

Plasma Catalysis: A Review of the Interdisciplinary Challenges Faced

Realising the potential of plasma catalysis on a commercial scale

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The work presented here introduces the topic of plasma catalysis through selected work in scientific literature and commercial applications, as well as identifying some of the key challenges faced when attempting to utilise non-thermal atmospheric plasma catalysis across multidisciplinary boundaries including those of physics, chemistry and electrical engineering. Plasma can be generated by different methods at many energy levels and can initiate chemical reactions; the main challenges are to selectively initiate desirable reactions either within a process stream or at the surface of a material. The material, which may have intrinsic catalytic properties, the nature of the process gas and the geometry of the reactor will influence the products formed. Previous work has shown that the mechanism for plasma-initiated reactions can be different to that occurring from more traditional thermally stimulated reactions, which opens up possibilities of using different catalytic materials to optimise the reaction rate and product speciation. In addition, the influence of a plasma at the surface of a material and the effects that can be introduced will be discussed.

Introduction

One area where physics and chemistry come together across the disciplines is in the field of plasma catalysis. A plasma can be described as a 'soup' of species including molecules and atoms

that are charged or excited and free electrons. Depending on the energy of the plasma it can be fully ionised and have a bulk temperature of tens of thousands of kelvin (or in the case of nuclear fusion millions of kelvin) or it can be in a low temperature non-equilibrium state where only a small portion of the gas phase is energised. At the lower end of the energy spectrum a non-thermal or cold plasma will have a bulk temperature a few tens of degrees above ambient and yet still have some exceedingly high energy species present. Even though the majority of the species in the plasma are not in equilibrium, there can exist some partial equilibria among species with similar kinetic temperatures existing at localised sites (1).

This energy can be used to initiate chemical reactions in the gas phase and on the surface of solids. The term plasma catalysis can be used to describe both the use of plasma to initiate a reaction directly and the use of plasma in combination with a catalytic material. The catalyst can be positioned after a plasma zone as post plasma catalysis (PPC) or within the plasma zone as in-plasma catalysis (IPC). The PPC configuration allows the longer-lived excited species and the products from the plasma reaction to interact with the catalyst and the IPC configuration allows a greater opportunity for the catalytic material to influence the nature of the chemistry by directly interacting with the plasma excitation as well as the products from the plasma-initiated reactions.

With the introduction of a plasma to a catalytic reactor the standard models of the chemistry and the traditional understanding of the mechanisms by which reactions take place start to become less relevant due to the non-equilibrium concentration of excited species such as free atoms, electrons and radicals (2).

Plasma Generation

Within the universe around us there are many examples of plasma (3) including the sun, stars, auroras, lightning, welding arcs and fluorescent lighting tubes. A plasma can be generated in different ways, but all require energy to be applied, either as heat in the case of a thermal ionisation or through the generation of an intense electric field *via* the use of electrodes, radio frequency (rf) or microwave (MW).

Electrical excitation is one of the most feasible ways for producing well controlled plasma discharges at industrial scale. This type of excitation is controlled by three main parameters: (a) the applied voltage amplitude, (b) the applied frequency and (c) the waveform shape. The combination of the aforementioned parameters defines different operating regimes (4). The main types are:

- Direct current (DC) – earliest power supplies where constant high voltage in tens of kilovolts are applied between the electrodes for creating a sustainable discharge between fixed anode and cathode electrodes. A resistor may be used to limit the current and high voltage cables are used for power delivery to the electrodes
- Sinusoidal – high voltage (0–40 kVp) continuous power sources in the frequency range of 50 Hz to 150 kHz are mostly used in dielectric barrier discharges (DBD). Those sources are easier to manufacture and operate in a wide frequency and power range
- rf – continuous sinusoidal sources with hundreds of volts operating at 13.56 MHz. For optimal operation a matching network is used to restrict the reflected power
- MW – continuous sinusoidal source operating normally at 2.45 GHz. Rectangular waveguides or coaxial cables are used for delivering the energy to the load
- Pulsed – fast pulses with well-defined pulse rise time, duration and voltage created by switching a DC high voltage power supply. The fast transition times and control capabilities allow operation at higher power per pulse.

From the regimes described above, sinusoidal and pulsed power sources present the advantage of producing non-thermal plasma without the need for noble gasses and low pressure. Moreover, the use of dielectric barrier material protects the electrodes from erosion in chemical processes and limits the power needed for initiating and maintaining plasma discharge.

It is also possible to influence the nature and stability of the plasma through external forces such

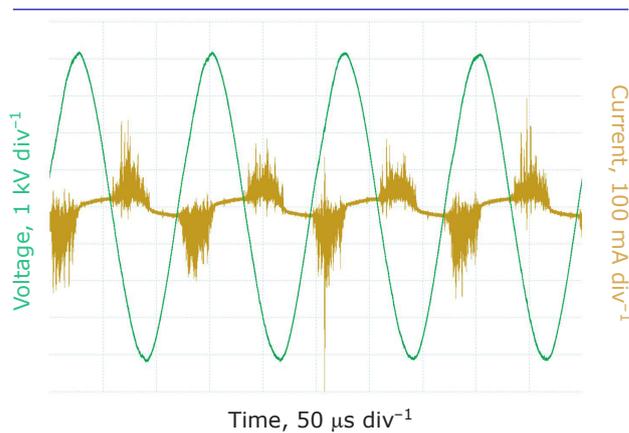


Fig. 1. Typical signals for sinusoidal voltage, current and time

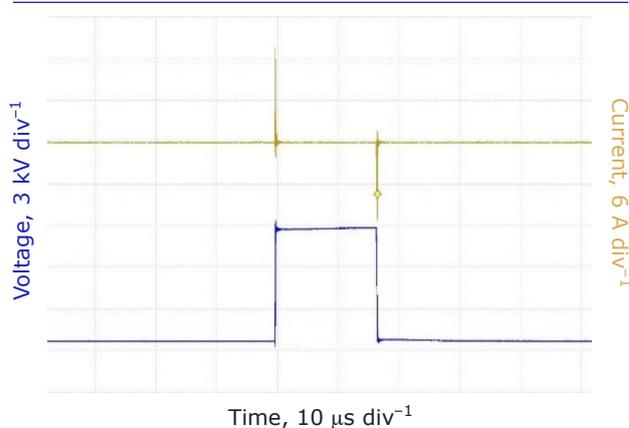


Fig. 2. Typical pulsed sources signal for current, voltage and time

as the introduction of an applied magnetic field, a vortex flow or by reducing the pressure within the system.

In scientific and industrial applications, average power delivered in the plasma discharge is critical. Accurately measuring and monitoring the power consumption in plasma discharges is not a straightforward task. Average power consumption is calculated through the measurement of voltage and current waveforms. Although the voltage signals are monitored with high accuracy through capacitive voltage dividers, current waveforms as shown in **Figure 1** and **Figure 2** present significant measuring difficulties. Current spikes with very short (nanosecond) duration and high amplitude and frequency are imposed over the sinusoidal low frequency and amplitude signal. Monitoring those high dynamic range waveforms can be erroneous and special care needs to be taken in the method of acquiring those signals. In the literature (5), three distinct ways are described for measuring directly the current or the charge in plasma.

- Shunt resistor method – a known resistor is inserted between the reactor and the ground electrode. The voltage drop across the resistor is logged and is converted to current using Ohms law
- Monitor capacitor method – an integrating capacitor with known value is inserted between the plasma reactor and the ground electrode. Plotting its waveform *versus* the voltage generates a Lissajous curve in which the average power can be calculated
- Rogowski coil – an inductive coil is used to measure the current through the ground electrode of the reactor.

Although the above measurements have comparable accuracy in scaled plasma reactors, in industrial environments it is preferable that *in situ* non-invasive techniques are used. Rogowski coils have an intrinsically safe way of operation given that they are galvanically isolated from the main circuit without compromising the accuracy.

Accurate power measurement and delivery in combination with optimised mechanical and electrical design can lead to improvements in energy efficiency. This is a critical parameter that must be considered, especially when scaling up plasma systems. It is unavoidable that some part of the initial energy is lost in the electrical transformation to high voltage and in the plasma reaction as heat. By carefully selecting the electric field and reactor characteristics those losses can be minimised. Modelling can significantly enhance the understanding of the plasma transitions in short time and space frameworks (6). The next improvement step involves the synergistic effects of plasma catalyst interaction. By introducing a catalyst in the plasma region or next to it, different works have shown considerable improvement in conversion and in total efficiency (7). All these optimisations allow energy consumption of the plasma system to be decreased and make plasma technologies feasible from the view point of economic and life cycle assessment. For example, a recent paper by Rooij *et al.* (8) shows that the combination of plasma with renewable energy sources is an economical method even for such an expensive process as carbon dioxide (CO₂) reduction. The techno-economic solution will of course be different for each market application based upon comparison to current scaled state of the art techniques.

Mechanisms of Excitation

Even the simplest of plasma generation arrangements takes in aspects of a wide range of

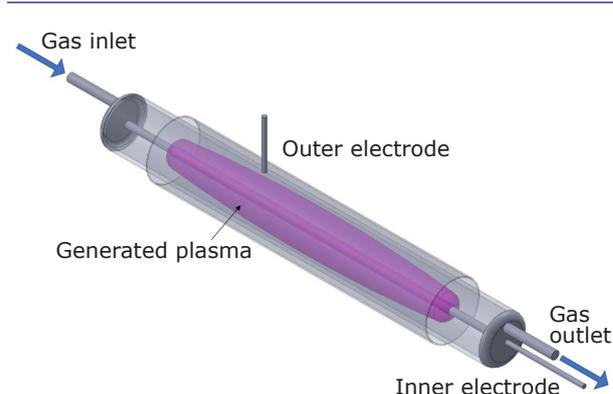


Fig. 3. Schematic of a typical continuous flow cylindrical plasma tube

physics disciplines. A schematic of a simple plasma tube is shown in **Figure 3**. Gas is passed through the cell, where a high voltage is applied across a central cylindrical electrode and a cylindrical outer electrode. The generation of the plasma in the cell leads to a shift in chemical make-up across the cell, hence the potential to use such cells in chemical processing. Even prior to the excitation of any plasma, the gas flow through the cell has the potential to become a complex fluid mechanics problem. Once a plasma is generated the equations of magnetohydrodynamics become applicable. This apparently innocuous point massively increases the experimental phase space that needs to be controlled and understood. A general introduction into the topic of magnetohydrodynamics can be gained from reading "An Introduction to Magnetohydrodynamics" by P. A. Davidson (9). The bulk physical continuous control parameters in a traditional reactor vessel can be broadly listed as temperatures, pressures and flow rates. In a plasma cell we have in addition voltages, currents and frequencies which must be controlled and monitored. This opens huge opportunities in chemical processing as significant parts of this phase space remain largely unmapped.

One of the oldest applications of plasma is in fluorescent lighting. This fact means that there has been a significant amount of study into the behaviour of plasma cells where there is no flow. The graph shown in **Figure 4** is a schematic illustration of the characteristic (current vs. voltage) curve of a typical gas discharge in neon gas at a pressure of 1 torr, between two planar electrodes separated by 50 cm. This figure has been recreated from the information presented by Gallo (10). There are broadly speaking three classes of behaviour. A dark discharge region, a glow region and an arc region. In the dark discharge region, a voltage lower than the breakdown voltage of the gas is applied to the tube. External radiation such as gamma photons and beta particles then

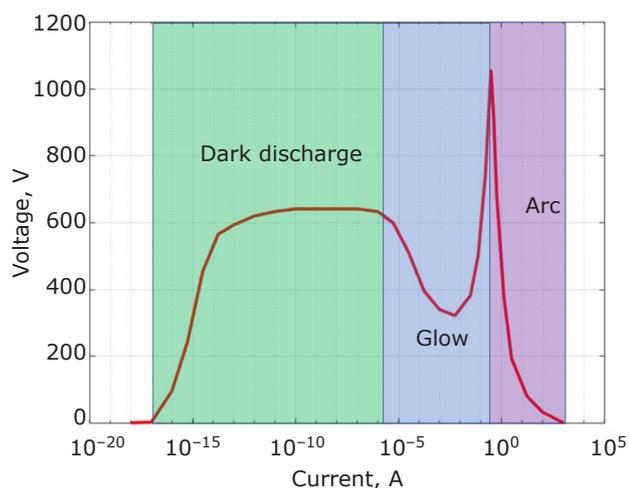


Fig. 4. Transitions occurring in a fixed glow tube

trigger a Townsend cascade within the tube. This behaviour is utilised in a number of simple nucleonic detection devices, notably Geiger counters (11). In this region the current is limited to remain low and the discharge is reliant on external excitation. In the glow region, the current is no longer limited, and the accelerated electrons excite further electrons and the voltage then drops. The gas emits light causing a glow, an effect utilised in fluorescent lighting. If the current is high enough the neutral gas in the tube becomes heated and arcs start to form which is the final region.

The graph shown in **Figure 4** illustrates that the behaviour of plasmas is complex and many transitions occur in a cell where all of the standard chemical processing variables are fixed i.e. pressure is constant, temperature is fixed and the flow rate is zero. In this example there was no time dependence to the applied voltage and current.

Practical Industrial Examples of Plasma Application

There are an increasing number of references in the scientific literature giving examples of laboratory scale plasma catalysis (12, 13) or industrial processes being investigated at semi-industrial level (14). However, there are currently no known large-scale industrial applications that combine plasma with a catalytic material. The following two examples show the scaled production of chemicals using plasma excitation.

Ozone Production

Plasma is used to generate ozone (O_3) industrially for applications including cleaning, disinfection,

deodorisation and sanitisation. Commercially this is done using ultraviolet (UV) light at a wavelength of 185 nm, electrolytically or *via* a DBD plasma depicted in **Figure 5**. Siemens, Germany, were the first to use plasma for an industrial application in 1857 to produce O_3 (15). This plasma is generated as a large number of statistically distributed micro-discharges between electrodes where the potential is insufficiently high to create an arc. Diatomic oxygen is broken down through interaction with the electrons produced within these micro-discharges that have sufficient energy to split the O_2 double bond. These newly separated O atoms then combine with other diatomic O_2 molecules to produce O_3 . The micro-discharges are individually only present for a few nanoseconds each and the number of micro-discharges generated is dependent upon the gap between the electrodes, the humidity and pressure of the air, the properties of the dielectric barrier and the characteristics of the electrical supply (16). O_3 production can be as high as 100 kg h^{-1} from a horizontal honeycomb reactor and is closely related to the specific voltage and frequency applied, with typical voltages being 7–30 kV and frequencies between 50–1000s Hz.

Acetylene Production

Thermal plasma has been used to produce acetylene (C_2H_2) since the 1940s in the Huels process. The original Huels plant used the low-boiling components of the motor fuel industry as raw material; however, a wide range of hydrocarbons including natural gas were shown to be suitable as process feed stocks. The equilibrium formation of C_2H_2 is characterised by the requirement of very high temperatures, around 3000°C . Therefore, the reaction gas should be rapidly cooled by liquid water spray injection downstream of the plasma reaction zone to avoid formation of solid carbon that is a thermodynamically preferred product between about 1000°C and 2500°C . This fast quenching prevents decomposition of the C_2H_2 formed in the plasma. Because the formation of C_2H_2 from methane (CH_4) is strongly endothermic, relatively large amounts of energy are required. In industry the best energy performance was shown by the DuPont process (a modification of the Huels reaction) with the specific energy consumption 8.8 kWh kg^{-1} of C_2H_2 (17).

More recently different methods of C_2H_2 formation in plasma were compared (18) and it was found that pulsed spark discharges gave the highest C_2H_2 yield (54%) with 69% of CH_4 conversion in a pure CH_4 system. It was suggested that the

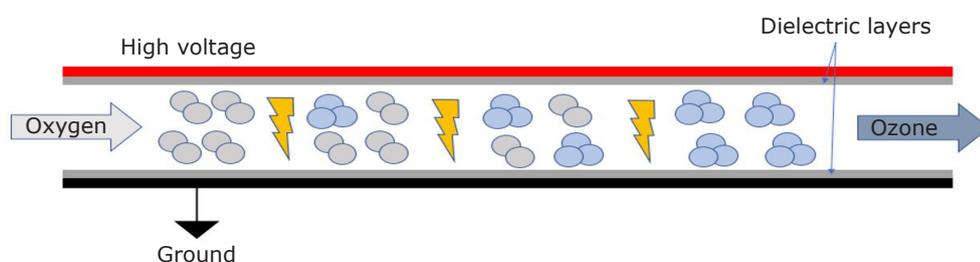


Fig. 5. O_3 is formed by passing oxygen through an electrical discharge that is diffused over an area using a dielectric to create a corona discharge

main disadvantage of the plasma method of C_2H_2 production was the fact that excited species reacted with formed C_2H_2 and decomposed it to undesirable byproducts. As a result, the energy costs for CH_4 conversion and C_2H_2 formation increased with CH_4 conversion percentage and were found to be best in pulsed spark discharges (highest CH_4 conversions 18–69%). A Korean group reported the energy cost in its systems as $9 \text{ kWh kg}^{-1} C_2H_2$. They calculated their theoretical minimum energy requirement as $4.03 \text{ kWh kg}^{-1} C_2H_2$ based on heat of reaction (19). In this publication, it was also found that hydrogen in the plasma counterintuitively increased the selectivity to C_2H_2 in the process, from a respectable 70% to well above 90%. The paper claims that it is possible to decrease the specific energy consumption to $6 \text{ kWh kg}^{-1} C_2H_2$ in the low-temperature arc with the application of argon as the recycling reactant. It is close to the theoretical limit of 4.03 kWh kg^{-1} of C_2H_2 , which is 50% of the energy required for the DuPont process. These numbers show that there is space to improve energy efficiency of the industrial production of C_2H_2 by plasma methods.

Plasma Catalysis

It is possible to introduce a catalyst after a plasma zone and transform some of the still excited species present in the gas phase into products at the surface of the catalyst, known as PPC (20).

Plasma can also generate activated species at a surface as well as in the gas phase. There are many terms used to describe the use of a catalyst and a plasma together, including plasma catalysis, plasma enhanced catalysis, plasma assisted catalysis, plasma driven catalysis (21); this IPC uses the excitation of both the catalyst surface and the gas phase reactants to effect chemistry through reactions between:

- Excited gas phase species interacting with a non-excited catalyst surface
- Excited surface species interacting with non-excited gas phase reactants
- Excited gas phase interactions with excited surface species.

These plasma and catalyst interactions can be thought of as occurring between one or more excited states and can be representative of both the surface and the gas being excited. An electrically induced surface potential of a material is equally defined as a catalyst as a material that satisfies more traditional thermal catalysis ideals of adsorption and reaction, such as the use of glass beads for CH_4 conversion (22).

In addition to the above interactions, further thought should be given to the interdependency of the plasma formed on the properties of the catalytic material present, and *vice versa* where the plasma will have an impact on the properties of the catalyst surface, including even impacting upon the physical morphology of the material. These synergistic interactions have been proven to offer a different mechanism for chemical reaction when the excitation comes from electrical plasma rather than thermal means (23). A study of plasma activated catalytic (palladium/aluminium oxide (Pd/Al_2O_3)) CH_4 oxidation, conducted in a synchrotron beamline, concluded that the Pd nanoparticles are heated within the plasma but the temperature of the nanoparticles remains lower than that required to initiate the thermal CH_4 oxidation reaction. Thus, an alternative reaction mechanism with a lower activation barrier must be taking place (24).

There have been many studies looking at the application of plasma catalysis for chemical synthesis. In particular, small molecules that are difficult to activate using more traditional thermal methods, such as CO_2 and CH_4 lend themselves towards activation using plasma techniques (13). A special issue of the journal *Catalysts* titled 'Plasma Catalysis' was recently published including papers covering the application of plasma catalysis for CO_2 splitting (25), ammonia (NH_3) synthesis (26) and CH_4 reforming (27).

A key challenge for plasma catalysis is to design a reactor that is suitable to house a plasma and a catalyst that has low backpressure, but retain good catalyst and gas-plasma interaction similar to the ceramic monolith widely used in automotive emission treatment. Uytendhouwen *et al.* (1) identify power, pressure and gap size in a reactor

as key process parameters for utilisation in design of plasma reactor and then go on to discuss their effect on CO₂ disassociation in a DBD microreactor.

Mizuno (28) describes multiple approaches to tackle this problem in his review: including (a) micro-discharge plasma with the process gas flowing through a catalyst coated metal plate with very narrow (micron) gaps to improve the catalyst-gas interaction, (b) a metal mesh DC powered electrode in front of a ceramic monolith and a packed bed alternating current (AC) electrode at the rear of the ceramic monolith in order to introduce surface streamers along the monolith channels and (c) a sliding three-electrode DBD system combining a negative AC electrode, a DC electrode and a ground to create more homogeneous and widely dispersed surface plasma (29).

Plasma catalysis has been studied for automotive emission control in both the PPC and IPC configurations. Some of the first studies were conducted using a packed bed for nitrogen oxides (NO_x) control (30, 31) and proposed a two-stage process whereby the nitric oxide (NO) was oxidised to nitrogen dioxide (NO₂) which was then subsequently selectively reduced over the catalyst by the hydrocarbons present. This system has also been proposed as a pre-particulate filter plasma reactor to attain additional particulate matter oxidation benefits from the increased NO₂ generated by the plasma (32). A successful demonstration of a combined plasma and catalytic system has also taken place for CH₄ removal from dual fuel engines at low temperatures (33).

Plasma Surface Treatment

If the plasma can generate excited species at a surface, then it follows that it should be possible to change the surface by plasma treatment of a material. One area where plasma surface treatment has garnered significant interest is in the treatment of plastics and polymers. Plasma treatment of plastics and polymers can have a significant effect on the chemical and physical properties of the materials, these changes occur rapidly, often within seconds (34), through the following proposed mechanisms (35):

- Etching and stripping surface material: plasma which reacts with the surface to clean it of contaminants, for example an oxygen plasma, or in more extreme cases such as with the inclusion of tetrafluoromethane (Freon™ (Chemours, USA)) to etch the surface itself. This happens through breaking of the polymeric

covalent bonds due to the bombardment of the surface with high energy particles

- The partially destroyed polymers can react with other similarly separated units and form crosslinks, thus extending polymeric chains and mechanically stabilising the surface
- The surface can become functionalised by including a functional molecule in the plasma gas.

Examples of surface functionalisation include the incorporation of hydroxyl groups (OH) from humidity present in the plasma or N fixation using an NH₃ plasma. The introduction of polar groups such as hydroxyls allows for a significant improvement in the wettability of polymers and therefore has significant advantages for the printing and adhesives markets. This is a complex area and large bodies of work have been produced documenting the effects of different types of plasma on different polymeric materials and summarised elsewhere (34, 36).

Increasingly plasma has been used for vapour deposition (VD) processes applying a uniform thin film coating to a material (37). These films are usually within the nanometre thickness range and used for modification of optical, chemical, electronic, physical and decorative properties of the materials. The methods of plasma application for physical VD include sputtering, ion plating and cathodic arc deposition. Sputter deposition involves deposition onto a substrate of a molecule previously vaporised from a target. The target is vaporised through the mechanism of momentum transfer from gaseous ions accelerated from a plasma. The plasma ion plating process uses the material vaporised from a target (by whichever method is suitable) and bombards the depositing film with molecules produced from a reactive gas plasma as the film is deposited in order to change the properties of the depositing film. Arc VD occurs when an electrode is vaporised through the application of high current across a biased cell with the vaporised molecules being accelerated towards, and deposited on, the polarised substrate.

These treatment and deposition techniques require an understanding of physics and electrical engineering to generate, measure and optimise a plasma in order to effect the chemical change on, or within, a surface.

Plasma for Catalyst Preparation

It has been reported that using plasma as a preparative technique can improve catalyst



Fig. 6. A catalytic DBD plasma reactor used for the demonstration of CH₄ removal from an engine exhaust

dispersion, increase metal-support interactions and change metal particle morphology, which in turn can lead to improved catalytic activity and stability (38). An example of improved activity from plasma preparation is the supported nickel catalysts used for steam reforming; using a DBD plasma reactor to decompose the precursors such as nickel nitrate, for catalyst preparation it is possible to increase the proportion of the (111) Ni facets which show enhanced performance and coke resistance.

Another example of plasma used for catalyst preparation is the use of DBD plasma instead of the standard thermal calcination for silicon dioxide (SiO₂) supported cobalt materials for Fischer Tropsch synthesis. Li *et al.* found that plasma prepared materials had enhanced activity and a greater yield of heavy hydrocarbons when compared to the thermally calcined materials. This performance was attributed to the measured increase in Co dispersion, smaller Co(II,III) oxide (Co₃O₄) cluster size and more even Co distribution. A byproduct of the plasma preparation is the claim that this route can be a 'greener' method of preparing materials: using a low temperature electron reduction instead of using H₂ as a reductant removes the need for dealing with H₂ in the process (39).

Another advantage of the low bulk temperature plasma treatment as a preparative technique in comparison to a standard thermal treatment is the ability to remove precursors without inducing the detrimental changes that are associated with the temperatures normally required to oxidise the precursor molecules. An example of where this is useful is in the preparation of zeolite materials through plasma template removal. Liu *et al.* have conducted the removal of zeolite templates at around 125°C using a DBD plasma technique with

O₂. They identified the two major reactions taking place as the dissociation of template molecules by active species such as electrons or excited O₂ and oxidation by excited O₂ or O₃ molecules (40). When directly comparing template removal from ZSM-5 zeolite by thermal and plasma techniques Liu *et al.* found that the rate of removal was approximately eight times higher using the DBD plasma method (41).

Plasma for Catalyst Modification

Using a DBD system AZO Materials, UK, reported differences in the temperature and in the intensity of the peaks resulting from temperature programmed reduction of magnesium oxide (MgO) supported Ni catalysts compared to non-plasma treated materials (42). The differences were attributed to Ni particle morphology and dispersion.

Zhu *et al.* also treated supported Ni catalysts with DBD plasma and found an increase in the catalytic activity and stability for the partial oxidation of CH₄ (43). The scanning electron microscopy (SEM) images support a case for enhanced dispersion and increased interaction between the 10% Ni and the Al₂O₃ support. As well as a measurable increase in catalytic activity (3–5%) they also report a reduction in the formation of C around the Ni. This is consistent with a change in the Ni particle morphology towards having more (111) facets, as observed by others during the plasma preparation of catalysts (38).

Plasma for Material Regeneration

The literature related to the plasma application for material regeneration is limited. The current state and perspectives of plasma applications for catalyst regeneration was discussed in a recent review (44). Plasma regeneration was successfully applied for the reduction of oxidised catalysts and removal of poisons and C deposits. The largest advantage of plasma is that it allows catalyst regeneration to be performed at temperatures lower than those of typical thermal regeneration. The supply of gaseous reactive species and alteration of the surface structure to a more energetic state were identified as prerequisites of successful low-temperature regeneration and it was also shown that plasma can supply heat in a more cost-effective way than conventional thermal treatment. The energetic species produced in non-thermal plasma can initiate diverse reactions and open up or enhance reaction pathways other than those

expected for equilibrium chemistry. As thermal regeneration can result in catalyst sintering and thus a reduced number of active sites, plasma is a viable alternative to thermal treatment.

The advantage of plasma regeneration was shown in the recent work that has been undertaken at the University of Central Lancashire, UK, studying deactivated coked zeolite regenerated with the application of different techniques including thermal, MW plasma and DBD discharge plasma (45). This work showed that plasma not only removes C from the deactivated catalyst but increases the activity of the catalyst significantly. Toluene disproportionation was used as the probe reaction in this study. Unlike thermally regenerated catalysts the material regenerated by plasma shows improved catalyst performance and the activity of the regenerated catalyst is even higher than that of the virgin material. Characterisation methods including pyridine and collidine infrared studies, NH₃ temperature programmed desorption and solid state nuclear magnetic resonance were used to explain the changes in catalytic activity. Results showed MW plasma regeneration extended the catalytic life of zeolite due to the destruction of Brønsted acid sites caused by dealumination, without loss of crystal structure. In the toluene disproportionation reaction, this reduces the amount of cracking which occurs, subsequently leading to less coke deposition and therefore an extended catalytic life.

Cross Disciplinary Challenges

A key challenge for the field of plasma catalysis is to assemble teams with the relevant complementary skills in electronics, physics, engineering and chemistry together to gain an understanding of the system in order to produce the desired technological progress. A subset of this challenge is the communication between the different disciplines; involving not just the different language used, but also the models derived to express the concepts and understanding of processes which are often not ideally accessible to other branches of science and engineering.

As well as the broader topic of reducing barriers for communication, there are key challenges remaining within each of the disciplines required, including but not limited to:

- Electronic engineering: nanosecond pulsed plasma sources tend to provide the most energetic waveforms for plasma systems. For that reason, it is critical that solid state

nanosecond (5–100 ns) high voltage switches with high frequency capabilities are to be commercially available. Other important components in order to improve electrical and chemical efficiency are high dielectric strength materials with different dielectric constants (6) and reduction of electromagnetic interference (EMI) presented in such fast-rising waves

- Physics: determining the appropriate signals to measure to obtain information that can be analysed in new ways. Analytical techniques borrowed from nuclear physics may be appropriate, for example pulse height spectrometry and more familiar optical spectrometry techniques can and should be used to characterise the species that are generated in real time. The outstanding challenge is to map out the outcomes and determine what they mean in the very large potential experimental space that presents itself in these systems
- Engineering: scaling up a plasma reactor that requires both an interelectrode gap and sufficient gas-plasma-surface interaction to take advantage of the plasma and catalyst synergies, while simultaneously having a low pressure drop
- Chemistry: knowledge around the catalogue of catalysts for thermally activated heterogeneous reactions is not fully valid for plasma activated catalytic processes and a relevant body of knowledge does not currently exist. An additional challenge is to address the limited penetration depth of plasma into structures (46) and to develop methods for treating coated components including monolithic low pressure drop structures
- Data analysis and modelling: large amounts of data generated from multiple variables increases the complexity of the experimental design and interpretation. This therefore makes the dataset an obvious candidate for supervised machine learning with input expertise from each technical discipline.

Concluding Remarks

It is necessary to understand physics to be able to correctly use electronic engineering to generate the requisite plasma to react with the designed catalyst in order to affect the desired chemistry. Whether this chemistry change is in the gas phase, at the surface of a catalyst or within the surface, there are clearly a large number of challenges to be faced when considering the large experimental space brought

by the additional variables from non-chemistry fields. The general challenges for plasma catalysis can be expressed in broad terms of, for instance, increased efficiency, targeted catalysts or improved scaling of reactors; however within each of these targets underlying incremental improvements are required from additional scientific and engineering disciplines to achieve this.

Therefore, a key challenge for the field of plasma catalysis is to assemble teams with the relevant knowledge and skills in their own area of expertise that can work together and communicate ideas to initiate and progress the technology. Within Johnson Matthey there are teams with expertise across all the relevant disciplines who can overcome these barriers and work successfully together to realise the potential of plasma catalysis on a commercial scale.

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