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International Workshop on Plasmas for Energy and Environmental Applications

Improved efficiencies and carbon capture using recent advances in plasma technology

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Introduction

The International Workshop on Plasmas for Energy and Environmental Applications (IWPEEA) was held in Liverpool, UK, between 21st–24th August 2016. The event was organised by the Technological Plasmas Research Group at the University of Liverpool, UK. It included five plenary lectures, four invited lectures, 36 oral and 42 poster presentations.

The workshop brought together people from academia and industry who are interested in the latest scientific and technological advances in core areas of emerging plasma technology for environmental clean-up and energy applications. It covered the following topics:

- plasma generation, diagnostics and modelling for energy and environmental applications
- plasma chemistry for energy conversion and fuel and chemical synthesis
- plasma environmental clean-up
- plasma treatment of waste liquid
- plasma solid waste treatment (plasma gasification, pyrolysis and vitrification)
- plasma synthesis of catalysts and energy materials.

The workshop attracted nearly 100 delegates (mainly academic) from around ten countries.

Plasma Carbon Dioxide Conversion and Utilisation

This was the biggest topic at the workshop. Nearly 50% of the presentations were about plasma for carbon dioxide utilisation. The main idea is to use sustainable energy generation by means of wind or from solar radiation as a 'free' source of energy for a plasma system that converts CO_2 into fuel.

The Symposium was opened with a plenary lecture by Professor Christopher Whitehead (The University of Manchester, UK) on 'Plasma Catalysis: What do we Still need to Know?'. He highlighted the importance of understanding at a molecular level what is happening within the plasma and on the catalyst surface in real time with a wide range of timescales and with spatial resolution. We need to know about the binding energies and collisional behaviour of the transient, radical and excited species uniquely created by plasma with the catalytic surface and within the gas phase.

Professor Gerard van Rooij (Dutch Institute for Fundamental Energy Research, The Netherlands) gave a lecture entitled 'Efficient CO_2 Reduction in Microwave Plasma *via* Vibrational Excitation'. It was suggested that a microwave plasma approach potentially offers high energy efficiency (up to 90%) due to selectivity in the reaction processes that can be tailored *via* its inherently strong out-of-equilibrium processing conditions. At the same time, it is characterised by efficient and fast power switching, low investment costs, no requirement for scarce materials and high power density, which are all advantageous for industrial applications.

Plasma modelling is useful for optimisation of dielectric barrier discharge, microwave and gliding arc plasma reactors, as shown by Professor Annemie Bogaerts (University of Antwerp, Belgium) in her plenary lecture: 'Plasma Chemistry Modelling for CO_2 Conversion: A Better Understanding of Energy Efficiency and Product Formation'. The chemical kinetics model was developed for CO_2, CO_2/CH_4 and CO_2/H_2O gas systems which therefore is directly connected with CO_2 utilisation.

The application of a plasma-catalytic dielectric barrier discharge reactor for the decomposition of CO_2 to carbon monoxide and oxygen was presented by Xin Tu (University of Liverpool). A number of different catalytic and photocatalytic systems were investigated here. A schematic diagram of the plasma system as well as the effect of different catalysts are shown in **Figure 1**.

Industrial Session

Martina Modic (Jožef Stefan Institute, Slovenia) in her invited lecture on 'Plasma Technology as a Tool for the Inactivation of Food-related Microorganisms' described the possible application of cold atmospheric pressure plasma to bio-pollutant control. The organisms considered include fungi and bacteria, which are a major cause of food spoilage and biofilm contamination. A surface barrier discharge (SBD) was considered to offer the perfect compromise between stability, scalability and energy efficiency. The SBD was situated remotely from the sample being treated; consequently, reactive plasma species such as atomic oxygen and hydroxyl do not reach the bacteria. The antimicrobial effect of the SBD is attributed to longer lived plasma generated species such as ozone (O_3) and oxides of nitrogen (NOx). It was demonstrated that SBDs produced in ambient air are a viable means to

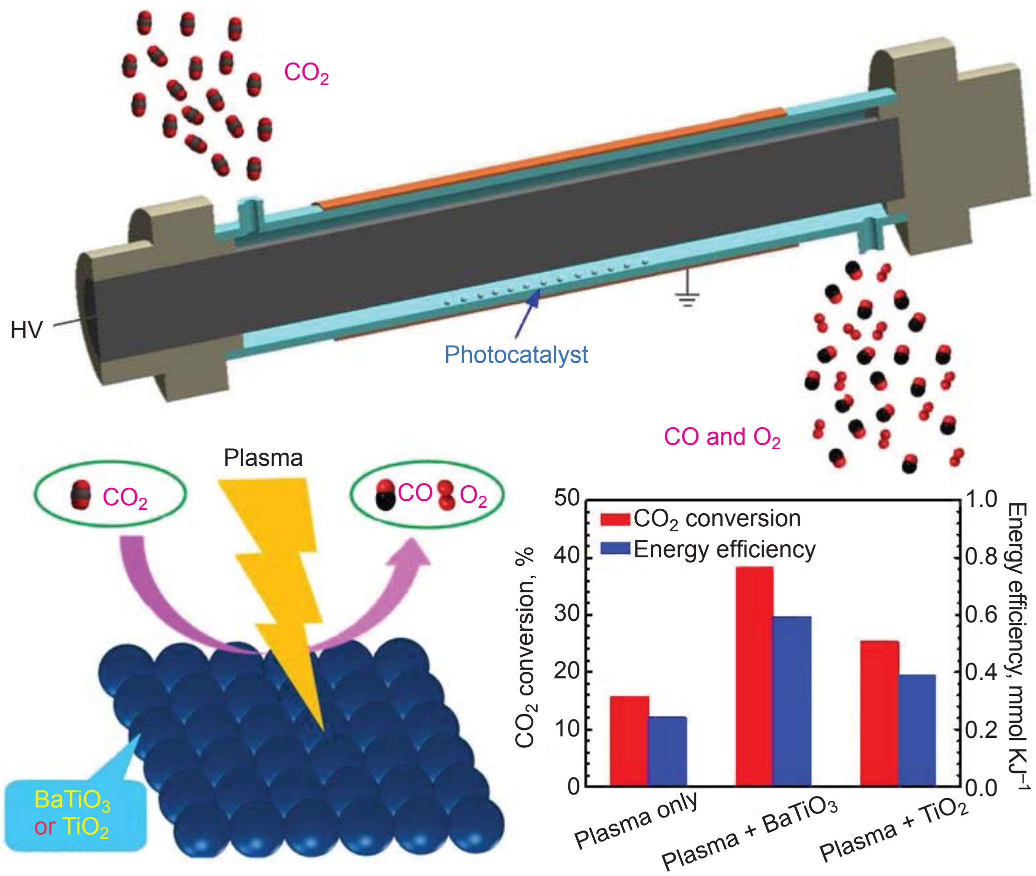


Fig. 1. Conversion and energy efficiency for the CO_2 decomposition reaction using various catalysts (Reproduced with kind permission from Xin Tu, University of Liverpool)

inactivate fungi and biofilms, as such they have the potential to become a highly effective decontamination technology for the food processing industry.

The results of trials of a plasma system which allowed the volume of waste from the nuclear industry to be reduced by up to 90% compared with alternative remediation approaches were given in a presentation by Bryony Livesey (Costain, UK) on 'Plasma Vitrification of Intermediate Level Nuclear Waste'. Another thermal plasma reactor was described by Yu Rong (Tetronics International, UK) in the presentation 'Treatment of EfW Air Pollution Control Residues using Tetronics' DC Plasma Arc Technology'. The application of thermal plasma for waste conversion into energy helped to avoid the formation of highly hazardous waste containing volatile heavy metals, dioxins, furans, chlorine and a high soluble salt content.

The conversion of waste and biomass was discussed by Ben Herbert (Stopford Energy & Environment, UK) in his presentation: 'Microwave Induced Plasma for the Thermal Conversion of Waste and Biomass Fuel Upgrading'. It was mentioned that microwave plasma has a higher energy efficiency and a lower temperature compared with thermal plasma.

The report 'RF-plasma for Environmental Applications: From R&D to Commercial' was about the use of plasma for waste treatment and was given by George Paskalov (Plasma Microsystems LLC, USA). Radio frequency (RF) plasma technology has been used for the treatment of hydrogen chloride and medical waste. In addition it has been used for processing of waste tyres. The conditions under which typical products are distinguished during the tyre recycling process, such as syngas, liquid hydrocarbons and carbon black were determined. The particle size of carbon black is within the nanosize range.

Plasma Synthesis of Catalysts and Energy Materials

The effect of plasma treatment on catalyst properties was discussed in a plenary lecture: 'Plasma Assisted Preparation of New Catalysts for Hydrogenations' by Professor Wei Chu (Sichuan University, China). For example, cobalt dispersion in a silica-supported Fischer-Tropsch synthesis catalyst was significantly enhanced by plasma treatment. Cobalt particle size was a function of plasma intensity; higher plasma intensity led to higher cobalt dispersion and as a result to higher efficiency.

Plasma treatment was studied for the preparation of catalysts for selective hydrogenation. It was found that plasma treated palladium/titania catalyst showed higher acetylene conversion and higher ethylene selectivity for acetylene selective hydrogenation. The dispersion of Pd metal in Pd/TiO_2 plasma treated catalyst was higher than that in untreated catalyst. In addition a nickel-zirconia/silica catalyst was prepared by impregnation and treated with plasma in a hydrogen atmosphere. This plasma treated catalyst showed a higher efficiency in the selective hydrogenation of CO_2 to synthetic natural gas.

Plasma Liquid

Professor Bruce Locke (Florida State University, USA) in the plenary lecture entitled 'Chemical and Physical Processes in Plasma Formed at a Gas-liquid Interface' discussed the direct discharge in liquid phase that is an alternative way to remove biological and chemical pollutants from water due to the formation of highly reactive species such as the hydroxyl radical, ozone and hydrogen peroxide.

Rajendra Singh (Indian Institute of Technology Delhi, India) in his presentation on 'Disinfection of Water using Atmospheric Pulse Corona Discharge: Effect of System Parameters and Mechanistic Study' mentioned that the decontamination efficiency increased with increasing applied voltage and frequency, with the disinfection efficiency being high when pH was less than 7. The presence of alkalinity, natural organic matter and turbidity reduced the disinfection efficiency significantly.

Most pharmaceutical residues are non-biodegradable and resistant against conventional wastewater treatment. Nevertheless the application of electric discharge can be effectively applied to solve this problem as shown by Kosar Hikmat Hama Aziz (Brandenburg University of Technology, Germany) in the presentation: 'Degradation of Pharmaceutical Residues in Aqueous Solution by Non-thermal Plasma (Dielectric Barrier Discharge) using a Planar Falling Film Reactor'.

Plasma Synthesis of Fuels and Chemicals

Atmospheric pressure plasma can be used for the synthesis of metallic, metal oxide and semiconducting nanomaterials from liquid solutions, as reported by Professor Davide Mariotti (University of Ulster, UK) in his plenary lecture on 'Third Generation Photovoltaics with Atmospheric Pressure Plasmas'.

Ammonia synthesis was the topic of an invited lecture given by Hyun-Ha Kim (National Institute of Advanced Industrial Science and Technology, Japan): 'Plasma-Catalysis: From Catalyst Screening to NH_3 Synthesis'. It was shown that unlike the Haber-Bosch process, plasma allows ammonia to be generated at atmospheric pressure. The application of a ruthenium/alumina catalyst and pulsed discharge decreased the energy consumption significantly, as shown in **Table I**.

Nevertheless plasma still consumes nearly ten times more energy for ammonia production than the Haber-Bosch process.

Plasma allows methane to be converted directly to liquids even at atmospheric pressure and nearly room temperature (30ºC), as shown in the presentation of Guozheng Wang (University of Liverpool) on 'One-step Synthesis of Value-added Liquid Chemicals from CO_2 in a Dielectric Barrier Discharge Reactor'. The use of a catalyst significantly increases the yield of liquid product and changes the product distribution.

Plasma Environmental Clean-up

This section contained a number of works related to the application of plasma technologies for removal of organic compounds from air. An interesting approach for plasma cleaning was suggested by Professor Antoine Rousseau (Ecole Polytechnique, France) in the plenary lecture: 'Air Treatment using Plasma-sorbent Coupling'. The idea is to apply plasma to very dilute mixtures where pollutants are adsorbed on the material first. Then the adsorbed organics are oxidised by switching on the plasma. It allows organic substances to be concentrated on the surface and avoids wasting plasma energy on NOx and O_3 formation. The key issue here is the catalyst selection. The catalytic material should selectively adsorb organics at high humidity; in addition it should remove the formed ozone and CO at room temperature.

Nevertheless care must be taken with the use of plasma for indoor air cleaning due to the possible formation of harmful compounds in plasma.

Concluding Remarks

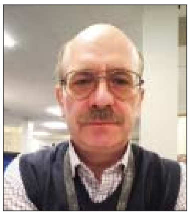
This workshop made it very clear that plasma technology attracts huge scientific and industrial interest. Plasma is a proven technology for solid waste control; its use has been demonstrated in waste to energy or waste to chemicals processes and for vitrification of nuclear waste. Plasma can be applied for water treatment and air pollutant control. Plasma can be considered as a possible method for CO_2 capture and its conversion into fuel by use of sustainable energy generated by means of wind or solar radiation.

The abstracts of oral and poster presentations given at this conference are available by contacting the conference organisers.

Table I Ruthenium/Alumina Catalyst and its Energy Yield at Various Temperatures

Catalyst	Power supply	Temperature, ºC	Energy yield, g_{NH_3} kWh^{-1}
$Ru/\gamma\text{-}Al_2O_3$	AC	200 250 300	1.3 2.0 3.5
$Ru\text{-}Mg/\gamma\text{-}Al_2O_3$	AC	250 300	6.4 9.8
$Ru\text{-}Mg/\gamma\text{-}Al_2O_3$	Pulse	250 300	25.5 35.7

The Reviewer



Vladimir Demidyuk was born in Rivne, Ukraine. He received his MSc and PhD degrees in Physical Chemistry from Moscow State University, Russia, and became a Lecturer at that university. Then he spent five years in South Korea working as a Visiting Researcher at Inha University. For the last 12 years he has been working in academia and in industry in the UK. He joined Johnson Matthey Technology Centre, Sonning Common, UK, in 2015. His research interests are heterogeneous catalysis and the application of plasma technologies for industrial purposes.