals, make ita powerful medium to promote high heat transfer rates and chemical reaction (Venkatramani, 2002).

Plasma jets, or plasma plumes are a kind of atmospheric pressure gas discharges where the plasma (usually obtained from a noble gas) is extended beyond the plasma generation region into the surrounding ambience (Lu&Laroussi, 2012).

The last few decades have seen a rapid growth in the use of plasmas for various applications.Today, onehas a whole gamut of industrial applications where the use of plasmas-based technologies offers distinct advantages over other more conventional technologies (Ganguli&Tarey, 2002)

Considering the rapid evolution of plasma and plasma jets in various industrial applications, this review paper attempts to describe the various types of plasma, plasma jets and their applications across different sectors, with special focus on space travel.

The paper is organized as follows. The next section discusses the research methodology adopted. This is followed by the findings of the systematic literature review and divided into types of plasma, types of plasma jets and applications of both in various industrial sectors. Finally, the conclusion section provides the practical implications of the study, limitations and further scope for research.

II. Methodology

This study followed a systematic literature review approach. Scientific research databases Elsevier and IEEE were used to search for research papers using the key words ‘plasma’, ‘plasma jets’ and ‘applications of plasma’. The initial search led to 326 research papers. After a preliminary review, research papers deemed unsuitable were discarded, leaving the researcher with a final set of 42 research papers. The literature review was conducted on these 42 research papers.

Plasma: The fourth state of matter

Plasmais known as the ionized state of matter, obtained by dissociating atoms into positive ions and electrons (John, 1993). The term plasma was introduced in the earlier third of the twentieth century and refers to gas containing an appreciable number of ions and electrons. Some examples of plasma devices are electric arcs, such as those used in welding, and electric discharges, such as in neon displays (Kash,1960).

Plasma may be an exceptional state on earth, but it is the most prevalent state of matter in the universe. Plasma comprises the stars and much of the material in space. Plasmas and plasma phenomena are destined to play an increasingly important role in our developing technology, especially in areas such as communication, space propulsion, power production, among others (Kash, 1960).

The plasma state is uniquely different from the ordinary states of matter in a number of ways. First of all, plasma contains free electrons and ions, which being electrically charged, can respond to external electromagnetic energy fields and transport electromagnetic energy. The fluid properties are enhanced by the particles setting up internal self-consistent electric and magnetic fields, resulting in the generation of collective effects like flows, waves, instabilities and self-organisation. It is, in general, a multi species fluid, with electrons, ions and neutral particles having independent thermal distributions, which need not to be in equilibrium. The internal energy is composed of thermal, electric, magnetic and radiation fields, whose relative magnitudes allow the plasma state to exist in a large parameter space (John, 1993).

Plasma is generated by ionization, which happens when atoms are divided into positive ions and electrons. The electrons can be removed from the bound state by different means, all of which require imparting energy to the bound electron to allow it to free itself from the attractive force of the nucleus. The minimum energy required by the electrons to do this is the ionization potential of the atom. The process of ionization can be achieved thermally, by heating the gas to very high temperature; by photons as happens in the ionosphere, chemically as in flames or through energetic electrons(John, 1993). Ionization leads to the generation of highly excited atomic, molecular, ionic and radical species. The development of high frequency torches in 1948, of the DC arc torch and of improved analysis techniques in the 1970s led to better understanding of the kinetics and mechanism of plasma reactions, allowing a better connection between plasma process conditions and reaction product. This lead to a significant increase in the number of studies onplasma.

Types of Plasmas

Plasma can be classified based on the temperature relationships within the plasma,into two categories: thermal and non-thermal plasma sources.

Thermal Plasma

Thermalplasmas are produced by plasma torches also known as plasmatrons. Depending on the primary source,which can be direct current, alternating current at mains frequency, or at radio frequency, they are known as DC,AC OR RF torches (Venkatramani, 2002).

Thermal plasmas such as plasma torches (Surov et. al., 2017) and arc jets (Liu, Park, Hamdan&Cha, 2018) utilize high temperature chemistry as well as plasma generated reactive species (electrons, ions, radicals, photons, etc.) (Hamdan&Cha, 2016).

Thermal torches and arcs are high-temperature sources (>10,000 degreesC) that are used for a variety of materials applications, including melting and deposition, spray coating and ceramic powder synthesis(Uhm& Hong, 1997).Thermal-plasmas are atmospheric pressure plasmas characterized by high enthalpy content and temperatures around 2000-20,000 °C.

Contrary to non-thermal plasmas, thermal plasmas, such as torches and arc jets, provide a good efficiency by combining the chemical reactions induced by plasma species (electrons and ions) with those induced thermally.

Non-Thermal Plasma

Non-thermal plasmasincludepulsed-nanosecond discharge (Hamdan& Cha, 2016), dielectric barrier discharge (Laurita, Barbieri, Gherardi, Colombo&Lukes, 2015), and plasma jet (Robert, Darny, Dozias, Iseni&Pouvesle, 2015). All these have been extensively investigated for liquid processing. Such plasmas have shown great potential for controlling the electron induced chemistry (Lebedev, 2017), because electron energy is selectively augmented while the gas temperature (i.e., the energy of heavy species) is somewhat unchanged. Gas temperature of non-thermal plasmas remains close to room temperature, even as the electron energy is relatively high (several eVs), which gives them an excellent ability to process temperature-sensitive materials such as polymers, biological liquids, and living cells (Liedtke et. al., 2017).

Perhaps the most widely used plasma jet configuration is based on the dielectric barrier discharge employing a noble gas such as helium or argon. The gas is typically flushed through a dielectric capillary and subjected to an applied voltage using one or more electrodes placed inside and/or outside of the capillary. This is also known as low temperature or cold plasma. It is a non-thermodynamic equilibrium category normally formed in low or atmospheric pressure systems.

Electrically generated Plasma

Depending on the means of producing the primary electrons, energizing them and how they partition their energy to the plasma particles, we can classify industrially relevant electrically generated plasmas in the following way:

Metal vapour arc plasmas: These plasmas are maintained at very low pressure by melting and evaporating one of the electrodes. They are industrially used for ion plating and thin metallic film coatings. For e.g.,depositing titanium nitride coatings, when the arc is run in a low-pressure nitrogen environment(John, 1993).

Glow Discharge plasma:Glow discharge plasma are produced by both reactive and non-reactive gases when they are broken down by high voltages at medium pressures These plasmas are industrially used for ion implantation like in ion nitriding, plasma chemistry, plasma polymerization etc.(John, 1993).

Arc Plasmas:At high pressure nearing atmospheric pressure, glow discharge plasma transitions to arc plasmas. The gas and plasma temperatures can reach tens of thousands of degrees in arc plasmas and hence they are high energy density thermal sources. These plasmas are widely used in metallurgical and engineering plasma processing (John, 1993).

Plasma Jets

Plasma jets, or plasma plumes, belong to a large family of gas discharges whereby the discharge plasma is extended beyond the plasma generation region into the surrounding ambience, either by a field (e.g., electromagnetic, convective gas flow, or shock wave) or a gradient of a directionless physical quantity (e.g., particle density, pressure, or temperature).

This physical extension of a plasma plume gives rise to a strong interaction with its surrounding environment which alters the properties of both the plasma and the environment, often in a nonlinear and dynamic fashion. The plasma is therefore not confined by defined physical walls, thus extending opportunities for material treatment applications as well as bringing in new challenges in science and technology associated with complex open-boundary problems.

Some of the most common examples may be found in dense plasmas with very high dissipation of externally supplied energy (e.g., in electrical, optical or thermal forms) and often in or close to thermal equilibrium. For these dense plasmas, their characteristics are determined predominantly by strong physical forces of different fields, such as electrical, magnetic, thermal, shock wave, and their nonlinear interactions (Reed, 1961).

Plasma jets, which can deliver plasma up to a few meters distance, are unique in producing reactive chemistry at room temperature. Jet plasma with a privilege of lower shock risk, compared with DBD and corona discharges, can penetrate and propagate inside small holes and flexible dielectric tubes (Johnson, Zhu,Wang, Sivaram, Mahoney& Lopez, 2011), which is quite useful for medical applications (e.g., treatment of colorectal and pancreas cancers) (Stoffels, 2007) and other applications (e.g., surface treatment) (Stoffels, Flikweert, Stoffels, &Kroesen, 2002).

Types of Plasma Jets

Plasma is used for material treatment in much wider fields, such as surface activation, etching, cleaning, decontamination and thin-film coating (Ghasemi, Sohbatzadeh&Mirzanejhad, 2015). Industrial plasmas operate either at low pressures (<1 Torr) or at atmospheric pressure (Sun, Li,Bao, Wang,Zeng, Gao& Luo, 2007).

In principle, atmospheric pressure plasma devices can provide a crucial advantage over low-pressure plasmas because they eliminate complications without need for vacuum systems and allow for continuous in-line processing

Low Pressure Plasma Jets (LLPJs)

Low-pressure plasmas are those where the electrons and ions do not interact too frequently and thermal equilibrium between these species is absent. Electrons and ions usually have very different temperatures in such plasmas (Ganguli&Tarey, 2002).

Low-pressure plasmas have several applications in materials processing and play a key role in manufacturing semiconductor devices (Schmid,Kegel, Petasch&Liebel, 1996). A uniform glow discharge can be generated, so that material processing proceeds at the same rate over large substrate areas.

Low-pressure plasma discharges are widely used in materials processing, because they have a number of distinct advantages such as:1) low breakdown voltages; 2) a stable operating window between spark ignition and arcing; 3) an electron temperature capable of dissociating molecules (1–5 eV), but a low neutral temperature; 4) relatively high concentrations of ions and radicals to drive etching and deposition reactions; and 5) a uniform glow over a large gas volume.

On the other hand, operating the plasma at reduced pressure has several drawbacks. Vacuum systems are expensive and require maintenance. Load locks and robotic assemblies must be used to shuttle materials in and out of vacuum. Also, the size of the object that can be treated islimited by the size of the vacuum chamber.

Although low-pressure plasmas have found their wide applications in the last few decades, operating at reduced pressures requires expensive and complicated vacuum system which results in a high cost, size limitations on the treated objects and the need for complex robotic assemblies to shuttle materials in and out of vacuum chamber (Forster, Mohr&Viol, 2005).

Atmospheric Pressure Plasma Jets (APPJs)

There are various methods to generate atmospheric pressure plasmas, such as microwave discharge, radio frequency (RF) discharge, dielectric barrier discharge (DBD), and direct current (DC) discharge(Laroussi& Akan, 2007).All of these methods have unique features that are suitable for certain applications. The simplest method of generating plasma is the use of DC discharge, although it requires RF for ignition. This type of APPJ has been widely described in existing research(Liao, Chang, Yang, Hsu, Cheng&Chen, 2014).The APPJ system does not require a vacuum chamber, thus allowing for the building of small and low-cost plasma sources. The simplicity, low cost, and wide possibilities for surface treatment and modification have made APPJs popular in industrial use.

In principle, atmospheric pressure plasma devices canprovide a crucial advantage over low-pressure plasmasbecause they eliminate complications without need forvacuum systems and allow for continuous in-line processing.(Lu, Naidis, Laroussi, Reuter, Graves&Ostrikov, 2016).

Applications of Plasma

Plasma technology has given a new direction and impetus to many industrial operations by opening up a widerange of mechanical, chemical and metallurgical processing techniques. The high temperatures together with the high reactivity due to the presence of free ions and radicals, make plasma a powerful medium to promote high heat transfer rates and chemical reactions.

Atmospheric pressure plasma jets have been widely used in many healthcare and materials processing applications, ranging from etching and deposition to microbial decontamination and cancer therapy (Morabit,Whalley,Robert, Hasan&Walsh, 2019).

Traditional sources include transferred arcs, plasma torches, corona discharges, and dielectric barrier discharges.PPJs have been found to be very effective for materials processing and suitable for materials sensitive to thermal damage. In particular, the hydrophilic character of certain materials can be improved by argon plasma treatment. (Fricke, Steffen, von Woedtke, Schroder&Weltman,2011).

Deposition of coatings by APPJs: The deposition of coatings by APPJs involves supplying an additional precursor such as silicon–organics, metal–organics, or various solutions as a vapor rather than in a gaseous state.

Materials Etching: Atmospheric pressure plasma jets can be used for etching materials at atmospheric pressure and between 100 and 275 degrees C. Thermal torches and arcs are high-temperature sources (>10 000 degreesC) that are used for a variety of materials applications, including melting and deposition, spray coating and ceramic powder synthesis(Uhm&Hong, 1997).

Biomedical Applications of APPJs

Low Temperature APPJ in Biology and Medicine: Nonthermal AP plasmas perform at temperatures only slightly above room temperature (30–50degrees C) while maintaining the benefits and characteristics of high-temperature plasma and itscharacteristics (Isbary et. al.,2010). Because such plasmas are cold and produce low heat, they offer great potential in a broad range of biomedical applications.

In the mid-1990s, experiments demonstrated that low temperature atmospheric pressure plasmas (LTP) can be used to inactivate bacteria (Laroussi, 2008). By the early 2000s, research expanded to include eukaryotic cells (a cell containingmembrane-bound organelles such as a nucleus,and mitochondria) when small doses of LTP were found to enhance phagocytosis, (a process by which certain living cells ingest or engulf other cells)accelerate the proliferation of fibroblasts,(a cell in connective tissue which produces collagen and other fibres) detach mammalian cells without causing necrosis (death of most cells due to injury) and under some conditions, lead to apoptosis(programmed cell death)(Stoffels,Flikweert, Stoffels&Kroesen, 2002). Today, the field of plasma medicine encompasses several applications of low temperature plasmas in biology and medicine (Laroussi, 2008). These include:Sterilization, disinfection, and decontamination,Plasma-aided wound healing, Plasma dentistry, Cancer applications or "plasma oncology,"Plasma pharmacology and Plasmatreatment of implants for biocompatibility.

Atmospheric pressure plasma jets (APPJ) are accepted as suitable sources of cold atmospheric pressure plasma (CAP) for biomedical research and applications (Weltmann&VonWoedtke, 2017). Some of the useful features of APPJs for biomedical applications are: firstly, the possibility to adjust the dimensions of the plasma jet and secondly, the plasma not being bounded by the electrodes. These features allow for local treatment of various irregular and hardly accessible surfaces. So far, the main clinical application of APPJ has been in dermatology, but new therapeutic options may include oncology and dentistry, as well (Mance et. al., 2014).

Atmospheric pressure air plasma, and turbulent flow used as cooling mechanism, can generate a simple, but effective system for fungal decontamination on sensitive surfaces such as mammalian skin. This "microplasma jet" therefore offers an effective method to treat yeast infections on skin, which may even be extended to other microbes and possibly even viruses. The major advantage is that healthy cells do not seem to be affected, while pathogens can be eradicated

High Temperature APPJ in Biology and Medicine: High-temperature plasma is a well-known method for sterilization of equipment and cosmetic restructuring of tissue (Lee, Nam, Mohamed, Kim&Lee, 2010). However, using high-temperature plasma in therapeutic applications maycause lethal damage to living systems.

In Dentistry

Atmospheric-pressure non-equilibrium plasma jets (APNP-Js) have attracted attention in the past two decades. Researchers have found that APNP-Js could be used in various applications of dentistry. APNP-Js can effectively kill biofilm in teeth root canal. Safety studies indicated that the APNP-Js have no harmful effects on the normal oral tissues. The studies of the application of APNP-Js in tooth bleaching show that APNP-Js can effectively remove stains from extracted teeth stained by either coffee or red wine. In addition, the experimental results of the surface treatment of dental implants using APNP-Js show that the surface hydrophility of VPS is significant improved after the plasma treatment, while the cytotoxicity of sample has no obvious difference. Further studies show that the adhesion between the ceramic and the composite resin is enhanced with 1, 3-BD plasma deposition using APNP-Js(Wu, Cao& Lu, 2016).

Very Low-Pressure Plasma Spray for Metal Coating

The VLPPS process allows rapid preparation of thin ($1 < t < 100$ micron), dense coatings. There are many promising applications of VLPPS processes. Primary among them are thermal barriercoatings and solid oxide fuel cells. VLPPS offers the ability to create columnar and mixed mode microstructures. The VLPPS process, by accessing new regions of parameter space, should enable a variety of newcoating applications. Current work is focused on thermal barrier coatings and SOFC electrolytes; however, one can envision many other opportunities for VLPPS ceramic, metal, and composite coatings(Smith, Hall, Fleetwood& Meyer, 2011).

Applications in Space Travel and Rocket Technology

Plasma propulsion provides one of the more promising engines tor futuristic space travel. It enables acceleration of propellant material to large velocities by the use of electromagnetic forces.

The principal attraction of electrical propulsion, such as plasma propulsion, is the long-range possibility it offers toprovide a large ratio of payload weight to initial vehicle weight. This large ratio results from the projected use of higher velocity propellants. The larger the exhaust velocity of the propellant, the larger the payload fraction will be for any given mission (Kash, 1961).

Among the plethora of available and emerging space propulsion systems, the thrust platforms that utilize plasma (Tiwari, Bhandari&Ghorui, 2018) and ionized gas (Furukawa, Shimura, Kuwahara&Shinohara,2019) to create reactive thrust are currently attracting the strongest attention due to many potential advantages of these devices(Mazouffre,2016) particularly for their ability to deliver a very high specific impulse (Ding et.al., 2017) and potentially long service life(Croes et. al.,2018).

Conventional rockets generate thrust by burning chemical fuel. Electric rockets propel space vehicles by applying electric or electromagnetic fields to clouds of charged particles, or plasmas, to accelerate them. Although electric rockets offer much lower thrust levels than their chemical cousins, they can eventually enable spacecraft to reach greater speeds for the same amount of propellant. Electric rockets' high-speed capabilities and their efficient use of propellant make them valuable for deep-space missions (Choueiri, 2009).

Dawn, which took off in September 2007, is powered by a kind of space propulsion technology that is starting to take center stage for long-distance missions—a plasma rocket engine. Such engines, now being developed in several advanced forms, generate thrust by electrically producing and manipulating ionized gas propellants rather than by burning liquid or solid chemical fuels, as conventional rockets do. Dawn's mission designers at the NASA Jet Propulsion Laboratory selected a plasma engine as the probe's rocket system because it is highly efficient, requiring only one tenth of the fuel that a chemical rocket motor would have needed to reach the asteroid belt. If project planners had chosen to install a traditional engine, the vehicle would have been able to reach either Vesta or Ceres, but not both(Choueiri, 2009).

Plasma propulsion Engines for Space Travel

There are several types of propulsion engines feasible for space travel including chemical propulsion, nuclear-chemical propulsion, propulsion by electric arc heating, ion propulsion and plasma propulsion. The latter three are propulsion techniques that use plasma technology.

Propulsion by electric arc heating (plasma jet):Higher temperatures and velocities may be obtained by heating the gas electrically as with a plasma jet. In a plasma jet, a gaseous propellant (e.g., hydrazine, hydrogen) is heated to high temperature by passing it through a high-current electric arc (Comae, 1959). Electric forces are used to heat the gas, but not to accelerate it. The gas is accelerated by expanding it through a nozzle, as in the case of the chemical or nuclear- chemical engine. The propellant velocity of a plasma- jet engine is also limited by material temperatures, but may achieve values between 15-20 km /sec.

Ion propulsion:Ion propulsion illustrates the simplest means of accelerating material by electromagnetic forces. Ions are directly accelerated by strong electric fields, similar to the acceleration of electrons in cathode ray tubes. To maintain overall charge neutrality on the vehicle, as many positive as negative charges have to be eliminated. Further- more, in order to provide a neutral space environment in the vicinity of the ion engine, the positive and negative charges should leave the vehicle with about the same velocity (Forrester and Speiser, 1959).

Plasma propulsion:In plasma propulsion engines, a neutral plasma is accelerated with the aid of electric and magnetic fields. The magnetic fields can be provided by currents in the plasma, or they can be provided independently. The propellant energy is supplied by the electric fields; however, the magnetic fields are required to orient the gas and give it a net momentum. Operation of a plasma device does not require the separation of the positive and negative charges. The plasma device can therefore handle larger amounts of propellant and can provide a larger thrust per unit area. There are two types of plasma propulsion devices- steady-state plasma accelerator and pulsed plasma accelerator (Kash, 1960).

i) Steady-State Plasma Accelerator

The steady- state plasma accelerator is often called a crossed electric and magnetic field accelerator and is similar to that of the electromagnetic pump presently used for metal liquids. In a simple version of the crossed field device, a plasma arc jet is used to produce a high-temperature partially ionized gas, to which somealkali metal vapor, such as potassium, may be added to increase its electric conductivity. The plasma gas then passes between a pair of electrical plates to produce a current transverse to the flow, and a set of coils which provide a magnetic field at right angles to both the current between the plates and the direction of flow. The resultant interaction between the current and the magnetic field provides the force for accelerating the gas. The steady-state devices may be suitable for the acceleration of plasma to intermediate velocities, up to about 50 km/ sec(Kash, 1960).

ii) Pulsed Plasma Accelerator

This is an intermittently operated device and can produce a per-unit-area thrust intermediate between the ion accelerator and the steady-state plasma-accelerator. In this device bursts of plasma are driven by rapidly varying magnetic fields produced by large currents in the plasma discharge. Here, a plasma introduced into the discharge region or produced by the discharge, is accelerated by the interaction of the current elements in the plasma and the current elements in the fixed part of the discharge circuit. The accelerating forces arise from the interaction of the current elements with the magnetic field produced by the current in the discharge circuit.

The pulsed devices can be utilized to accelerate plasmas in the velocity range of about 10-500 km/ sec but are better suited for producing velocities greater than that of the steady- state devices (Kash, 1960).

III. Conclusion

Using a systematic literature review approach, this study attempted to describe the current and future applications of plasma and plasma jets. The review reveals that different types of plasma (thermal and non-thermal) as well as plasma jets (atmospheric pressure plasma jets and low-pressure plasma jets) have a wide range of applications in various industries such as production of bio-diesel fuel, materials processing, biomedicine including dentistry, and most notably, space travel.

The study has some limitations in terms of the number of research papers reviewed and the focus on certain industrial applications only, chief of which is space travel.

Further research in this area can be in the form of larger literature reviews that cover the applications of plasma and plasma jets in greater depth, and even address the challenges of using this technology.

This study adds to the existing literature on applications of plasma and plasma jets and is a valuable resource to beginner students and researchers in the field.

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