# Anisotropic plasma etching of Silicon in gas chopping process by alternating steps of oxidation and etching

Andrey Miakonkikh*[1], Sergey Averkin[1], and Konstantin Rudenko[1]

[1]Institute of Physics and Technology RAS, Moscow – Russie

**Résumé**

Gas chopping plasma etching of Silicon is well known process providing deep anisotropic etching of microstructures for MEMS applications, TSV for 3D integrations of ICs etc. It includes the alternative steps: the passivation of surface sidewalls and then etching the bottom of structure. Polymerizing fluorocarbon based plasmas of 4F8 (CHF3) gas is used at passivation step in Bosch process C4F8 / SF6 giving CxFy polymer film on surface. After completing of microstructure etching the polymer layer should be removed from sidewalls by additional plasma stripping and wet chemistry operations.
There exists more clean cryogenic deep silicon etching processes. First version is continues regime with SF6+O2 plasma and the second is gas chopping process SF4+O2/SF6 which is patented as STiGer etch process. Both processes requires cooling the Silicon wafer up to -100oC and utilizes the SixFyOz passivation layer stable at cryogenic temperature. This layer completely evaporates at room temperature after etching.

Obviously, the temperature stability of SixFyOz film depends on content of fluorine, and without fluorination the SiOx film is remarkably stable at rt and higher temperatures. In the present work a two-stage process for deep etching of Silicon based on alternating steps of etching in SF6 plasma and Silicon oxidation in O2 plasma is proposed. This developed Ox-Etch process has advantages of free from deposited polymers and does not use cryogenic equipment.

Processes were performed at room temperature in plasma etchers with high density ICP plasma source (RF frequency of 13.56 MHz and 2 MHz was used, RF power 800 – 1750 Watt) at chamber pressures of 5-30 mTorr.Wafer bias was in range of 30 – 50 V during etching step, and 0-30 V during oxidation step. Experiments were carried out on Silicon wafers(100) (n-type, 10-20 Ohm•cm). Hard mask of SiO2layer of 1-2 um was made by lithography with test topology of cylindrical holes and lines sized at 2-75 um.

Silicon oxidation by O2plasma was studied by *in situ* spectral ellipsometry on bare wafer surfaceduringOxy-step of process. It was shown that without D bias the oxide film grows upto 5 nm within time of 3-5 seconds. Under bias of 30-60 V oxide thickness saturates at 5-7 nm where growth of SiOx stops due to balance between oxidation and ion sputtering rates.The main condition for success of Ox-Etch gas chopping process implies that reduction in sidewall oxide thickness during the etching step should be compensated during following oxidation step. Typical duration of passivation and etching steps do not exceed 10 sec, and the mean etch rates of Silicon up to 3 um/min are achievable without noticeable undercut.

*Intervenant

Etched structures show anisotropic profile with vertical scalloped walls similar to Bosch and STiGer processes. Selectivity of Silicon etching with respect to silicon oxide musk is up to 20:1.Main controlling parameters for Ox-Etch processwhich determines the etch rate and degree of anisotropy are the duration of stages. The investigations on etching rates, aspectdependent etching, and sidewall roughness are presented.

Ox-Etch process could be applied to application where contamination of Silicon walls after etching could be a critical obstacle. After Ox-Etch process the passivation layer on walls of microstructures is close to native SiO2.
To reduce the bombardment of the sidewalls by scattered ions it is essential to use low pressure dicharge (2-10 mTorr) and a sufficient plasma density. Therefore, the process could be realized only in reactors with HDP-sources of plasma.

# Reactive magnetron sputter deposition of titanium oxynitride TiNxOy coatings: influence of substrate bias voltage on the structure, composition, and properties

Nadia Saoula*[1], Farroudja Lamdani[1], Larbi Bait[1], Noureddine Madaoui[1], Hanane Mechri[2], Mourad Azibi[1], Samira Sali[3], and Abdelkader Hammouche[1]

[1]Division Milieux Ionisés Lasers, Centre de Développement des Technologies Avancées CDTA; Cité du 20 août 1956,Baba Hassen, BP n 17, Alger, Algérie – Algérie

[2]Laboratoire Science et Génie des Matériaux, Université des Sciences et Technologies Houari Boumedienne BP n 32, El-Alia, Bab Ezzouar, Alger, Algérie. – Algérie

[3]Centre de Recherche en Technologie des Semi-conducteurs pour l'Energétique CRTSE - 02, Bd. Dr. Frantz Fanon, B.P. 140 Alger-7 Merveilles 16038, Algérie – Algérie

**Résumé**

TiN coatings is widely used as a metallurgical coating for instance in cutting tools as a wear-resistant coating and as a diffusion barrier in large scale integrated circuits. However, TiN coatings are limited for their poor oxidation resistance at high temperature. That's why the ternary systems of Ti-O-N have been an alternative to TiN because of their high hardness and high oxidation resistance. The incorporation of oxygen into TiN leads to two types of coatings: titanium oxynitride TiOxNy for high N content and Oxygen-rich TiNxOy (N-doped TiO2) for low N content. In fact, the interests in titanium oxynitride films have increased and have been extensively studied due to their improved the combined properties of metallic oxides (color, optical properties) and nitrides (hardness, wear resistance). The titanium oxynitride films are used in optically selective absorbing films to enhance the contrast of cathode-ray tube displays. It's also could be used as insulating layer in metal–insulator–metal (MIM) capacitive structures to avoid interfacial oxide layer formation. Additionally, several other useful applications of TiNxOy coatings, such as anti-reflective coating, solar selective absorbers, electrically switchable windows, transparent IR window electrodes, effective diffusion barriers for semiconductor applications and wear resistant coatings have been reported. Finally, its chemical inertness gives rise to its application as corrosion protective coating or as a biologically active *bone-like* apatite layer between the implant and bone.

The aim of this work is to investigate the effect of deposition parameter on the structure and properties of the TiOxNx thin films for biomaterials applications. The TiOxNy films were grown onto 316L stainless steel substrate using radio-frequency (rf) magnetron sputtering from a pure titanium target in Ar-O2-N2 gas mixture.

The deposited films were characterized by X-rays diffraction, nanoindentation and potentiodynamic polarization. In order to simulate natural biological conditions, physiological serum (pH = 6.3), thermostatically controlled at 37◦C, was used as the electrolyte for the study of the electrochemical properties. Comparison between the corrosion resistance of the

*Intervenant

uncoated and coated samples showed a reduction in corrosion current density for coated samples compared to the uncoated one. The contact angle measurement was carried out on TiON coatings in order to estimate their wettability characteristics. The contact angle can be defined as the angle between the liquid phases formed on the surface of a sample and the line tangent to the droplet radius from the point of contact with the surface of sample. Contact angle have been conducted by DIGIDROP contact Angle Meter system (GBX Scientific Instrument) with distilled water. Droplet of ($2\mu$l) was dispensed onto surface by syringe and the images of the droplets were captured directly after 10s. The contact angle tests were conducted at an ambient temperature. Each measurement was repeated five times. A perpendicular image was recorded by the camera interfaced to a computer. The contact angle was determined by numerically fitting to the droplet image. Error estimation of the contact angle is $\pm 1$.

# Experimental investigation of the repeatability of direct damage induced by lightning strikes on metallic panels

Christine Espinosa[1], Iman Alhossen*[1], Anis Hor[1], Estelle Pierré[2], Stéphane Vilcocq[2], Rémy Chieragatti[1], Thomas Montel[1], and Oscar Gnangnon[1]

[1]ICA, Université de Toulouse, ISAE-SUPAERO, IMT MINES ALBI, UTIII, INSA, CNRS, Toulouse, France – Université de Toulouse, CNRS, INSA, ISAE-SUPAERO, Mines Albi, UPS, Toulouse France – France

[2]DGA Techniques Aéronautiques – Ministère des Armées – France

**Résumé**

Metallic parts of aircrafts used for fuel tanks areas or even for the fuselage can suffer from severe direct damage due to lightning strikes. Metallic aircrafts are naturally protected against current flows because of their high electrical conductivity. But at the arc attachment location, there is a major risk of perforation which can result in a dramatic explosion due to fuel tank ignition. A lightning strike is a current discharge between opposite charge locations inside clouds and on the ground. Currents under considerations here are D+B+C* current waveforms prescribed by the standard regulations and reproduced in by specific current delivery devices at DGA-Ta lightning lab. It is well known that the risk to perforate a metallic panel directly increases with the duration of the C* component, mainly because of heat transfer at the arc root. But it is nevertheless not well understood how the variability of the test parameters of the electrical charge and the electro-thermo-mechanical behaviour of the structure influence the variability of the critical perforation point.

This paper presents the analysis synthesis of experimental investigations on the risk of perforation of a metallic panel to a laboratory prescribed D+B+C* lightning strike. A sensitivity analysis compares different tests campaigns and gives insight into the damage patterns related to perforation risk grades. The effect of the variability of some lab test parameters is reported. It is shown that a linear but not monotonously increasing relationship exists between the damaged zone in the panel and the delivered current charge. The perforation risk is shown to be not proportional to the current charge but rather to damage instability.

*Intervenant

# VAPOR PHASE DEPOSITION USING A PLASMA SPRAY PROCESS

Alexander Barth*[1], Malko Gindrat[1], and Richard Schmid[1]

[1]Oerlikon Metco AG, Wohlen – Suisse

**Résumé**

Plasma spray - physical vapor deposition (PS-PVD) is a low pressure plasma spray technology recently developed by Oerlikon Metco AG (Switzerland) to deposit coatings out of the vapor phase. PS-PVD is developed on the basis of the well established low pressure plasma spraying (LPPS) technology. In comparison to conventional vacuum plasma spraying (VPS) and low pressure plasma spraying (LPPS), these new process use a high energy plasma gun operated at a work pressure below 2 mbar. This leads to unconventional plasma jet characteristics which can be used to obtain specific and unique coatings. An important feature of PS-PVD is the possibility to deposit a coating not only by melting the feed stock material which builds up a layer from liquid splats but also by vaporizing the injected material. Therefore, the PS-PVD process fills the gap between the conventional physical vapor deposition (PVD) technologies and standard thermal spray processes. The possibility to vaporize feedstock material and to produce layers out of the vapor phase results in new and unique coating microstructures. In contrast to EB-PVD, PS-PVD incorporates the vaporized coating material into a supersonic plasma plume. Due to the forced gas stream of the plasma jet, complex shaped parts like multi-airfoil turbine vanes can be coated with columnar thermal barrier coatings using PS-PVD. Even shadowed areas and areas which are not in the line of sight to the coating source can be coated homogeneously.

This presentation reports on the progress made by Oerlikon Metco to develop a thermal spray process to produce coatings out of the vapor phase. Columnar thermal barrier coatings made of Yttria stabilized Zircona (YSZ) are optimized to serve in a turbine engine. This includes coating properties like strain tolerance and erosion resistance but also the coverage of multiple air foils. Also newly discussed chemistries with higher resistance to CMAS attack or improved sintering resistance were applied in a columnar structure and the PS-PVD technology turns out to be adaptable to a large range of chemical compositions of the feedstock. Multiple measures on improving the economic aspects and process stability were conducted and implemented in an industrial enviroment. Numerical simulations were used to develop spray nozzles and injector port designs to industrialize the process and improve process performance and robustness. Secondly the application of the coating on turbine components was demonstrated and optimized to coat multiple components simultaneously increasing the productivity.

*Intervenant

# Advances and Challenges in Modeling and Simulation of Thermal Plasma Flows

Juan Trelles*[1]

[1]University of Massachusetts at Lowell – États-Unis

**Résumé**

Thermal plasmas are at the core of a wide range of industrial applications, such as spraying, welding, cutting, mettalurgy, particle and chemical synthesis, waste treatment and resource recovery. Computational modeling and simulation has proven essential to provide insight into characteristics no practically accessible experimentally, and to guide equipment design and process optimization. Representative advances and current challenges for the computational modeling and simulation of thermal plasma flows are presented.
The modeling and simulation of thermal plasma flows faces compound challenges found in other fields, such as combustion, aerodynamics, and magnetohydrodynamics. There has been remarkable advances in the computational modeling and simulation of thermal plasma systems. These have allowed thermal plasma flow simulations within industrially-relevant configurations and for a broad range of operating conditions, which often involve the description of intricate multiphysics phenomena, complex three-dimensional domains, highly nonlinear properties, large solution field gradients, and highly dynamic time-dependent features.

Despite the remarkable progress achieved to date, several challenges remain. These challenges are generally addressed by methods designed for multiphysics and multiscale problems and can be broadly categorized in terms of model fidelity and numerical resolution. Fidelity refers to the degree of underlying phenomena captured by the model, whereas accuracy to the precision of the numerical solution of the model equations. In general, fidelity is a major challenge in multiphysics problems, whereas accuracy is a major challenge for multiscale problems. An important characteristic of thermal plasma flows is that their comprehensive simulation often stresses the need for both, fidelity and accuracy.

Major fidelity challenges include: (1) chemical nonequilibrium, of major relevance when complex molecular gas mixtures are used, in chemical synthesis processes, and when metal vapors are present; (2) thermodynamic nonequilibrium, found during intense interactions between plasma and processing media, such as a gas stream, electrodes, or feedstock material; (3) multi-phase interactions, as found near the plasma-electrode and solid material interfaces, as well as in novel processes such as liquid and vapor spraying; and (4) radiative transport, of major relevance during high-power operation, and particularly complex for molecular gas mixtures and high degree of nonequilibrium.

Major resolution challenges comprise: (1) flow stability, including fluid dynamic, thermal, and electromagnetic, often originated at the plasma periphery and leading to macroscopic

*Intervenant

flow reconfigurations; (2) pattern formation and self-organization, especially encountered in plasma-electrode interactions, which can cause enhanced erosion or process nonuniformities; (3) turbulence, the paramount example of multiscale phenomena and a major driver of gas entrainment and mixing; and (4) complex spatial and temporal configurations, as often found in modern plasma sources, such as multi-electrode or alternating power torches.

The need for increased fidelity and accuracy can be potentially unbounded, whereas computational resources are necessarily bounded. This dicotomy implies that the modeler often faces the choice between performing "better" simulations (e.g. higher dimensionality, higher resolution) or using "better" models (e.g. greater span of phenomena accounted for, fewer modeling assumptions). Some recent developments that seek to mitigate such trade-off, such as heterogeneous modeling approaches, are briefly described.
Acknowledgements: Financial support provided by the U.S. Department of Energy through award DE-SC0018230 and the U.S. National Science Foundation through award CBET-1552037 is gratefully acknowledged.

# Energy and momentum transport in thermal arcs: a simple method for modelling

Youssef Abdo*[1], Laurent Fulcheri[2], and Vandad Rohani

[1]MINES ParisTech, PSL-Université de Recherche, PERSEE, – MINES ParisTech - École nationale supérieure des mines de Paris – France

[2]Centre Procédés, Énergies Renouvelables, Systèmes Énergétiques (PERSEE) – MINES ParisTech - École nationale supérieure des mines de Paris – CS 10207 rue Claude Daunesse 06904 Sophia Antipolis Cedex, France

**Résumé**

We propose a simple and practical method for the modelling of the local and total magnetic force generated at the cathode. We prove that, if the current density profile obeys the same distribution along the axial-direction, the axial force depends only on the total current and the ratio of the arc spot radius to the radius of the arc column. We also give lower and upper estimate bounds for the radial force. Including the magnetic force as a source term in numerical modelling makes this approach particularly attractive for large scale industrial applications in which the arc region is very small compared to the entire domain. The use of source terms prevents one from solving Maxwell's equations that require fine meshing in the arc region and imprecise boundary conditions, which results in a substantial increase in computational time and cost. The power generated by Joules heating is also inserted as a term source in the energy balance equation. This also renders this approach even more advantageous as it circumvents the extra complications in computation that are related to the cathode and anode falls. In the case of a mono-phase or 3-phase arc, if steady-state simulations are desired, a time-average is calculated. Numerical results are also provided. The arc is perceived as an energy and momentum source. The major contribution to the arc momentum is mainly due to the cathode jet, which results from the magnetic pinch in the vicinity of the cathode tip. Analytical expressions for the radial and axial forces are obtained and included as source terms in the momentum equations.

*Intervenant

# A Hybrid Finite-Element-Finite-Volume Mixed Method for Thermal Arc Simulations

Youssef Abdo*[1], Laurent Fulcheri[2], and Vandad Rohani

[1]MINES ParisTech, PSL-Université de Recherche, PERSEE, – MINES ParisTech - École nationale supérieure des mines de Paris – France

[2]Centre Procédés, Énergies Renouvelables, Systèmes Énergétiques (PERSEE) – MINES ParisTech - École nationale supérieure des mines de Paris – CS 10207 rue Claude Daunesse 06904 Sophia Antipolis Cedex, France

**Résumé**

Over the past few decades, numerical computation has proved to be a powerful tool in understanding thermal arcs behaviour and characteristics. Most of the numerical methods in use, are often based either on finite volume or finite element approaches but very seldom on both of them. In the present work, we propose a new combined finite-element finite-volume method for stationary and unsteady schemes. The main advantage of this approach is double-fold: on one hand, the flow, energy and species equations are solved using a classical finite-volume (FV) method which enables us to express them as flux transport equations providing a robust physical meaning. On the other hand, Maxwell's equations are solved using special finite-element (FE) analysis methods which aims to directly compute the magnetic field (for stationary and unsteady schemes) without adding additional equations and imprecise boundary conditions. The reason an FE analysis is proposed resides in its ability to efficiently handle the mathematical formulation of Maxwell's equations involving (**curl**)-operators. The usual treatment of the Maxwell's equations for the arc consists in solving for the potential vector  with arbitrary boundary conditions that could lead to some discrepancies and is very difficult to solve in unsteady schemes. The choice of  instead of  is very attractive because it allows one to write the equation for  in a TADR (transient-advection-diffusion-reaction) form suitable for most FV and ordinary FE solvers. We propose two separate approaches for the FE-method: one that is only suitable for a steady-state scheme and another that could be applicable for both steady and unsteady cases. Some numerical results are also provided.

*Intervenant

# Phenomena during wire arc spray applications

Jochen Schein*[1], Stefan Kirner[1], Guenter Forster[1], Michal Szulc[1], and Karsten Hartz-Behrend[1]

[1]Universitaet der Bundeswehr Muenchen – Allemagne

**Résumé**

The wire arc spray system is a widely used coating application tool offering high deposition rates at comparably low operational cost. An arc is ignited between two wire electrodes, which are constantly fed to compensate for the molten droplets detached from the tips by a strong perpendicular gas flow. Even though it is a commercially highly successful procedure, the investigations that have been reported on this method are still limited due to the highly complicated interactions between strong gas flows, changing electrode structures and reactive process gases. This paper aims at demonstrating some recent investigations into this technology to help understand the fundamental mechanisms as well as offering new diagnostic, which may be used to control the process to obtain higher quality and a better reproducibility.
High-speed imaging shows a constant motion of the arc between the electrodes in the direction of the gas flow with regular re-ignition at the narrowest distance between the two wire tips. Droplet detachments vary depending their origin from the anodic and cathodic electrode due to the differences in arc attachment and energy input leading to a bimodal primary particle distribution, which has been modelled in good agreement with experimental results.

The re-ignition between the wire tips may influence the primary particle production as the residence time of the arc attachment on the electrodes influences the particle production as well as metal vapor production, which in turn interacts with the movement of the attachments. It has been found that by using pulsed currents the re-ignition can be influenced significantly as long as it is close to the natural ignition frequency, which is approximately 1 kHz. The resulting behavior on primary particle production will be presented.
Due to the strong gas flow and thus the significant gas consumption for coating production, usually nitrogen or compressed air are used as the standard process gases. The use of air – cost-wise the preferred choice – leads to strong oxidation in the coating. This oxidation also depends on the process parameters. In order to obtain reliable information about the oxidation percentage the coating has to be analyzed post application by destructive methods. A new method has been developed to track oxidation during flight by using spectrally resolved emission data from the particles. By comparing temperature, independently of emissivity of the particles, with absolute intensity of the radiation, which is highly dependent on emissivity, the emissivity values of the sprayed particles can be determined. Using these data and comparing them with emissivity values posted in literature the oxidation can be determined non-destructively. The results of these investigations will be presented as well.

*Intervenant

# High-Speed Visualization of Temperature Field in Diode-Rectified Multiphase AC Arc with Bipolar Electrode

Manabu Tanaka*[1], Tsugio Matsuura[2], and Takayuki Watanabe[1]

[1]Department of Chemical Engineering, Kyushu University – Japon
[2]Taso Arc Corp. – Japon

**Résumé**

An innovative multiphase AC arc (MPA) was drastically improved by diode rectification technique with bipolar electrodes. Temperature fields of the diode-rectified MPA (DRMPA) were successfully visualized on the basis of a high-speed camera with appropriate band-pass filters.
The MPA is expected to be utilized in massive powder processing as novel heat source because MPA possesses many advantages; high energy efficiency, large plasma volume, low gas velocity, and low cost. However, a few issues remain to be solved. In particular, electrode erosion is one of the important issues to be solved.

Electrode erosion mechanism in the MPA had been investigated by high-speed visualization technique. Erosion due to larger droplet ejection than 100 $\mu$m in diameter is dominant at cathodic period while evaporation at anodic period is dominant mechanism. The droplet ejection at cathodic period is caused by the electrode melting due to high heat flux to electrode at anodic period. Therefore, the DRMPA was successfully established based on the diode-separation of AC electrode into a pair of cathode and anode to solve the electrode erosion. However, fundamental phenomena in the DRMPA are still poorly understood because of its novelty, although spatiotemporal characteristics of the arc and/or electrode temperature are necessary to develop the DRMPA for industrial applications. The purpose of the present study is to clarify temperature fluctuation of arc and the electrodes in DRMPA by high-speed visualization technique.

Twelve-diodes were placed between the electrodes and the transformer. Thus, the electrodes were divided into pairs of cathode and anode, namely bipolar electrodes. Each electrode consisted of cathode made of indirect water-cooled oxide-doped tungsten with 3.2 mm in diameter and anode made of water-cooled copper rod with 20 mm in diameter. Six pairs of electrodes were symmetrically arranged at the angles of 60 deg. DRMPA were generated among these parallel rod electrodes in argon atmosphere. Arc temperature field and electrode temperature fluctuation were visualized by high-speed camera with appropriate band-pass filters. Transmission wavelengths for arc temperature visualization were 794 nm and 675 nm, while these for electrode temperature measurement were 785 nm and 880 nm. Remarks obtained from the high-speed visualization are as follows;

*Intervenant

(1) Temporal and spatial characteristics of the DRMPA was investigated. Anode jet in the DRMPA was weaker than that in the conventional MPA due to the negligible metal vapor in the DRMPA system. In contrast, strong cathode jet was confirmed in both the DRMPA and the conventional MPA due to the high current density near the tungsten-based electrode. Arc region in the DRMPA was widely distributed compared with the MPA. Therefore, arc region in the DRMPA is more suitable for nanomaterial synthesis and/or waste treatment at a high processing rate.
(2) Erosion rate of the electrode in the innovative DRMPA was drastically improved. Anode erosion in the DRMPA was reduced due to higher thermal conductivity of copper in the DRMPA than that of tungsten in the MPA. Moreover, cathode erosion in the DRMPA was also reduced because of the absence of the anodic heat transfer to the tungsten-based electrode. Temperature of tungsten-based electrode in the MPA was higher than the melting point of tungsten, while that in the DRMPA was significantly lower than the its melting point, resulting in negligible erosion.

# Aluminum oxynitride nanopowders synthesis in a reactor with a confined plasma jet

Aleksey Astashov*[1,2], Andrey Samokhin[2], Nikolay Alekseev[2], Mikhail Sinayskiy[2], and Inessa Pahilo-Daryal[2]

[1]A. Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences – Russie
[2]Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences – Russie

**Résumé**

Experimental studies of aluminum oxynitride nanopowders synthesis in a reactor with a confined plasma jet by the interaction of disperse aluminum with ammonia and oxygen in the flow of nitrogen plasma generated in an electric arc plasma torch are carried out. Experimental studies were preceded by calculations of the equilibrium compositions and thermodynamic characteristics of the multicomponent Al-O-N system.

Efforts to select the optimal design of the reaction prechamber of the reactor were made.

Powders with an average particle size in the range of 20-200 nm, having a cubic structure and consisting of aluminum oxynitride phases, were obtained.

It has been established that the specific surface area of the obtained powders increases from 20 m2/g to 71 m2/g with an increase in the flow rate of quenching gas from 1.8 m3/h to 6.0 m3/h, the nitrogen content of the obtained nanopowders increases from 3.6 to 14.7 wt.%. And at the same time oxygen content decreases from 35.5 wt.% to 25.5 wt.%. At minimal quenching gas low rate, metallic aluminum and its oxide phases are present in obtained powders. With an increase in the amount of quenching gas, the conditions for mixing aluminum vapors with oxygen and atomic nitrogen obtained during the decomposition of ammonia are improved, which leads to the formation of oxynitride and aluminum nitride.

Studies of the dependence of powder phase composition on the amount of ammonia introduced into the system with a constant ratio of the amount of oxygen to the amount of aluminum were made. Based on the results of XRD, with an increase in the ratio ammonia concentration to aluminum concentration from 6 to 30 the content of the oxide phase of aluminum in the powder composition is reduced, which is completely absent in the powders obtained in experiments where the ratio of ammonia to aluminum is greater than 15. At the same excess polytype of the cubic phase of aluminum oxynitride appears.

The work was performed as the state task No. 007-00129-129 18-00 and was financially supported by the Russian Science Foundation, grant no. 16-19-10213.

*Intervenant

# Modelling of the plasma parameters of an arc discharge with sputtered metal-graphite anode

Alexander Fedoseev*[1], Nikon Demin[1], Salavat Sakhapov[1], Alexey Zaikovskii[1], and Dmitriy Smovzh[1]

[1]Institute of Thermophysics SB RAS – Russie

**Résumé**

Arc discharge is one of the most researched and simple ways in nano-materials production [1]. However, there are only a few theoretical models (e.g. [2,3]) devoted to the synthesis of nano-particles in the anodic arc discharges when the anode material is sputtered. In the work, a global integral model of an arc discharge is developed to describe the main processes occurring in the synthesis of nano-materials with a composite metal-graphite anode. The main feature of the model is the simultaneous consideration and the relationship between the plasma discharge gap parameters, the cathode and the anode layers, the current continuity, the thermal regime of the electrodes and the evaporation of the anode. A stationary regime of arc discharge with a constant spatial gap between the electrodes, constant current and voltage of the discharge in helium is considered.
As a result of the modeling, the following discharge parameters were calculated: heat balance in the whole discharge gap (including anode and cathode, radiation losses, losses for materials heating), the temperatures of the electrodes, charged particles concentration in the discharge gap (electrons, carbon ions and catalyst ions), electron temperature, voltage drop in the anode and the cathode layers and in the discharge gap, the ratio of the ion and the electron currents at the cathode, the ablation rate of the evaporated anode material as a function of external parameters of the discharge (discharge current and voltage, discharge and electrodes geometry, buffer gas pressure, composition of the anode).

The calculated data show a good agreement with the experimental and calculated data of the other authors, in particular, a good correspondence between the absolute values of the electron density and temperature, the discharge voltage and the anode ablation rate as a function of the discharge current. Calculations of plasma arc parameters during the evaporation of the composite anode with the addition of aluminum, magnesium and zirconium were performed in. The results show that even a small ($< 1\%$ mass fraction) addition of metal to the core of the graphite anode leads to a significant change in all plasma discharge parameters.

The work is supported by the Russian Science Foundation, Grant No. 18-19-00213.

1. Keidar M. Factors affecting synthesis of single wall carbon nanotubes in arc discharge // Journal of Physics D: Applied Physics. 2007. V. 40, No. 8. P. 2388

2. Keidar M., Beilis I. Modeling of atmospheric-pressure anodic carbon arc producing carbon nanotubes // Journal of Applied Physics. 2009. V. 106, No. 10. P. 103304.
3. Kundrapu M., Keidar M. Numerical simulation of carbon arc discharge for nanoparticle synthesis // Physics of Plasmas. 2012. V. 19, No. 7. P. 073510.

*Intervenant

# Tribological investigations of YSZ-CuAg composite coating

Yan Wang*[1], Yongli Zhao[2], Geoffrey Darut[2], Thierry Poirier[3], Jorge Stella[4], Hanlin Liao[2], and Marie-Pierre Planche[2]

[1]UTBM – Université de Technologie de Belfort-Montbeliard, Université de Technologie de Belfort-Montbeliard – France

[2]UTBM – Université de Technologie Belfort-Montbéliard – France

[3]Institut de Céramique Française – Institut de Céramique Française – France

[4]Universidad Simon Bolivar – Venezuela

**Résumé**

A considerable aspect of yttria-stabilized zirconia (YSZ) coating investigated intensively is as a friction protection layer for cylinders and clutch in automotive engines. It has been demonstrated that additives such as gold, silver and other solid lubricant in YSZ powder contribute to a remarkable improvement of tribology properties. In the present study, different amounts of CuAg (30 and 50 wt.%) were blended with YSZ powder as feedstocks. The YSZ-CuAg composite coatings were prepared with atmospheric plasma spray (APS). Then the as sprayed coatings were post treated in an argon atmosphere at 850 and 950 ◦C respectively for a duration of 1 h. The composition and microstructure of as-sprayed and post-treated coatings were characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD). The results indicate that CuAg additive was beneficial for densifying the plasma sprayed YSZ coatings. As a consequence of the metallic particles addition, wear resistance of the composite coating was improved, presumably due to both aspects: the lower porosity present in the coatings and the lubricant effect. Heat treatment promotes porosity in the coating because of the Kirkendall effect. The tribological properties were improved after heat treatment attributed to the improved splats interfaces.

*Intervenant

# Two-dimensional estimation of number density distribution of precursor molecules during TiO2 nanopowder synthesis using induction thermal plasmas

Naoto Kodama[1], Yasunori Tanaka*[1], Kazuki Onda[1], Kotaro Shimizu[1], Yoshihiko Uesugi[1], Tatsuo Ishijima[1], Sueyasu Sueyasu[2], Shu Watanabe[2], and Keitaro Nakamura[2]

[1]Kanazawa University – Japon

[2]Nisshin Seifun Group Inc. – Japon

**Résumé**

The induction thermal plasma (ICTP) has been frequently used for nanopowder synthesis with solid feedstock powder injection.

It is thus important to clarify where the feedstock is evaporated and how the precursor vapor is generated and distributed in the ICTP torch to investigate nucleation and particle growth processes during this nanopowder synthesis. For this purpose, the authors developed a two-dimensional (2D) measurement method of temperature and Ti vapor admixture ratio in the pure Ar ICTP with Ti feedstock for Ti nanopowder synthesis. In addition, we also successfully estimated the number density distributions of Ti atoms and electrons under the local thermodynamic equilibrium (LTE) assumption using the estimated temperature and Ti vapor admixture ratio in the pure Ar ICTP with Ti feedstock.

The present paper describes estimated results on 2D distributions of temperature and number densities of TiO and TiO2, i.e. precursors for TiO2 nanoparticles, in a Ar-O2 ICTP with Ti feedstock. Experimental conditions were set as follows. Input power was fixed at 20 kW. The gas mixture of Ar and O2 was used as sheath gas with flow rates of 90 L/min Ar and 10 L/min O2. The pressure was controlled to be 300 torr. The Ti feedstock powder was continuously injected into the ICTP torch with a feeding rate of 2 g/min. The Ar gas was used as feedstock carrier gas with a flow rate of 2 L/min. The 2D-OES was carried out for the thermal plasma torch during TiO2 nanopowder synthesis processing. The observation region was set at $52\times52$ mm$^2$ region below the coil-end. Two Ti I atomic lines at wavelengths 453.32 nm and 521.04 nm were observed as well as O I atomic line at 777.54 nm. The following assumptions were adopted to estimate temperature and particle number densities: (a) LTE, (b) constant pressure, and (c) Ar and O2 gases were uniformly mixed. The Ti excitation temperature was estimated using the two-line method for observed two Ti I atomic lines. The Ti vapor admixture ratio in the experiment was determined by comparison between the measured intensity ratio and the calculated emission coefficient ratio of Ti I at 521.04 nm and O I at 777.54 nm at the estimated temperature. As results, the estimated Ti excitation temperature was found about 3.0 kK around on-axis region while it was between 4.0-5.0 kK in off-axis region. The main reason of this temperature difference is that the temperature increases due to joule heating in the off-axis region whereas it decreases due to

*Intervenant

energy consumption by feedstock evaporation at the on-axis region. It is also found that the downstream temperature was slightly lower than the upstream temperature. In addition, the estimated TiO density was $10^{14}$ m$^{-3}$ below the coil-end region, and TiO density became more than $10^{16}$ m$^{-3}$ at downstream region. In addition, TiO2 number density was also found to be much higher at downstream region. These results indicate that relatively high number density of precursor TiO and TiO2 molecules can be formed at downstream region in the ICTP torch during TiO2 nanopowder synthesis.

# Parameters of the atmospheric pressure CW microwave discharge sustained by focused gyrotron radiation

Sergey Sintsov*[1], Alexander Vodopyanov[1], Mikhail Viktorov[1], and Dmitry Mansfeld[1]

[1]Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS) – Russie

**Résumé**

A nonequilibrium plasma of a microwave discharge, supported by continuous wave (CW) of a gyrotron at a frequency of 24 GHz, was investigated. The discharge is realized by focused microwave radiation on the flow of argon from the gas tube at atmospheric pressure. The value of the electric field strength in focal waist reached 1.8 kV/cm. A spark discharge was used to initiate the microwave discharge. The radiation power of the gyrotron varied from 900 to 5000 W. The emission spectra of pure argon plasma were recorded in the range 300-1000 nm using an ASEQ LR1 emission spectrometer with a resolution of 0.3 nm. The relative intensity of the emission lines of argon atoms was used to determine the electron temperature. The electron temperature was in the range from 0.3 to 1.5 eV, depending on the heating power and the gas flow rate. The gas temperature was estimated by comparing the continua of the spectra obtained with the spectrum of blackbody radiation with given temperature. According to the estimations, the gas temperature did not exceed 3000 K. Based on the obtained results on the measurement of temperatures, it can be asserted that the investigated atmospheric pressure discharge is nonequilibrium.
The electron density in the discharge was measured using microwave interferometry. The essence of the method consists in recording the change in the phase of the probe radiation as it passes through the plasma torch. Knowing the length of the path traversed in the plasma, it is possible to determine the average value of the electron density. The Gunn diode with a frequency of 35 GHz was used as a source of probing wave. To determine the phase change, the Keysight Infiniium Z oscilloscope with a transmission frequency of up to 63 GHz was used. It was possible to observe a phase change of the probing wave at a frequency of 35 GHz on the oscilloscope screen in real time. As a result, it was found that the average value of the electron density was close to the cut-off density for the frequency of 24 GHz and was 5 ± 2x10ˆ12 cmˆ(-3). Depending on the heating power and the gas flow rate, the values of the average electron density remain constant practically.
The realization of a CW nonequilibrium microwave discharge at atmospheric pressure is especially important for various plasmachemical applications. In such a discharge, it becomes possible to accelerate the plasma-chemical reactions due to the high electron temperature. The increased pressure in the discharge provides high production rate, which makes this type of plasma torch attractive for industrial applications. The use of powerful microwave radiation of the gyrotron to sustain a nonequilibrium plasma at atmospheric pressure will allow the decomposition of highly stable molecules, for example, volatile fluorides and halides.

*Intervenant

# Development of distributed ferromagnetic enhanced inductively coupled plasma source for plasma processing

Gennadiy Sukhinin*[1], Mikhail Isupov[1], Ivan Yudin[1], and Alexander Fedoseev[1]

[1]Institute of Thermophysics SB RAS – Russie

**Résumé**

A new source of plasma based on the principle of a distributed ferromagnetic enhanced inductively coupled plasma generation [1] has been developed to obtain a large volume of dense (1010-1012 cm-3) uniform plasma at low pressures (1-100 mTorr) for plasma processing of the 450 mm wafers. To control the uniformity of the plasma density profile inside a gas discharge chamber, a well-known dual power approach relying on a radio-frequency (13.56 MHz) auxiliary ICP source was used [2]. In contrast to [2], in order to increase the power factor of ICP coil and eliminate the capacitive coupling between plasma and the coil [3, 4] an auxiliary plasma source is proposed based on additional ferromagnetic enhanced inductively coupled plasma sources with a frequency of 100 kHz.

Mechanisms of the plasma density profile formation in the large discharge chamber (internal diameter of 700 mm) are discussed, depending on the ratio of electrons and metastable atoms free paths to the discharge chamber radius. Mechanisms of generating charged and excited particles in U-shaped discharge tubes placed on the sides of a large discharge chamber (for details see [1-3]) are analyzed for the tube diameter of 5 cm and plasma forming gas pressure of 1-100 mTorr. Spatial distributions of charged and excited particles in the main discharge chamber have been estimated, based on the accounting for the diffusion fluxes from the U-shaped discharge tubes into the main chamber. Possible ways of manipulating the plasma density profile are discussed, by changing the plasma forming gas pressure, the ratio of the main and the auxiliary plasma sources power, and the positions of the U-shaped discharge tubes on the sides of the main discharge chamber.

**Acknowledgment**.: The work is supported by the Russian Science Foundation grant No. 18-19-00205.

1. Kyeonghyo Lee, Youngkwang Lee, Sungwon Jo, Chin-Wook Chung, and Valery Godyak Characterization of a side-type ferrite inductively coupled plasma source for large-scale plasma processing. *Plasma Sources Sci. Technol.* (2008) Vol. **17,** 015014.

2. Jin-Young Bang, Jin-Yong Kim, and Chin-Wook Chung Electron energy flux control using dual power in side-type inductively coupled plasma. *Physics of Plasmas.* (2011), Vol. **18,** 073507.

3. Valery Godyak. Ferromagnetic enhanced inductive plasma sources. - *J. Phys. D.: Appl. Phys.* (2013), Vol. **46,** 283001.

*Intervenant

4. Isupov M.V., Fedoseev A.V., Sukhinin G.I., and Ulanov I.M. An investigation of electrophysical and thermophysical characteristics of low-frequency inductive discharge of transformation type. - *High Temperature.* (2015),Vol. **53**., Issue 2, P. 179.

# Nonequilibrium effects in the arc in crossflow

Vyasaraj Bhigamudre[1] and Juan Trelles*[1]

[1]University of Massachusetts at Lowell – États-Unis

**Résumé**

Industrial plasma applications such as wire-arc spraying, circuit breakers, and arc heaters involve the interaction between an electric arc and a perpendicular stream of gas flow, a configuration commonly referred as the arc in crossflow. The arc in crossflow has been extensively studied by both, experimental and computational, means due to its marked importance in applications as well as its role as a canonical model for arc-gas flow interactions. The arc in crossflow experiences highly-coupled fluid-dynamic, heat transfer and electromagnetic interactions that make the flow prone to instabilities and even turbulence. Previous computational investigations have modeled the arc in crossflow assuming Local-Thermodynamic Equilibrium (LTE), i.e., heavy-species (molecules, atoms, ions) and free electrons are in kinetic equilibrium and therefore can be characterized by a single equilibrium temperature. Nevertheless, LTE is generally valid in the plasma core but often it is not applicable near the peripheries of the arc. A non-LTE (NLTE) plasma flow model would provide fundamental understanding, elucidate the intrinsic arc dynamics, and depict the energy interdependence between the heavy-species and the electrons. This research focuses on the computational investigation of the arc in crossflow using a time-dependent three-dimensional NLTE (two-temperature) plasma flow model. The NLTE model is casted as a single transient-advective-diffusive-reactive system of transport equations and solved using a Variation Multiscale (VMS) Finite Element Method, a comprehensive and robust formulation for the solution of general multi-physics and multi-scale transport problems. Simulation results show that the heavy-species and electron temperature distributions enclose the experimentally-measured temperature distribution (determined assuming LTE), where the heavy-species temperature distributions are relatively more constricted. The results also show that the plasma arc interacts strongly with the imposed gas-flow leading to intricate phenomena, such as arc deflection, convective heat losses, and the thermodynamic nonequilibrium. The characteristics of the flow are investigated using as controlling parameters the Reynolds number, which relates the strength of advection over diffusion, and the Enthalpy number, which measures the amount of flow energy to the electrical energy. The arc becomes bow-shaped and constricted for high Reynolds numbers and cusp-shaped and relatively more diffuse for low Enthalpy numbers. The maximum arc voltage varies proportional to both, the Reynolds and Enthalpy numbers, while the maximum degree of nonequilibrium and the maximum arc power dissipation vary directly with the Reynolds number and inversely to the Enthalpy number. The analysis of the relative effect of the controlling parameters can help in understanding the interaction dynamics of the arc and thus assist in equipment design and process optimization.

*Intervenant

# Trial Synthesis of Silicon Nanoparticles using a Newly Developed Tandem Type of Modulated Induction Thermal Plasma with Lower-Coil Current Modulation

Kazuki Onda*[1], Naoto Kodama[1], Yosuke Ishisaka[1], Kotaro Shimizu[1], Yasunori Tanaka[1], Uesugi Yoshihiko[1], Tatsuo Ishijima[1], Shiori Sueyasu[2], Shu Watanabe[2], and Keitaro Nakamura[2]

[1]Kanazawa University – Japon

[2]Nisshin Seifun Group Inc. – Japon

**Résumé**

We have developed the pulse-modulated induction thermal plasma (PMITP), which is sustained by the coil current modulated into rectangular waveform. Such an amplitude modulation of the coil current can provide a temporally varying temperature field in the torch. Using this PMITP, we have developed a high rate production method of nanoparticles [1]. However, the PMITP is sometimes extinguished when too heavy-load feedstock is injected into the PMITP. To improve this low stability of the PMITP, the authors have developed a tandem type of PMITP (tandem-PMITP) system with two different coils; upper and lower coils. The upper coil current can be used, for example, for more stable operation of the induction thermal plasma, while the lower coil current can be modulated to create a temporally-varying temperature fields with robustness against a large disturbance.

In this report, silicon nanoparticles were in trial synthesized by using the developed tandem-PMITP system with lower coil current modulation. Si nanoparticles are expected as the anode material for next generation lithium ion battery. In tandem-PMITP system, two eight-turn coils with an axial length 155 mm were located in one cylindrical quartz tube with a length of 425 mm. The upper and lower coils are severally connected to two different rf inverter power supplies with driving frequencies of 450 kHz and 320 kHz through matching circuits. The reason why different driving frequencies for upper and lower coils are used is to reduce magnetic coupling between the upper and lower coil circuits. Furthermore, using two different rf supplies, two coil current can be independently modulated.

Experimental condition was shown as follows. The time-average input power for upper and lower-coil were set to each 10 kW. The upper coil current was not modulated, while the lower coil current was modulated. The modulation cycle was set to 15 ms, and the on-time and the off-time were set to 10 ms /5 ms, i.e. a duty factor of 66%. The SCL, which is an indicator for modulation degree [1], was set to 50% and 0%. The condition 0%SCL corresponds to the condition in which the coil current becomes zero during the off-time, that is, a large modulation degree condition. The pressure was set at 300 torr. Argon sheath gas was fed with a flow rate of 90 L/min. In addition, Ar carrier gas is also supplied with a

*Intervenant

rate of 4 L/min through the water-cooled tube for feedstock feeding. The metal-grade Si powder (99.5%-purity) was used as feedstock. Its mean diameter of feedstock was about 19.2 m. Carrier gas with feedstock was intermittently fed into the torch using solenoid valve as synchronized with the modulated current for the lower coil. The feeding rate of feedstock was set to 3.5 g/min and 5.7 g/min, respectively. Quenching gas flowing into downstream of the plasma torch is not used for simplicity.

The tandem-PMITP could be found to be sustained stably with a feedstock injection with a rate of 5.7 g/min. From FE-SEM images synthesized particles under 0%SCL and 50%SCL conditions, many nanosized particles were obtained. The mean diameters of synthesized particles was estimated as 62.0 nm and 47.4 nm, respectively, for a lower coil modulation condition of 50%SCL and 0%SCL. This indicates that smaller size nanoparticles were obtained by lower SCL condition even without quenching gas injection.
N. Kodama, Y. Tanaka, et al., *J. Phys. D: Appl. Phys.* **47**, 195304(2014)

# Introduction of Molecular Dynamics (MD) as a tool for the investigation of gridded ion thrusters

Karsten Hartz-Behrend*[1] and Jochen Schein[1]

[1]Universitaet der Bundeswehr Muenchen – Allemagne

**Résumé**

Gridded ion thruster (GIE) performance relies on numerous parameters. To be mentioned here are the production, acceleration and neutralization of the produced ion beam, which is responsible for thrust. After ionization the charged particles have to be extracted through a multi grid system, where it is essential that no collisions with the grid material occur.
Hence, a reliable calculation of the ion trajectory is necessary. After leaving the grid system, the produced ion beam needs to be neutralized in order to avoid space charge buildup and spacecraft charging. The beam behavior as well as the interaction with the neutralizing ion beam is thus also of significance to GIE performance. Computational supported particle trajectory predictions should be implemented to enable reliable design of grid system and neutralizer performance and location. This will be introduced here by using Molecular Dynamics (MD).
MD is a computer simulation technique where the time evolution of a set of interacting particles (like atoms, molecules, or ions) based on the fundamental forces between them is followed by integrating their equations of motion, i.e. the $N$-body problem of classical mechanics is solved numerically. At this conference, first results for the temporal development of a xenon ion beam are presented.

*Intervenant

# Determination of residual stress by X-ray diffraction in a weld cordon

Driss Dergham*[2,1]

[2]Centre de développement des technologies Avancées – Algérie
[1]Driss Dergham (LMDM UMC1) – Algérie

**Résumé**

In this study, the implementation of the method for determining residual stresses by X-ray diffraction and apply it to the case of a bead of solder. Welding processes induce changes in the microstructure and residual deformations and stresses that it is so difficult to control that important To study this phenomenon of welding two pieces and low alloy low carbon, were welded to the electrical arc with coated electrode of mild steel. The morphology of the samples was characterized by optical and electron microscopy, showing the significant change in the microstructure in the different area of the cord. The hardness profiles obtained show that the hardness is stable (200 Hv) in the base metal and increases in the cord (230 Hv). In this work, the X-ray diffraction was used to analyze the residual stresses. The results of measurements on the crude sample show that the constraints are all compression, with a higher level in the side region to the cord and in the base metal. The relief annealed at 650 ◦ C relaxes the constraints to a lower level while remaining compressive. These results show that the present solder interesting mechanical and structural characteristics, having regard to the present of residual compressive stresses, the absence of structural defects and cracks. This promotes good

*Intervenant

# Study of electric arc extinction in aeronautical environment

Loïc Hermette*[1], Guillaume Belijar[1], Gaëtan Chanaud[1], Emeric Boliga[1], Yann Cressault[2], and Philippe Teulet[2]

[1]IRT Saint Exupéry – IRT Saint exupéry, IRT Saint-Exupéry – France

[2]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

**Résumé**

Current development of more electrical aircraft and future all electrical aircraft leads to increased power densities and power on board. The increase in power densities takes the form of increased voltage (230/400 Vac, ± 270 Vdc), power (more than 1 MW for the Boeing 787) and/or decreased distances between conductors. Altogether, these evolutions leads to higher probability of arc ignition, particularly in the electric distribution system. Electric arc can have in such confined location is a major concern for aircraft safety (fire, loss of control ...). The aim of this work is to investigate the electric arc behavior ignited between two bus bar and contaminated by different insulating material. The electrical parameters meet the aeronautical standards, i.e. 230/400 Vac at 400 Hz and 800 Hz. A statistical study of the impact of different insulating material on the arc lifetime and power are carried out with the aim to guide the development of passive protections (new insulating material, Arc Fault Circuit breaker...). The electric measurement are compared with high speed camera images of the arc to find a correlation between events and electrical signatures. In a second time a one-dimensional hydrodynamic model has been developed to study arc extinction with different type of mixture, air mix with metal and organic vapours. Radial temperature profiles and radial conductance profiles obtained from the model are calculated during arc decay. The experimental results show a reduction of the electric arcs lifetime in the case of nylon contamination. Moreover, the model shows good agreement with the experimental results.

*Intervenant

# Characterization of laser-induced plasmas

Arnaud Bultel*[1], Aurélien Favre[1], Vincent Morel[1], and Gilles Godard[1]

[1]COmplexe de Recherche Interprofessionnel en Aérothermochimie CORIA – Université de Rouen, CNRS : UMR6614 – France

**Résumé**

**Characterization of laser-induced plasmas**
Arnaud BULTEL, Aurélien FAVRE, Vincent MOREL, Gilles GODARD

*CORIA UMR 6614 – CNRS et Université de Rouen, 76801 St-Etienne du Rouvray, France*

arnaud.bultel@coria.fr

Laser-induced plasma is produced when a high-energy laser pulse is focused on matter in any phase. The electric field within the pulse is sufficiently strong to give momentum to free electrons already present in the sample or to promote free electrons in the case of a dielectric medium by multiphoton ionization. Then the remaining energy is absorbed by these electrons, producing additional energetic electrons by collisions and heating the whole by inverse Bremsstrahlung until temperatures of the order of several 10,000 K. This neutral to plasma transition takes place on some nanoseconds, which leads to an increase in the pressure much higher than the environment's one. The plasma then expands according to a hypersonic regime and cools. The collapse of the collision frequency may lead to a significant departure from Local Thermodynamic Equilibrium (LTE).

The characterization of these plasmas is crucial in terms of departure from LTE since they can be used to perform the multi-elemental composition analysis of samples in the framework of the LIBS (Laser-Induced Breakdown Spectroscopy) diagnostics. Indeed, the LIBS diagnostics is based on the analysis of the emission spectrum, therefore on that of the relative population number density of the upper state of the observed transitions. The relative population number density on the ground state of the components can therefore be determined directly in case of LTE by a simple assumption of the Boltzmann type. If LTE is not fulfilled, the relationship between ground and excited states can only be obtained using a collisional-radiative model, the use and validation of which are rather tricky.

We have analyzed laser-induced plasmas using Optical Emission Spectroscopy on different types of metallic samples (aluminum and tungsten) and gases (argon, air and air saturated with acetone vapors). The different plasmas have been mainly obtained with a lambda_1 = 1064 nm picosecond laser source. The emission spectra exhibit lines mainly broadened by Stark effect whose analysis leads to the determination of the electron density ne. The thorough analysis of the emission spectra has also led to the excitation temperature determination. The influence of the absorption of a second laser pulse of the nanosecond type (double pulse experiments) at lambda_2 = 532 nm has been also studied with respect to

*Intervenant

energy and gate delay.

These measurements have been coupled with the aerodynamic behavior of the obtained plasmas by studying the propagation of the shockwave and of the contact surface between the central plasma and the surrounding shock layer using Laser Shadowgraphy and Schlieren Imagery.

Finally, Laser-Induced Absorption Spectroscopy experiments have been performed. They consist in absorption spectroscopy done on the continuum emitted by a laser-induced plasma produced on the optical axis on the other side of the plasma to be analyzed and delayed with respect to the latter.

# Understanding chemical kinetics of CH4 and C2H2 dissociation by optical emission spectroscopy during graphene nano-flakes production in an inductively coupled plasma reactor

Antaryami Mohanta*[1], Briac Lanfant[1], and Marc Leparoux[1]

[1]EMPA – Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Advanced Materials Processing, Feuerwerkerstrasse 39, CH–3602 Thun, Switzerland – Suisse

**Résumé**

Radio frequency (RF) inductively coupled plasma (ICP) has demonstrated its ability to produce a great varieties of high purity ultra-fine nanoparticles, and has recently been considered for graphene nano-flakes (GNF) production by injecting CH4 precursor into Ar and H2 mixure (Ar/H2) plasma. Although theoretical modelling based on fundamental theory and computational fluid dynamics (CFD) has been made to describe the growth mechanism of GNF, experimental studies on in-situ investigation of induction plasma to understand chemical kinetics of precursor dissociation have not been discussed in detail. We have considered CH4 and C2H2 as precursor and compratively examined Ar/H2/CH4 and Ar/H2/C2H2 induction plasma by optical emission spectroscopy at different synthesis process conditions such as pressure, plate power and CH4 or C2H2 flow rate. The optical emission spectra of both Ar/H2/CH4 and Ar/H2/C2H2 plasma contain emissions from C2 Swan system, CH and C3 radicals which indicate similar pathways for precursor dissociation. The preexisting electrons and atomic hydrogens in Ar/H2 plasma leads to the dissociation through electron impact and dehydrogenation processes. Furthermore, C2 species are generated due to the energy transfer from the excited state argon atoms (Ar*) to the hydrocarbons resulted during dissociation containing C2 and less number of hydrogen such as C2H2 and/or C2H. Besides C2, CH and C3 radicals, a broadband continuum emission is observed in Ar/H2/CH4 plasma emission spectrum at appropriate growth conditions which is an indicator of the particle formation in the vapor phase. For example, at plate power of 15 kW, pressure of 400 mbar and CH4 flow rate of 0.7 slpm, C2 Swan system dominates the emission spectrum with absence of continuum emission that is consistent with no GNF production. At plate power of 15 kW, pressure of 700 mbar and CH4 flow rate of 0.7 slpm, continuum emission dominates the emission spectrum where GNF production rate is 16 mg/min. At 400 mbar, lower thermal gradient in plasma causes no production of GNF. In this condition, C2 species are believed to be converted into hydrocarbons by collision with the hydrogen molecules without producing any allotropes of carbon. The production of GNF is observed at 700 mbar due to condensation of C2 species caused by higher thermal gradient in plasma through homogenoeus nucleation where condensation rate sufficiently exceeds the evaporation rate that causes higher supersaturation and formation of stable particles. At optimized growth condition, the maximum GNF production rate achieved is 165 mg/min. C2H2 is injected under same condition as that of CH4 i.e. at plate power of 15 kW, pressure of 700 mbar and

*Intervenant

C2H2 flow rate of 0.7 slpm and the corresponding emission spectrum of Ar/H2/C2H2 plasma is analyzed. Careful comparison of emission spectra between Ar/H2/C2H2 and Ar/H2/CH4 plasma reveals that C2 Swan system dominates the emission spectrum of Ar/H2/C2H2 plasma where continuum emission is absent that is consistent with zero production. On the other hand, continuum emission dominates the Ar/H2/CH4 plasma emission spectrum. The C2 vibrational temperature is 6200 K in Ar/H2/C2H2 plasma which is much larger than that of 3500 K in Ar/H2/CH4 plasma. The higher C2 vibrational temperature in Ar/H2/C2H2 than that in Ar/H2/CH4 betokens that less energy is consumed in dissociating C2H2 than CH4 to result C2 species which supports the concept of aforementioned energy transfer process from Ar* to C2H2 and/or C2H.

# Challenges in modelling of non-equilibrium transport processes in high-pressure thermal plasmas

Heping Li*[1], Heng Guo[1], Wen Zhou[2], Jian Chen[1], Jing Li[1], and Zeng-Yao Li[2]

[1]Department of Engineering Physics, Tsinghua University, Beijing 100084, P. R. China – Chine
[2]Key Laboratory of ThermoFluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, P. R. China – Chine

**Résumé**

Promoted by large-scale industrial applications of thermal plasmas, considerable advances have been achieved during past decades in theoretical and experimental investigations on the complicated fundamental processes in arc discharges. Previous results indicated that the interaction between the arc and electrode plays a significant role for producing and sustaining the arc discharges in which the sheath region with extremely small spatial scale and large parameter gradient deviates from the local thermodynamic and chemical equilibrium states and charge neutrality condition [1,2]. Due to the small spatial scale and large parameter gradients within the sheath, there exists a strong electric field inside the sheath which leads to complicated potential, current density and heat flux distributions. Meanwhile, experimental measurements are hardly employed to study the effect of the sheath behavior on the characteristics of the high-pressure thermal plasmas. Therefore, numerical simulation has become a powerful tool for investigating the non-equilibrium transport processes in thermal plasmas with the fast development of the computer hardware and software.

In this study, we first review our recent work on the numerical studies concerning the non-equilibrium transport processes in a thermal plasma system. In the first case, a two-dimensional non-equilibrium model combining a thermal-chemical non-equilibrium fluid model for the quasi-neutral plasma region and a simplified collisionless sheath model for the electrode sheath region was employed to reveal the non-equilibrium synergistic effects in an atmospheric argon arc plasma [3]. In the second case, a 1D3V (one-dimensional in space and three-dimensional in velocity) implicit particleincell Monte Carlo collision (PIC-MCC) method was used to study the cathode sheath also in an atmospheric direct-current arc plasma [4]. Based on these modeling results, the sheath characteristics obtained from the analytical model in the first case and those from the kinetic model in the second case are compared with each other. It is shown that, on one hand, both the kinetic model and the analytical model can provide the information on the heat flux, current density and temperatures along the plasma-sheath and sheath-electrode interfaces; while on the other hand, only the kinetic model can provide the spatial profiles of the potential, species number densities, and in particular, the energy distributions of electrons and ions inside the sheath. The predicted spatial distributions of the preceding key plasma parameters indicate that the plasma inside the sheath is in a complete non-electrical-thermal-chemical equilibrium state, and the energy distribution functions of electrons and ions both deviate from the Maxwellian distributions. In our opinion, it is a big challenge to investigatge the synergistic non-equilibrium mass, momentum and energy transport processes based on a combined hydrodynamic and

*Intervenant

PIC-MCC model for a thermal plasma system in future research.

**References:**

R. N. Franklin, J. Phys. D: Appl. Phys., 2003, 36: R309.

M. S. Benilov, Plasma Sources Sci. Technol., 2009, 18: 014005.

H. Guo, X.-N. Zhang, J. Chen, H.-P. Li, K. Ostrikov, Sci. Rep., 2018, 8: 4783.

W. Zhou, H. Guo, W. Jiang, H.-P. Li, Z.-Y. Li, G. Lapenta, Plasma Sources Sci.Technol., 2016, 25: 05LT01

**Acknowledgement:**

This research has been supported by the National Natural Science Foundation of China (11775128).
* Corresponding author: liheping@tsinghua.edu.cn.

# Overview of the ITER Research Plan and the Challenges Ahead

Timothy Luce*[1]

[1]ITER Organization – ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, F-13067 St Paul Lez Durance Cedex, France – France

**Résumé**

The ITER tokamak, now under construction in France, represents an essential step toward a practical technical demonstration of fusion energy. Realizing the full potential of the facility will require vigilance during the present manufacturing and construction activity, then careful planning and execution of the commissioning phase to prepare for full nuclear operation of the facility. A brief overview of the project and the status will be given, highlighting the unique nature of the ITER facility. Using an activity-based metric, $> 50\%$ of the work required to reach First Plasma has been accomplished. First examples of all of the major components of the tokamak (cryostat, vacuum vessel, magnetic coils) have been fabricated, and major systems (steady-state and pulsed electrical power, cooling water, and cryogenic systems) are under construction on site. The present plan projects Integrated Commissioning to begin in 2025, culminating in achieving First Plasma by the end of the year. Following this discussion, the scientific and technological objectives of the project will be presented, tracing these back to features of the facility capabilities or size, when possible. The fundamental physics objectives of ITER are twofold. One of the two objectives is to sustain a plasma generating 500 MW of fusion power with an energy gain of 10 for more than 300 s. The second is to demonstrate in-principle steady-state operation with an energy gain of 5. An overview of the ITER Research Plan, which has recently been updated for the revised timeline for delivery of various systems, will be provided. That Plan describes the present vision for how these project objectives will be achieved. The objectives at each stage of the Plan will be discussed. As part of the overview of the Plan, key physics and technology R&D issues that can be addressed in existing research programs will also be presented.

*Intervenant

# 3D simulation of a point to plane air corona discharge

Olivier Eichwald*[1], Olivier Ducasse[1], and Joseph Marie Plewa

[1]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – Université Paul Sabatier [UPS] - Toulouse III, Université Paul Sabatier (UPS) - Toulouse III – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

**Résumé**

Positive corona discharges generated between a point and a grounded plane show a large tree structure composed of multiple streamers that propagate simultaneously between the electrodes. In the present conference, new results coming from a 3D simulation using the High Performance Computing (HPC) managed with the Message Passing Interface (MPI) library are presented. The streamers development and interactions are followed using the classical first order fluid model and the photo-ionisation is taken into account with an initial background electronic density. The set of the strongly coupled equations are discretized using the Finite Volume Method (FVM). The 3D MUSCL superbee scheme and an optimized SOR method are implemeted to solve the transport fluxes of charged species and the Poisson equation, respectively. The study is focussed on the development of several streamers in ambient air until they reach the cathode plane with a gap distance of millimetre order. The results are analysed through the electronic density and the electric field.

*Intervenant

# Control and Stabilization of Flames with Plasma Assistance

Christophe Laux*[1]

[1]Laboratoire d'Énergétique Moléculaire et Macroscopique, Combustion – CentraleSupélec, Université Paris-Saclay, Centre National de la Recherche Scientifique : UPR288 – France

**Résumé**

Hydrocarbon-based fuels will represent the main energy source for automotive and aeronautical transportation on a worldwide scale for the foreseeable future. However, increasingly stringent regulations force manufacturers to improve engine technologies to reduce pollutant emissions and greenhouse gases. To achieve these goals, strategies based on the combustion of fuel-lean mixtures or fuel-air mixtures diluted by exhaust gas recirculation [1] have been proposed However, lean or diluted combustion slows the reaction kinetics, leading to irregular ignition, flame instabilities, or incomplete combustion. Thus, a major challenge is to ensure reliable flame ignition and to maintain stable combustion in lean or diluted mixtures. To address these challenges, several innovative plasma technologies have been proposed. Plasma discharges provide an effective way to produce high concentrations of reactive species (radicals, excited species, ions, electrons) to promote combustion kinetics with a small amount of electrical energy [2]. Beneficial effects have been observed in laboratory-scale burners under the action of corona [3,4], microwave [5], gliding arc [6], nanosecond repetitively pulsed [7-9], dielectric barrier [10-11], or volume nanosecond [12-13] discharges.
We report here on nanosecond repetitively pulsed (NRP) discharges which, compared to single pulse nanosecond discharges, present the advantage of producing strong synergistic effects from pulse to pulse, and which can be used in continuous operation. Based on results of fundamental studies, we illustrate the chemical, thermal and hydrodynamic effects of NRP discharges in plasma-assisted combustion. These discharges are shown to produce large amounts of atomic oxygen, with nearly full dissociation of molecular oxygen in the interelectrode gap, as well as some degree of gas heating. The isochoric energy deposition mechanism also induces strong hydrodynamic effects that help redistribute the reactive products over a large volume, effectively enhancing combustion through oxidation reactions and chain propagation reactions. The relative importance of these thermal and chemical effects will be discussed. Then we will present illustrative examples of effective plasma stabilization by NRP discharges in small and medium-scale combustors. These results demonstrate that plasma-assisted combustion is a promising method to improve combustion performance over a wide variety of conditions, but also suggest that additional research is required to translate their utilization in industrial-scale combustors.

References

A.H. Lefebvre, Gas Turbine Combustion, Taylor and Francis, Philadelphia, (1999).

A. Starikovskiy, N. Aleksandrov, Prog. En. Comb. Sci., 39(1) (2013) 61-110.

F. Wang, J.B. Liu, J. Sinibaldi, C. Brophy, A. Kuthi, C. Jiang, P. Ronney, M.A. Gundersen,

*Intervenant

IEEE Trans. Plasma Sci., 33(2), (2005) 844-849.

M. Bellenoue, S. Labuda, B. Ruttun, J. Sotton, Comb. Sci. Tech. 179 (2007) 477-496.

I.I. Esakov, L.P. Grachev, K.V. Khodataev, V.A. Vinogradov, D.M. Van Wie, IEEE Trans. Plasma Sci., 34(6) (2006) 2497-2506.

A. Fridman, A. Gutsol, S. Gangoli, J. Propulsion and Power, 24(6), (2008) 1216.

S. Pancheshnyi, D.A. Lacoste, A. Bourdon, C.O. Laux, IEEE Tr. Plas. Sci. 34 (2006) 2478-2487.

G. Pilla, D. Galley, D.A. Lacoste, F. Lacas, D. Veynante, C.O. Laux, IEEE Trans. Plasma Sci. 34 (2006) 2471- 2477.

W. Kim, H. Do, M.G. Mungal, M.A. Cappelli IEEE Trans. Plas. Sci. 34(6) (2006) 2545-2551.

N.B. Anikin, I.E. Mintoussov, S.V. Pancheshnyi, D.V. Roupassov, V.E. Sych, A.Yu. Starikovskii, 41st AIAA Aerospace Sciences Meeting, 2003-1053, Reno (2003).

K. Criner, A. Cessou, J. Louiche, P. Vervisch, Comb. Flame, 144 (1-2), (2006) 422-425.

S.A. Bozhenkov, S.M. Starikovskaia, A. Yu. Starikovskii, Comb. Flame, 133 (2003) 133-146.

A. Bao, Y.G. Utkin, S. Keshav, G. Lou, I.V. Adamovich, IEEE Trans. Plas. Sci. 35 (2007) 1628.

# Matrix Impact On Bacterial Biofilms Response and Resistance To Cold Plasma Treatments

Frédéric Marchal*[1], Maritxu Labadie[2], Elisabeth Girbal-Neuhauser[3], Catherine Fontagné-Faucher[4], Nofel Merbahi[5], and Claire-Emmanuelle Marcato-Romain[6]

[1]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – CNRS : UMR5213, Université Paul Sabatier - Toulouse III, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[2]Laboratoire de Biologie Appliquée à lÁgroalimentaire et à lÉnvironnement – Université Paul Sabatier - Toulouse 3 – France

[3]Université Paul Sabatier-Toulouse III [Toulouse] (LBAE) – Université Paul Sabatier (UPS) - Toulouse III – 118 Route de Narbonne 31062 Toulouse, France

[4]Laboratoire de Biologie Appliquée à l'Agroalimentaire et à l'Environnement (LBAE) – IUT A, Université Paul Sabatier - Toulouse III : EA4565 – 24 rue d'Embaquès 32000 AUCH, France

[5]LAPLACE-CNRS University of Toulouse (LAPLACE-CNRS Toulouse) – CNRS : UMR5213, Université Paul Sabatier - Toulouse III – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[6]Laboratoire de Biotechnologies Agroalimentaires et Environnementales (LBAE EA 4565) – IUT A, Université Paul Sabatier - Toulouse III – 24 Rue d'Embaquès, 32000 Auch, France

**Résumé**

Over innovative physical treatments for biofilm eradication, cold atmospheric-pressure plasma (CAP) have been described in several recent studies to have promising applications in industrial, food and health domains. The aim of the present work was then to study the effect of a CAP device on two model bacterial biofilms, a Gram-positive and a Gram-negative bacteria, which present different extracellular polymeric matrix. The studied bacterial strains were *Pseudomonas aeruginosa* ATCC 15442 and *Leuconostoc citreum* NRRL B-1299; this latter presents the distinctive feature to produce high level of extracellular glucans only when grown on sucrose-containing media, allowing to supplement the biofilm matrix in a controlled way. The biofilms were formed on porous membrane coupons fit on solid agar media, with controlled level of bacterial cells; the matrix composition was evaluated by infrared spectroscopy (FTIR). The corona discharge plasma device used in this study generates a low-temperature air plasma jet at ambient pressure and temperature, and mainly produces oxygen and nitrogen reactive species. Both surface-spread bacteria and 24-hour biofilms were exposed to different times of CAP treatment; the bacterial inactivation was evaluated by conventional cell count. Cells in 24-hour biofilms were less sensitive to plasma than surface-spread bacteria. Indeed, we could observed a 2.5 log10 reduction of surface-spread cells from 10 minutes of plasma treatment for both *P. aeruginosa* and *L. citreum.* In contrast, *P. aeruginosa* cell reduction was less than 0.2 log10 even after 20 minutes when cells were in biofilm form, with a protein-rich matrix. Otherwise, *L. citreum* biofilms formed without sucrose showed a cell reduction of only 1.5 log10 at the same time, but less than 0.5 log10 when extracellular glucans were present in the matrix. These results suggest that the extracellular matrix in which biofilm cells are embedded is likely to affect plasma sensitivity.

*Intervenant

# Plasma spraying at very low pressure (VLPPS): Model development and experimental validation beyond continuum conditions

Georg Mauer*[1], Dmitrii Ivchenko*[2], Gilles Mariaux[2], Armelle Vardelle[2], Simon Goutier[2], Tatiana Itina[3], Cong Zhao[1], and Robert Vassen[1]

[1]Forschungszentrum-Jülich GmbH, Institute of Energy and Climate Research (IEK-1) – Allemagne
[2]CNRS, IRCER, UMR 7315 – Université de Limoges – France
[3]Laboratoire Hubert Curien, CNRS – Université de Lyon — UJM St-Etienne – France

**Résumé**

Very Low Pressure Plasma Spraying (VLPPS) was developed on the basis of conventional Low-Pressure Plasma Spraying processes (LPPS, often termed as vacuum plasma spraying, VPS) operating at 5-20kPa. LPPS is mainly used to avoid the oxidation of the substrate and processed powder during the deposition process, or to spray very specific metals like beryllium. Typical operating conditions for VLPPS involve a lower chamber pressure ranging from 50 to 200 Pa and higher arc current up to 3 kA with a power level up to 150 kW and more. As long as the coating deposition is dominated by the liquid phase, thin and dense coatings can be manufactured, for example for gas separation membranes or electrolyte functional layers. However, if appropriate operating parameters and powders are selected, the feedstock material can be evaporated so that coatings are made out of the vapor phase. In this case, the process is termed Plasma Spray-Physical Vapor Deposition (PS-PVD) and makes it possible to manufacture columnar, strain-tolerant microstructures for thermal barrier coatings.
Under these conditions, the high-enthalpy plasma jet expands to a length of 1 to 2 m with a diameter of 0.2 to 0.4 m. The flow velocities are initially supersonic leading to the formation of typical series of expansion and compression cells. Moreover, high Knudsen numbers indicate the breakdown of continuum conditions in such rarefied flows. These peculiar plasma flow characteristics are challenging for modelling VLPPS. However, this is essential to better understand and optimize the process.

In this work, two numerical simulation models of the VLPPS process were developed: a continuum Computational Fluid Dynamic simulation (CFD) approach and a discrete molecular one (Direct Simulation Monte Carlo, DSMC). Two different plasma gas compositions (Ar and Ar+H2) were considered. To experimentally validate the model approaches, Optical Emission Spectroscopy (OES) was performed. Based on peak broadening analyses, electron densities as well as the temperatures of electrons and heavy species were determined in cross-sections of the plasma jet at 500 and 800 mm downstream the nozzle exit. Specific difficulties of separating the different broadening mechanisms are discussed.
The results are compared and discussed. In particular, the importance of considering the effects of the continuum breakdown is examined. Furthermore, images of the expanding plasma jet were taken, and the visible radiation intensity distributions were compared to the shock distribution shown by predicted temperature fields.

*Intervenant

# Characterization of a Helicon Plasma System for Deposition of Thin Film Coatings and for Surface Modification

German Cota*[1], Daniel Turgeon[1], and John Wills[2]

[1]Fuel Development Branch, Canadian Nuclear Laboratories, Chalk River, Ontario, Canada – Canada
[2]Atomic Energy of Canada Limited (Retired), Chalk River, Ontario, Canada – Canada

**Résumé**

Abstract
A Helicon Plasma System has been recently developed at Canadian Nuclear Laboratories to perform a variety of plasma processing experiments on nuclear materials, including surface modification, deposition of thin film coatings, and etching. Due to the high ionization efficiency and low temperature, helicon plasmas are well suited for processing materials whose microstructures are susceptible to changes at high temperatures.

Experimental studies focused on the characterization of plasma properties at different plasma conditions will be presented. The Helicon Plasma System includes a quartz plasma chamber, a Nagoya type III antenna powered by a 1.2-kW, 13.5-MHz radio frequency (RF) power supply, a solenoid powered by a 1.5-kW direct current (DC) power supply, and a stainless steel chamber equipped with a sample holder. A Langmuir probe diagnostic system and an optical meter were used to determine the effect of operating parameters on the plasma properties.

Characterization experiments were performed using argon as plasma gas, a plasma chamber pressure of 4.0x10-5 mbar and gas flowrate of 0.60 sccm. Well-defined current-voltage ($I$-$V$) curves were obtained at various distances from the plasma aperture, and ion and electron densities, and electron temperature were determined. The electron density at about 1.4 cm from the plasma aperture (substrate location) was also determined using two different plasma operating modes: the helicon and the inductively coupled plasma (ICP) operating modes. In the helicon mode, a 300W RF power was applied to the antenna and 15A direct current was applied to the solenoid to achieve an electron density of about 5.4x108 cm-3. In the ICP mode, 300W RF power was applied to the antenna and no power was applied to the solenoid. An electron density of about 8.7x107 cm-3 was determined in this mode.
The plasma characterization results show that at the same plasma operating conditions, higher ionization efficiencies are achieved in the helicon plasma operating mode than in the ICP operating mode.

*Intervenant

# Reduction in size and quantity of by-product particles using a low-pressure plasma reactor in SiO2 thin film deposition

Jae-Ok Lee*[1], Jin-Young Lee[1], Seok Jun Suh[1], Dae Woong Kim[1], Woo Seok Kang[1], and Min Hur[1]

[1]Korea Institute of Machinery  Materials – Corée du Sud

**Résumé**

Thin film deposition remains large amounts of by-product particles in a deposition chamber, from which they are exhausted during the cleaning step. A part of by-product particles, especially with large sizes, accumulates inside a vacuum pump, which reduces its lifespan1, 2. We carried out feasibility test of increasing the vacuum pump lifespan with a low-pressure plasma reactor. Our plasma reactor, characterized by a cylindrical high-voltage electrode, was placed downstream of PECVD equipment (P-5000, Applied Materials) where SiO2 thin film was deposited using TEOS[Si(OC2H5)4] and O2. Paschen curve was obtained as a function of the pressure and gap distance in cleaning gas, He/NF3/O2. The size distribution of by-product particles, collected on a particle sampler positioned before the vacuum pump, was compared between the plasma-on and plasma-off by using a scanning electron microscopy (SEM). The chemical composition of by-product particles was analysed by using an energy dispersive spectroscopy (EDS). Finally, the applicability of low-pressure plasma technology to an increase in vacuum pump lifespan was discussed on the basis of the experimental results.

References

M. Hur, J. O. Lee, W. S. Kang, and Y. -H. Song, "Low-pressure plasma after-treatment of pollutants emitted during semiconductor manufacturing", *Plasma Process. Polym.* **12** 583 (2015)

M. Hur, J. O. Lee, W. S. Kang, and Y. -H. Song, "Low-pressure plasma reactor with a cylindrical electrode for eco-friendly processing in the semiconductor industry", *Plasma Chem. Plasm Process.* **34** 1187 (2014)

*Intervenant

# Effects of discharge voltage and current on PFCs treatment process in an elongated arc reactor

K-T Kim1*[1], D. H. Cho1[1], D. R. Lee2[2], S. K. Jo1[1], D. H. Lee1[1], and Y-H Song1[1]

[1]Plasma Laboratory, Korea Institute of Machinery and Materials, 156 Gajeongbuk$_ro, Yuseong - gu, Daejeon34103, RepublicofKorea - -CoréeduSud$

[2]Department of Bio-Environmental Energy, Pusan National University, 2 Busandaehak-ro, Geumjeong-gu, Busan, Republic of Korea – Corée du Sud

**Résumé**

Perfluorocompounds (PFCs) have a higher value of the global warming potential than CO2. In this reason, PFCs were classified as non-CO2 green house gases and should be treated properly in semiconductor fabs [1]. Although conventional burn-type scrubbers are used on sites, because of unwanted secondary emissions, such as NOx, as well as its low removal efficiency, numerous plasma techniques for treating PFCs have been proposed [2]. However, non-thermal plasmas, such as DBD and pulsed corona, were not suitable for this purpose because these plasmas have relatively low gas temperature, though these have energetic electrons. On the other hand, considering high temperature plasmas, such as DC arc torches, high consumption of electricity and a low life-time of electrode will be problems to be adopted in a real system. In this study, CF4 treatment is investigated using an elongated arc reactor to have advantages of the both non-thermal and thermal plasmas.

As shown in the figure 1, the reactor consists of an inner conical high voltage electrode and an outer cylinder electrode. Initially an arc will be ignited at the shortest distance between electrodes (A-B), and owing to the convective flow effect it stabilizes at the longest distance (C-D).

Generation of this high temperature field could depend on the degree of the arc elongation [2-4]. To optimize the reactor geometry, we checked the effect of geometrical parameter, such as arc length (say, distance between C-D), on the removal efficiency.

In this experiment, effects of voltage–current characteristics on the discharge were investigated in an elongated arc reactor driven by two kinds of power supplies with different operational regimes. One power supply type A provides relatively higher voltages and lower currents than the other type B.

Our results could be used as a guide for the design of a practical and highly efficient elongated arc reactor.

Figure 1. Schematic of the elongated arc reactor

References

*Intervenant

W-T Tsai, H-P Chen, and W-Y Hsien 2002 A review of uses, environmental hazards and recovery/recycle technologies of perfluorocarbons (PFCs) emissions from the semiconductor manufacturing processes Journal of Loss Prevention in the Process Industries 15 65-75

K-T Kim, D. H. Lee, J-O Lee, M. S. Cha, and Y-H Song 2009 CF4 Treatments Using an Elongated Arc Reactor ISPC 19

N. K. Hwang, M. Hur, and Y-H Song 2011 Effects of Voltage-Current Characteristics on the Discharge Images in an Arc Reformer IEEE Trans. Plasma Sci. 39 2874–5

S Pellerin, J-M Cormier, F Richard, K Musiol, and J Chapelle 1999 Determinations of the electrical of a by dimensional d.c. Glidarc Appl. Phys. 32 891–897
* This work was supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIP) (No. CRC-14-1-KRICT)

# Densities of active species in R/N2 and R/N2-x%H2 (R = Ar or He) microwave early afterglows

Andre Ricard*[1]

[1]Univ paul sabatier LAPLACE (UPS) – Laplace – France

**Résumé**

**Densities of active species in R/N2 and R/N2-x%H2 (R = Ar or He) microwave early afterglows**
A. Ricard and J.P. Sarrette

LAPLACE, Université de Toulouse, CNRS, INPT, UPS 118 route Narbonne, 31062 Toulouse Cedex 9, FRANCE

*Thème 3 – Advances and challenges in plasma diagnostics*

Flowing afterglows have previously been studied [1] in N2 and Ar-N2 gas mixtures to produce N2 active species such as N-atoms, N2(A), N2(X,v > 13) metastable molecules and N2+ ions. The interest of flowing afterglows is to select N2 active species downstream the plasma, that is in conditions close to room temperature and without electric field. In long time afterglows (late afterglows), at times of 10-2-10-1 s, the dominant N2 active species are the N-atoms. At short times of 10-3-10-2 s (early afterglows), N2(A), N2(X,v > 13) metastable molecules and N2+ ions must be added to the N atoms.

Ar-N2 gas mixtures were previously studied [1] as they are easier to ionize than pure N2, producing a longer plasma column. It is presently compared the production of N2 active species in the early afterglows of Ar-N2 and He-N2 microwave plasmas at a constant gas pressure of 8 Torr, a flow rate of 1slm in a dia. 18 mm post-discharge tube at distances of 3 and 20 cm (times 10-3–3 10-2 s) and a transmitted power of 150 Watt. The interest of N2 dilution into Ar and He is to increase the electron energy in the plasma by avoiding the electron vibrational barriers at 3 eV in pure N2. The electron energy should be higher in He plasmas as a result of a lower electron excitation cross section (_˜ 3 10-18 cm2) compared with Ar (_˜ 3 10-17 cm2) and N2 (_˜ 3 10-16 cm2) and a higher excitation threshold (19 eV in He and 12 eV in Ar).

A pre-mixed N2-5%H2 mixture was also introduced in place of pure N2 to produce NH radicals and H-atoms in addition to the N2 active species.

Absolute concentrations of active species are deduced from optical emission spectroscopy (OES) after NO titration and simplified chemical schemes. In R/N2-x%H2 (R = Ar or He)

*Intervenant

mixtures, the NH radical and H-atom densities are evaluated by considering that the excitation of the NH(A) radiative states in the afterglow is produced by N2(X,v> 13) + NH collisions.

It appears that the He/N2-5%H2 gas mixture could give about the same order of N and H-atom densities. The interest of these results concerns the enhancement of surface nitriding by combination of N and H atoms in afterglow conditions.
H. Zerrouki, A. Ricard and J.P. Sarrette, (2014) *Contrib. Plasma Phys.*, **54**, 827-837 and *J. Phys.:Conf. Series,* **550**, 012045.

# An electric arc upon opening contacts of a low-voltage switch model.

Jessica Almurr*[1], David Rochette[2], and William Bussière[3]

[1]Laboratoire de Physique de Clermont – Université Clermont Auvergne : UMR6533, Centre National de la Recherche Scientifique : UMR6533 – France

[2]Laboratoire Arc électrique et plasmas thermiques (LAEPT) – Université Blaise Pascal - Clermont-Ferrand II – bat. Physique 5 24 Av des landais 63177 AUBIERE CEDEX, France

[3]Laboratoire Arc électrique et plasmas thermiques (LAEPT) – Université d'Auvergne - Clermont-Ferrand I – bat. Physique 5 24 Av des landais 63177 AUBIERE CEDEX, France

**Résumé**

Abstract: An electric arc upon opening contacts of a low-voltage switch model. This work is devoted for studying the electric arc behavior in a low-voltage electronic switch during the opening of its contacts. The problem is solved theoretically by developing a magneto-hydrodynamic MHD approach, then a 2D time dependent model is built using COMSOL Multiphysics software. The model implements the DC switch-off technique used in LBS (load switch breaker) with magnet technologies. This work is collaboration between the Socomec research group and the Physics Laboratory of Clermont (LPC).

In our study, the switch is used to conduct and interrupt a DC electric current in a RL circuit supplied by a 600 V under normal conditions in charge. Besides, the DC breaking technique consists on creating an electric arc between the electrodes while they are opening, and increasing its voltage so that the arc's potential is greater than the supplied voltage.

Since the electric arc is conductive and has its own resistivity, its voltage can be increased when its length increases. Thus, elongating arc decreases its temperature on one hand, and increases its resistance on the other hand, elevating its conduction voltage. Opening the contacts allows the creation and the elongation of the electric arc between them, and then the elongation is enhanced due to magnetic fields of the magnet. The electrodes of the contact open in a transitional motion with a high speed. Modeling the contacts motion and the elongation of the arc generated between them is the main part of our work.

Electric arcs are thermal plasmas that move under the action of Lorentz and aerodynamic forces. They are assumed to be in local thermodynamic equilibrium (LTE). This phenomenon could be described with a system of magneto-hydrodynamic equations (MHD). The MHD approach contains the 3 Navier-Stokes conservation equations for energy, momentum and mass; the equation of current continuity supplemented with Ohm's law and the equation for vector potential. These equations are implemented using electric, magnetic and fluid interfaces in COMSOL, the contacts motion is modeled using moving mesh interface. A simplified geometry of the dimension 70x70mm is used in order to reduce the complexity of the simulations. The electrodes are of 30 mm length and 3 mm width, the gap between them

*Intervenant

is 6 mm. The contacts open with a velocity 10 m/s. Moreover, an outlet at the end of the chamber connects the inner air volume with the atmosphere. Additionally, a large air domain with a diameter of 70 mm is set around the bus-bar electrodes in order to assume a magnetic insulation of the potential vector away from the arc chamber. As the large air domain costs more calculation, the meshing discretization between the plasma domain near the electrodes and the air domain far away from them needs to be compromised. The arc is connected to a RL circuit and supplied with a generator of 600 V for duration of 1 millisecond. This circuit is implemented in our model. Finally, the temperature and the current density distributions of the plasma in different time moments are presented. It is worth to note that modeling the electric arcs with a moving mesh in COMSOL Multiphysics software is a pioneer work.

# Experimental characterization of double pulse laser-induced plasmas.

Aurelien Favre*[1], Vincent Morel[1], Gilles Godard[1], and Arnaud Bultel[1]

[1]CORIA – Université de Rouen - Normandie et INSA de Rouen - Normandie – France

**Résumé**

Laser-induced plasmas can be used to determine the multi-elemental composition of solid, liquid or gaseous samples. Using a pulsed laser beam focused on the sample, the resulting absorption leads to temperature increase of several 10,000 K, therefore to a neutral phase to plasma transition. During the relaxation phase over which the recombination takes place, a continuum then lines radiation is emitted. Its analysis based on Optical Emission Spectroscopy (OES) may lead to the composition of the plasma, therefore to that of the sample if fundamental assumptions are fulfilled. The most restrictive one is the achievement of the Local Thermodynamic Equilibrium (LTE). Indeed, since only OES is used, the excited states number density is determined. Then, the ground states number density is obtained if LTE is observed and if electron temperature T_e is known, the electron density n_e being enough high. The characterization of LTE is therefore one of the key points of this analysis method, also known as Laser-Induced Breakdown Spectroscopy (LIBS).

For particular cases such as low elemental mole fraction in the sample or species difficult to excite, double pulse experiments may lead to significant improvements in terms of limit of detection. It consists in irradiating the plasma produced by a first laser pulse by a second one, whose duration, energy wavelength... may be different from the first laser pulse. The gate delay between the two pulses plays a very important role. The first pulse produces the plasma and the second one enables its heating until temperature higher than in the case where the total energy is put within a single pulse.

We have performed experiments in such configurations. The first pulse (1064 nm, 30 ps, 14 mJ) is used to produce plasmas in air, or on metallic samples (aluminum, tungsten) using a lens of 10 cm in focal length. The second pulse (532 nm, 6 ns, 65 mJ) is focused later (Dt of gate delay) with a second lens of 15 cm in focal length on the plasma produced by the ps laser pulse. The beam directions are perpendicular to each other. The characterization of the laser-induced plasmas is performed according to Dt. They enable the time evolution of the total radiance, n_e and T_e by a thorough spectroscopic study. They put into light the benefit of the use of this type of configuration.

*Intervenant

# Supersonic Plasma Deposition of Zinc Oxide Nanostructured Thin Films

Elisa Dell'orto*[1], Silvia Freti[1], and Claudia Riccardi[1]

[1]Dipartimento di Fisica - Università di Milano-Bicocca – Italie

**Résumé**

Recently there has been an increasing interest in the nanostructured thin films. They have successfully been applied in various fields, such as electronics, photovoltaics, environmental protection and chemical industry. A nanostructured thin film, depending on its nanostructures constitution, shows different electrical and optical properties rather than its crystalline counterpart. To maximize the advantages of this technology it is possible to study and develop processes capable of producing nanostructured thin films of desired characteristics by acting on the clusters which, once deposited, allow the growth. In general, at the nanoscale, the exposed surface appears to be much greater than the thickness of the structures, making the film excellent for increasing efficiency of the surface processes as, for example, the chemical reactivity of the material. The zinc oxide is a semiconductor having a direct band gap of 3.37 eV, in the ultraviolet region.
In the present work an innovative method of deposition of zinc oxide nanostructured thin films is proposed. Changing the process parameters, different degrees of purity and uniformity of the films can be obtained, as well as different morphologies. The deposition system is a patent designed and developed at the Centro PlasmaPrometeo of the University of Milano-Bicocca. This method aims to combine the versatility of the deposition processes mediated by plasma with systems of controlled aggregation of clusters, separating into two distinct phases the process of the creation of zinc oxide and the growth of thin films on the substrate. The reactor is constituted by two vacuum chambers, in order to decouple the deposition procedure. In the first chamber a very reactive inductively coupled plasma of argon and oxygen is ignited through a radio frequency signal. Subsequently a metalorganic precursor in gaseous form is first injected and then dissociated in the plasma, to obtain zinc oxide nanoparticles. The second chamber, at a lower pressure, is connected to the first one through a nozzle, which extracts a supersonic jet of plasma seeded by the particles to be deposited. The jet then impacts on the desired substrate, allowing the deposition of the clusters formed and thus the growth of a nanostructured thin film. In this way, the reactions that take place in the plasma phase are decoupled from aggregation phenomena that occur during the supersonic expansion. The latter allows the deposition of clusters on the substrate and the oriented jet favors the growth of columnar structures.

The low collisionality of particles in the jet also allows the creation of nanostructures of very small size.
The plasma analysis was carried out by optical emission spectroscopy, through which it was possible to evaluate the chemical composition inside the plasma chamber, the generation of radical oxygen, the production of ions and electrons and the precursor flow. Thin films

*Intervenant

achieved in different configurations were characterized by profilometry analysis in order to evaluate the deposition rate and the films thickness, as well as their uniformity. ATR/FTIR spectroscopy was performed to identify their chemical composition and therefore their purity. Using Raman spectrometry it was possible to confirm the wurtzite structure of the deposited zinc oxide. The ATR/FTIR analysis was used to correlate the presence of groups –CH and -CO in the deposits with the experimental conditions. The AFM analysis showed grain size of the order of tens nanometers and a good surface uniformity.

# Experimental arc root sweeping simulation and motion tracking for aeronautics applications

Clement Zaepffel*[1] and Rafael Sousa Martins[1]

[1]DPHY, ONERA, Université Paris Saclay, F-91123 Palaiseau - France – ONERA – France

**Résumé**

Arc sweeping occurs during the lightning strike of an aircraft. A lightning stroke may last one second. Due to the aircraft movement, its surface is swept by the arc root. During this phase, intensity of the arc is of a few hundred amperes. Simulation of this phase was done previously in our team but without experimental validation [1].
We improved a previously developed generator to produce similar DC current under 1600 V and study this lightning phase. This system permits the generation of long arc at atmospheric pressure ranging from 10 to 40 cm and the observation of tortuous arc shape. We propose here a study with a lower velocity of the arc root compare to in flight measurement but with geometry already present in the literature allowing a comparison and a discussion. The two studied geometry are parallel bars and bar/plane. In the case of the parallel bars, due to the Laplacian forces, the arc moved along the bars. Its movement reach a velocity of a few 10 m/s in the air. This velocity is smaller than the velocity obtained during a flight due to the movement of the aircraft but permits the validation of several diagnostics such as electrical measurement, high speed imaging and image tracking technics.
We selected copper and tungsten material for the bars and the plan used in the second configuration is made of aluminium. We obtained the velocity of the arc root on anode and cathode for several conditions of current and gap distance and compare it to other studies. We observed similar behaviour to the literature with "jump" movement on the anode and "smooth" movement on the cathode. By measuring voltage and current, we deduced the resistance of the arc column and corrected it from the electrode voltage drop. In a final part, this resistance value is used to design a wind tunnel experiment and define an arc length limit potentially achievable by the generator.

*Intervenant

# Chemical analysis of Plasma Activated Water using Gliding Arc Discharge at atmospheric pressure: influence of the water content on the activation process

Maxime Wartel*[1], William Desdions[1], François Faubert[1], Nadia Pellerin[2], Stéphane Pellerin[1], and Catherine Stride[3]

[1]Groupe de recherches sur l'énergétique des milieux ionisés – CNRS : UMR7344, Université d'Orléans – France

[2]Conditions Extrêmes et Matériaux : Haute Température et Irradiation (CEMHTI) – CNRS : UPR3079 – 1D avenue de la recherche scientifique 45071 Orléans Cedex 2, France

[3]Centre Technique de la Conservation des Produits Agricoles – CTPA – France

**Résumé**

**Abstract:** In the field of decontamination of fluids for environment and biomedical domains, the used of plasma technologies based on electric discharge offers an increasingly interest. Among all the new processes based on plasma technologies, our study concerns the production of plasma activated water (PAW) by use of gliding arc discharge (Glidarc) at atmospheric pressure. The main objective of this project is to purpose biocidal solution for the treatment of $\mu$-biological contaminated surfaces. Indeed, the Glidarc represents a bright plasma process owing to its ease of use, its robustness and its flexibility allowing a fast and easy implementation in a wide range of applications.

In this study, the Gliding arc discharge has been employed as an advanced oxidation process: this source of radiations and chemical species has been implemented above aqueous media leading to electrochemical reactions at the plasma/liquid interface. This oxidation leads to the formation of chemical species for which the reaction mechanisms are slightly governed by the plasma device including the shape and composition of the electrodes, the electrical parameters, the nature and flow of the feed gas employed in the gliding discharge, the plasma/fluid distance,... This preliminary analysis is focused on the plasma activation of water by gliding arc discharge in dry air at atmospheric pressure. Global parameters (temperature, pH and electrical conductivity) of the water sample have been measured after each experiment during 80 minutes in order to evaluate the activation level and the influence of post discharge reactions. Measurement of major ions concentrations has also been carried out to complete these results. One part of this work discussed in this presentation concerns the influence of initial chemical content of the water on the activation efficiencies of this process. Indeed, some anions and cations initially present in the tap water seem to have significant inhibiting effects on the activation, in particular on the increase of the acidity.

**Acknowledgements:**

*Intervenant

This work was supported by the Centre Technique de la Conservation des Produits Agricoles (CTCPA) within the NETLINE project
**@ Corresponding author:** Dr Maxime Wartel - E-mail: maxime.wartel @univ-orleans.fr

# Experimental and Numerical Approaches on 2D Rapid Surface Oxidation of Si/SiC Substrate by Exposure of Loop-type of Induction Thermal Plasmas

Yasunori Tanaka*[1], Takumi Tsuchiya[1], Atsushi Fujita[1], Tatsuo Ishijima[1], Uesugi Yoshihiko[1], Tetsuya Yukimoto[2], and Hiroshi Kawaura[2]

[1]Kanazawa University – Japon
[2]CV Research Co. – Japon

**Résumé**

Inductively coupled thermal plasma (ICTP) is characterized by high gas temperature, high enthalpy, and no contamination. From these characteristics, the ICTP has widely been adopted for various materials processing such as nanoparticle synthesis, thin solid film deposition. etc. However, the conventional cylindrical ICTP is hardly suitable to large-area materials processing because a large volume of ICTP is required for large-area processing; The large volume of ICTP needs a high input power to be sustained and it is shrunk by Lorentz force. For the purpose of large-area surface modification using ICTP, we have developed a unique ICTP, i.e. a loop type of ICTP (loop-ICTP) [1]. The loop-ICTP is formed in a loop quartz tube connected with a rectangular quartz vessel. On the other hand, a substrate is placed on the substrate holder in the quartz vessel. Then, a part of loop-ICTP is formed directly lying on the substrate with a linear shape. To this linear shaped ICTP on the substrate, scanning the substrate perpendicularly provides 2D exposure on the whole surface of the substrate. In this report, experimental results are shown on two-dimensional rapid surface oxidation of a 2-inch Si or SiC substrates using the Ar-O2 loop-ICTP. In addition, a numerical model of two-dimensional surface oxidation by thermal plasma was developed based on Deal-Grove model [2] to discuss 2D thermal plasma oxidation process of the substrate surface.

The experimental system in this report is the same configured to those in our literature [3]. Argon gas was used as a main plasma gas, which was supplied from the top of the loop torch with a flow rate of 0.5 slpm. On the other hand, Ar/O2 gas mixture of 0.5/0.2 slpm was fed from the top of the rectangular quartz vessel under the loop tube. These gas mixture was supplied through a porous ceramic almost uniformly onto the substrate. In the quartz vessel, a scanning substrate holder made of Si3N4 was located. This holder can be moved perpendicular to the loop plane. On this holder, a 2-inch Si or SiC substrate was placed. Under the above condition, the Ar ICTP was established in the loop tube, while also Ar/O2 ICTP was formed linearly on the substrate. Scanning the substrate offers a 2D oxidation processing of the substrate. Oxide layer thickness was measured with an interferometer. Finally, more than 100 nm oxide layer was created for the Si substrates, while 40 nm thickness of SiO2 was obtained on the SiC surface with one scan with 0.25 mm/s.

*Intervenant

A numerical model was also made to discuss two-dimensional rapid surface oxidation for a Si substrate by scanning loop-type of Ar-O2 thermal plasma. The model uses the 3D energy conservation equation to determine the substrate temperature, and the Deal-Grove model to obtain temporal variation in the thickness of oxide layer. As a result, the developed model shows that almost uniform oxide layer can be obtained only by one scan of the 2-inch Si substrate for one minute with oxidation rate of 100 nm/min.

Y.Maruyama et al., IEEE Trans. Plasma Sci., 44(12), 3164-3171,2016.12

B. E. Deal and A. S. Grove, J. Appl. Phys., 36, 3770-3778, 1965

T.Tsuchiya, Plasma Chem. Plasma Process. 2018.3, https:doi.org/10.1007/s11090-018-9881-7

# Investigations of Stark Profiles of Argon Lines using Laser-Induced Plasma, Thomson Scattering and Optical Emission Spectroscopy

Mamadou Sankhe[1], Tomek Pieta[2], Stéphane Pellerin[1], Krzysztof Dzierzega[2], and Maxime Wartel[*1]

[1]Groupe de recherches sur l'énergétique des milieux ionisés – CNRS : UMR7344, Université d'Orléans – France

[2]Marian Smoluchowski Institut of Physics, Jagellonian University – Pologne

**Résumé**

**Abstract:** Different kinds of argon plasmas are very attractive light sources for testing methods of plasma spectroscopy since argon produces favorable conditions for very stable discharges. It is also the most economical inert gas. Because of these very desirable properties, many new plasma diagnostic techniques as well as improvement of existing approaches have been tested on argon plasmas. Determination of argon spectroscopic data, such as Stark broadening and shift parameters, have been subjects of many studies performed by plasma's spectroscopists. These atomic data are not only important for scientific and industrial applications, but also essential for using argon as the test element for emission plasma spectroscopy.
The theoretical study of Griem [1] shows a quasi-linear variation of the Stark broadening with the electron density. This is generally well verified experimentally, especially for neutral or ionic argon lines [2, 3] at low electron density (up to 1017 cm-3). But some experimental works [4, 5] seem to show that a non-linear dependence appears at higher electron density (> 2x1017 cm-3) especially for the 696.5 nm Ar I and the 480.6 nm Ar II spectral lines.

This work concerns detailed investigations of the Stark profiles of the 696.5 nm ArI and the 480.6 nm ArII lines in the laser-induced plasma. The measured emission profiles, together with independently determined electron density of the plasma, are used to verify the results of other measurements and theoretical calculations. The plasma is generated as a result of the laser breakdown in pure argon gas under reduced pressure of 0.4 bar. High precision plasma diagnostics is performed using the laser Thomson scattering (TS), with a second harmonic of a Nd:YAG laser as the probe beam, as described in [6]. The widths and displacements of the two spectral lines determined in our experiments show a linear dependence in the whole studied range of electron density, i.e. from 1016 to 1018 cm-3, which contradicts the results [4, 5].

These results are important for validating the diagnosis of high electron density plasmas, such as laser induced breakdown in the context of LIBS applications. In addition, Thomson scattering technique and optical emission spectroscopy combination prove their usefulness to determine the unknown spectroscopic constants of different elements currently used in

[*]Intervenant

plasma diagnostics.

**References:**

H. R. Griem, *Plasma spectroscopy.* New York: McGraw-Hill, 1964.

S. Pellerin, K. Musiol, B. Pokrzywka, et J. Chapelle, "Stark width of - Ar I transition (696.543 nm)", *J. Physics B: Atomic, Molecular and Optical Physics*, **29**-17, pp.3911-3924, 1996.

S. Pellerin, K. Musiol, et J. Chapelle, "Measurement of atomic parameters of singly ionized argon lines-III. Stark broadening parameters", *JQSRT*, **57**-3, pp.377-393, 1997.

Y. Vitel et M. Skowronek, "Noble gas line profiles in dense plasmas. I. Argon", *J. Physics B: Atomic Molecular Physics*, **20**, pp.6477-6491, 1987.

E. Iglesias, Y. Guimerans, R. Castell, D. Mandelbaum, et A. Sanches, "Meas. of the stark broadening by plasmas of the neutral Argon line 13406,6 A", *Acta Cientifica Venezolana*, **34**-2, pp.84-88, 1983.

K. Dzierżega, A. Mendys, and B. Pokrzywka, "What can we learn about laser-induced plasmas from Thomson scattering experiments", *Spectrochim. Acta Part B*, **98**, pp.76-86, 2014.
**Corresponding author:** Dr Maxime Wartel - E-mail: maxime.wartel @univ-orleans.fr

# Study of GMAW regime transition in Ar-CO2/O2 shielding gases

Quentin Castillon[1], Nadia Pellerin[2], Stéphane Pellerin[1], François Faubert[1], Maxime Wartel*[1], Jean-Pierre Planckaert[3], and Francis Briand[3]

[1]Groupe de recherches sur l'énergétique des milieux ionisés – CNRS : UMR7344, Université d'Orléans – France

[2]Conditions Extrêmes et Matériaux : Haute Température et Irradiation (CEMHTI) – CNRS : UPR3079 – 1D avenue de la recherche scientifique 45071 Orléans Cedex 2, France

[3]CTAS-Air Liquide Welding – L'AIR LIQUIDE – Cergy-Pontoise 95315, France

**Résumé**

**Abstract:** The Gas Metal Arc Welding (GMAW) in presence of Argon and CO2 or O2 mixture as shielding gas is a largely developed process allowing the transfer of the liquid metal from the consumable wire electrode to the workpiece according to various modes (short-arc, globular, spray-arc). The presence of oxidants in the shielding gas leads to the formation of an oxide layer, or gangue [1, 2, 3, 4], wrapping the droplet, limiting the access to the spray-mode transfer (commonly used in industry), taking into account the conductivity and the viscosity of this layer.
Thus, the distribution of the operating transfer modes (globular or spray) and the transition limits according to the working parameters, are different depending on whether CO2 or O2 are added in shielding gas: in equal proportion. While the gangue formed in the globular regime with Ar-O2 mixtures is up to 20 times thicker than in Ar-CO2 mixtures, it is nevertheless easier to obtain the spray mode with oxygen-containing gas. Finally, the fast cinematography analyzes using an adapted interference filter [3], maked possible to study the column of arc, and to show that the range of spray mode was more extended in a mixture containing O2 than CO2.

In an attempt to understand these behaviors, we performed an optical emission spectroscopy diagnosis of the plasma column for different gas mixtures: pure argon, or mixed with a few percent of active gas (O2 or CO2) in order to analyze the spray mode. The temperature and electron density distributions, but also the proportion of Fe I in the arc column, were deduced from complementary methods: Sola method without hypothesis on the local thermodynamic equilibrium of the plasma [5], and by the classical method of the Boltzmann graph with the assumption of excitation equilibrium.

At the same time, studies have been carried out on the characterization of the influence of the gas composition on the chemical composition of the electrode wire, and especially on the gangue of oxides formed at its end. A microstructural analysis combining a chemical study by a Castaing microprobe, XRD and MEB-EDX analyses, allowed to highlight high disparities of the gangue in terms of its microstructural characteristics (thickness, porosity, etc.), its chemical composition and the type of iron oxide formed (variation of the oxidation

*Intervenant

state of the iron atoms) depending on the type and rate of used active gas.

The obtained results allowed to formulate hypotheses on the mechanisms involved in these phenomena, and in particular on the evolution of the spray / globular transition limit under Ar, Ar-CO2 and Ar-O2.

**References:**

F.Valensi *et al.*, J.Phys.D **43**, 434002 (2010).

F.Valensi *et al.*, J.Phys.D **46**, 224005 (2013).

Q.Castillon *et al.*, Proceeding of GD XX (Orléans), 2014.

F.Valensi *et al.*, Plasma Chem Plasma Process **38**, 177–205 (2018).

A. Sola et al., ICPIG XX (Barga, Italie), 1991 - Book of Contributed Papers p 1147.

**Acknowledgements:**

This work was supported in part by Air Liquide, Les Loges-En-Josas (France) in the frame of a CIFRE agreement, and by the Integrated Action Project Polonium 958055E.
@ **Corresponding author:** Dr Maxime Wartel - E-mail: maxime.wartel@univ-orleans.fr

# Interaction between electric arc and Ag-SnO2 electrodes.

Aurélien Fouque*[1,2,3,4,5,6,7,8]

[1]G. Cailletaud – MINES ParisTech - École nationale supérieure des mines de Paris – France
[2]V. Esin – MINES ParisTech - École nationale supérieure des mines de Paris – France
[3]R. Landfried – CentraleSupelec, Saclay, France. – France
[4]P. Testé – CentraleSupelec, Saclay, France. – France
[5]F. Houzé – CentraleSupelec, Saclay, France. – France
[6]A. Bonhomme – Schneider Electric – France
[7]J.-L. Ponthenier – Schneider Electric – France
[8]F. Chaudot – Schneider Electric – France

**Résumé**

The sizing of contactors requires the understanding of numerous phenomena such as mechanical, thermal, electrical, metallurgical, electromagnetic phenomena. The contact electrodes are submitted to the repeated action of electric arcs which gradually damage the electrodes. The huge power density brought by the electric arcs allows to reach the melting point of the material. On the long term, several phenomena can appear which contribute to the electrodes degradation:

erosion and deformation of the electrodes surface,

appearance of a network of cracks.

Moreover, spatial evolutions of the composition of the material possibly come in addition to these damages. Indeed, the particles of oxide of the composite with silver may disappear near the surface or move to the surface. An example of this phenomenon is given in figure 1 which represents a section of a contact disc after 50 000 arcs. In this figure, we can observe cracks, bubbles in the metal resulting from solidification of the melted metal and also demixing zones (separation between silver and tin oxide). These damages can be characterized by several techniques:

observation of the electrode surface with an optical 3D profilometer,

SEM analysis of a section of the contact disc,

Chemical analysis by EDS,

Mechanical hardness characterization by nanoindentation.

*Intervenant

The work presented here is the first step of a larger study intending to model the evolution of the electrodes material (Ag-SnO2) resulting from multiple opening cycles (with a maximum value around 50 000 openings). The modeling of the contact disc evolution requires several preliminary steps. First, it is necessary to know as accurately as possible the physical characteristics of the contact disc material (mechanical, thermal, electrical...). With this aim some studies have been done on test pieces of material or on real contact discs (used or not). The power flux characteristics (power and surface power density) brought by the electric arc to the electrodes should be estimated. To achieve this, an original experimental device has been developed allowing to obtain information concerning the temperature level reached by electrodes during the arc. The final step will consist of comparing the results obtained by the model with endurance tests made on contactors for several numbers of opening/closing cycles.

# Lightning: a constraining environment for aviation

Franck Flourens*[1]

[1]Airbus Operations SAS – Airbus Operations SAS – France

**Résumé**

Lightning is known as being a major hazard for any flying vehicle having to operate in all-weather conditions with no limitation: a hazard to flight safety, fully managed today by the aviation community, and a significant risk to operations with potentially penalizing consequences on the airline economics.
It is common to say that a passenger aircraft is exposed to an event about once a year despite the rules to avoid flying close to any thunderstorm cell. However, this rough statistics hide different realities experienced by the operators worldwide and regards their mode of operation. If the standards used by manufacturers and authorities are mature regarding safety because based on extreme scenarios, significant efforts are done to get more robust statistics to better anticipate effective operational impact. This is even more important in light of the dream mobilizing a lot of energy in industry today to bring urban mobility and short haul electrical flight to reality.

The feared consequences of a direct strike on an aircraft are multiple. The most visible one is the mechanical and thermal damage created at the arc root or by the transfer of intense currents of several tens of kA in structural joints or system components. The most dangerous one with no possible recovery by the crew would be the ignition of fuel vapor inside the structural fuel tanks due to sparks or "glows". The most insidious one is the induction of spurious transient into the aircraft wiring potentially source of computer upset or data misinterpretation.

The massive use of carbon fiber for the last generation of airliner put the lightning protection back on the critical path of the development. A regulation change pushed from the TWA800 accident in the 90s brought together with unexpected mechanisms of ignition obliged to go much deeper into the understanding of the disruptive phenomena in CFRP laminates. The challenge is to ensure that each potential ignition source cannot develop more than 200 uJ of energy when the strike hitting the fuel tank can be as intense as 100 kA. In addition, the protection performance must be robust against hidden failures and detrimental aging conditions or mistakes potentially made during maintenance operations.

Foreseen disruptive phenomena are clustered regarding their nature and associated protection means: corona effects, hot spots, surface discharges on anisotropic laminates, voltage breakdown and thermal sparks between parts, outgassing from uncontained plasma, and the recently identified edge glow. The last two ones are topics for intense research and technology development because the most constraining in term of design and quality control in production. One of the challenge is to move from a binary analysis (pass or fail, presence of light emission or nothing) to test procedures offering a real quantification of the phenomena,

*Intervenant

offering a notion of protection margin much easily. The accurate quantification of the spark energy was one item crucial for new composite with augmented bulk conductivity which provide excellent performances but can become the source of tiny "lights".

If the indirect effects of lightning are today optimally addressed with simulation integrated to engineering processes, it is not yet the case for effects involving disruptive phenomena, plasma, sparks or glows. Their versatility obliges manufacturers to run extensive test campaigns to verify that new materials or jointing techniques do not carry new risks, and to empirically characterize the performance domain and develop the design rules. This is where efforts to develop analysis tools are key to prepare the future composite aircraft generation.

# Musical Chairs with Waste-to-Energy Technologies

Jaco Van Der Walt*[1]

[1]South African Nuclear Energy Corporation [Pretoria] – Afrique du Sud

**Résumé**

The current effort which the world is investing into Waste-to-Energy technologies, and the associated possibilities to generate viable SMME's in this sector, causes waste to become a worldwide commodity. Waste has various sources that range from residences to office parks to hospitals, municipalities and industries amongst others. Each of these sources generates different quantities of waste which compounds the effect of disposal cost due to gate- or tipping fees. The disposal cost may vary from _˜$100 per ton to _˜$20 000 per ton depending on the hazard level of the waste. Most industries drive the reduction of this cost, thereby reducing their operational expenses. In addition to dealing with waste in a less costly manner, the possibility to convert it into a sellable energy product such as electricity or fuel, is very attractive. But how do you go about selecting the most appropriate waste treatment process? The concept used by the children's game, Musical Chairs could be used. If the different Waste-to-Energy technologies, with their individual attributes are the players and the waste treatment criteria, for a specific application are the chairs, an elimination process based on the Musical Chairs concept could be applied to select the most appropriate technology for the specific application.
This talk will elaborate on a few scenarios where the Musical Chairs concept could be used for technology selection. The role Plasma Waste-to-Energy technology plays in the modern waste to energy landscape will also be emphasized.

*Intervenant

# Effect of an external magnetic field on a DC plasma spray torch with a cascaded anode

Rodion Zhukovskii* , Christophe Chazelas[1], Armelle Vardelle[2], and Vincent Rat[3]

[1]IRCER CNRS UMR 7315 University of Limoges (IRCER) – Université de Limoges – 16, rue Atlantis 87068 Limoges Cedex, France

[2]IRCER, CNRS UMR 7315, University of Limoges (IRCER) – University of Limoges – France

[3]IRCER, CNRS UMR 7315, University of Limoges (IRCER) – University of Limoges, Limoges – France

**Résumé**

Plasma spraying is a well-established surface engineering technology used in all industrial fields, in particular aeronautics, industrial gas turbines and automotive. However, the basic tool of the process, a non-transferred arc plasma torch, still has two main drawbacks: plasma jet instabilities and electrode erosion. Torch manufacturers are trying to overcome them by using high arc voltage rather than high current (roughly, the anode erosion is proportional to the square of the arc current), fixing the mean arc length and using some modifications (e.g., swirling injection of the plasma-forming gas) to rotate the anode arc attachment in a plane orthogonal to the torch axis.

For example, the SinplexPro$^{TM}$ plasma torch of Oerlikon Metco uses a large rounded cathode (12.7-mm in diameter), an insert between cathode and anode to fix the arc length longer than the self-setting arc length and a vortex injection of the plasma gas. The arc voltage can reach about 100 V with a mean fluctuation in the order of 5-20 % but observations of the anode surface and calculations have shown that the arc attachment is displaced along a line on the anode wall and may cause rapid erosion. Since the vortex injection is not strong enough to act on the anode arc attachment, another well-known tool is the use of an axial magnetic field. The SinplexPro$^{TM}$ plasma torch involves a stack of copper rings insulated from each other and ending with an anode-ring on which the arc attaches. However, the stability of the plasma jet issuing from the torch when the external magnetic field is imposed on this last ring has been questioned.

This study attempts to answer this question using a 3-D, time-dependent MHD model of the plasma torch operation that couples the gas phase and electrodes. The self-magnetic field reaches a maximum value of 0.055 T for an arc current of 500 A and a gas flow rate of 60-slm Argon. The external magnetic field was imposed, through the Lorentz force in the momentum equation, inside the anode ring with values ranging between 0.05 and 0.2 T and outside the anode with a smooth linear transition to zero. The reattachment of the arc at the anode wall was modeled by using the model proposed by Nemchinsky that assumes the electron temperature in the cold boundary layer next to the anode wall, does not decrease as much as the heavy particle temperature and, so, some residual electrical conductivity subsists in this layer.

*Intervenant

# Modelling of the Negative Ion Source and Accelerator of the ITER Neutral Beam Injector

Gwenael Fubiani*[1], Jean-Pierre Boeuf[1], and Laurent Garrigues[1]

[1]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

**Résumé**

In this talk, we will describe in details the modelling of the ion source and accelerator of the International Thermonuclear Experimental Reactor (ITER)' Neutral Beam Injector (NBI). The ITER project is the first fusion device which will mainly be heated by alpha particles (H2+). The plasma will consist of Deuterium and Tritium ions providing 500 MW of fusion power. 50 MW of additional *external* power will be necessary in order to heat and control the plasma during the operating phase while the alpha particles will re-inject 100 MW of power to the fusion plasma (the total heating power is hence 150 MW). The remaining 400 MW will be carried by the neutrons toward the wall of the Tokamak.
In ITER, NBIs are designed to inject 33 MW of power (split over two beam lines) with an energy of 1 MeV [1]. Neutrals are insensitive to magnetic fields and can hence penetrate into the hot plasma core of the Tokamak. The neutral beams provide (1) power to the plasma, (2) current (which is necessary to sustain the poloidal field) and (3) are helpful to minimize the buildup of some type of instabilities. The NBI is mainly composed of (1) a negative deuterium ion source delivering a current density of the order of 28 mA/cm2, (2) an electrostatic accelerator which produces a 1 MeV, 40 A D- beam, (3) a neutralizer converting part of the beam into high energy neutrals, and lastly a residual ion dump. One of the main drawbacks of the negative ion electrostatic accelerators for high power NBIs is the significant number of secondary particles which are produced inside the accelerator [2]. Secondary particles originate from collisions between the accelerated negative ions and the residual background gas and from the collisions between particles and material surfaces in the accelerator (the negative ion source will also produce electrons that are co-extracted with the negative ions). The overall power deposition due to energetic secondary particles hitting the accelerator grids may be of the order of a few MW and consequently a precise characterization of the phenomenon is required for design improvement.

The modeling of the ion source and accelerator is a formidable task and we address the different issues separately (particle transport inside the ion source, beam extraction, secondary particle production, etc.) with dedicated models using simplifying assumptions. Most results presented and discussed in this work have been obtained either with the Particle-In-Cell Monte Carlo Collisions (PIC-MCC) technique or using test particles.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Support from CEA and from the French Fédération

*Intervenant

de Recherche sur la Fusion Magnétique is acknowledged. This work was granted access to the HPC resources of CALMIP supercomputing center under the allocation 2013-P1125.

Hemsworth et al., Nuclear Fusion 49, 045006 (2009)

G. Fubiani et al., Phys. Rev STAB 11, 014202 (2008)

G. Fubiani et al., New J. Phys. **19**, 015002 (2017)

# Effect of plasma torch operating parameters on plasma jet velocity at torch nozzle exit

Jérôme Betoulle[1], Simon Goutier*[2], and Michel Vardelle*[3]

[1]Ceramic European Center – University of Limoges – France
[2]IRCER – Université de Limoges – France
[3]IRCER – Université de Limoges, Centre National de la Recherche Scientifique – France

**Résumé**

In plasma spray, the velocity of the plasma jet issuing from the torch affects the residence time of the processed particles or droplets injected in the gas flow and, thus, their in-flight treatment and flattening onto the part to be covered. The plasma velocity is thus one of the key factors of the process. For a given inner geometry of the plasma torch, it can be varied in a ratio of one to three by changing the plasma –forming gas, its composition or the arc current. The gas temperature varies of about 15% under the same conditions, as at these temperatures, heat is stored in the gas species in the form of dissociation and ionization energy that act as a thermal inertia wheel and dampens the temperature variation in the plasma gas.
This study deals with plasma jet velocity measurement at the torch nozzle exit by using two techniques: i) following plasma fluctuations and ii) Particle Image Velocimetry (PIV) on plasma jets seeded by ceramic submicronic particles. Measurements were carried out for a commercial DC plasma spray torch (Oerlikon Metco F4 plasma torch) with a large range of operating parameters:

- Different plasma forming- gas mixtures (Ar, Ar-H2, Ar-He, Ar-N2) ,

- Torch nozzle diameters ranging from 6 to 12 mm,

- Use or not of a cylindrical nozzle extender (20-mm long) at the nozzle exit

These experimental velocity are aimed to be used as plasma jet model validation; they can also be useful to choose the spray conditions, in particular for suspension and solution plasma spraying, in which the feedstock is injected in the form of submicrometric particles or chemical precursors in a solvent.

*Intervenant

# Co-gasification of lignite and used car tires by H2O/air thermal plasma

Viktor Popov*[1], Dmitry Subbotin[1,2], Alexander Surov[1], Sergey Popov[1], and Evgeny Serba[1]

[1]Institute for Electrophysics and Electric Power of the Russian Academy of Sciences – Russie
[2]St. Petersburg State Technological Institute – Russie

**Résumé**

In recent decades, the recycling of used tires into energy products is being actively investigated. Its can be subjected to gasification in reactors of various types. To reduce the amount of tars in the produced synthesis gas, it is desirable to use downdraft gasifier. However, in this case, the reducing bed required for the decomposition of the tars will not be formed. This problem is solved by adding solid fuels (for example, lignite) as raw materials. To increase the hydrogen content in the synthesis gas, it is desirable to use steam as a gasifying agent, and for input of energy to use plasma torches. On this basis it is advisable to use air-steam plasma produced by the AC plasma torch. Its operating electrical characteristics, dependence of the thermal efficiency on arc current, flow rates and composition of the plasma-forming mixture were determined. Steam flow rate is 3.55 - 5.8 g/s, air flow rate is 1 - 3 g/s, arc current is 28 - 29 A, arc voltage drop is 1.15 - 1.85 kV, power is 57.6 - 87.5 kW, thermal efficiency is 94.3 - 95.3%.

Thermodynamic estimation of co-gasification of used car tires and lignite was carried out to evaluate the work of the plasma torch as part of a plasma gasifier. Lignite, a low-calorie fuel, was chosen deliberately to show the effectiveness of plasma gasification. Available enthalpy of blowing agent without regard to heat loss was 12.5 MJ/kg (steam: air = 5: 1 wt.). Further experiments are planned to carry out in the downdraft reactor, it was therefore it was provisionally selected the ratio of used car tires: lignite 30% to 70% wt. The inorganic portion of used car tires is assumed for iron and ash lignite is assumed for silicon dioxide.

As a result of calculations it was established that for 1 kg of mixed fuel it is necessary to supply about 8.3 MJ of energy, the synthesis gas is substantially free of ballast gases (nitrogen and other), lower heat value of product gas is 10 MJ/kg, the total concentration of H2 + CO is about 74% (in dry condition is 90%). In the case, if more high calorie fuel applies the results will be significantly better, in the first place, the water content in the product gas will be less. Subsequently, more powerful facilities on the basis of developed plasma torches operating with a wide range of gasifying agents can be designed, that allows to produce synthesis gas with higher molar ratio of H2/CO.

*Intervenant

# Use of plasma-arc source in large-scale additive-manufacturing, also for the deposition of materials of interest in plasma-confinement applications for fusion

Filomeno Martina*[1], Philippe Bridgeman[1], Gianrocco Marinelli[2], Jialuo Ding[2], Supriyo Ganguly[2], and Stewart Williams[2]

[1]Cranfield University – Royaume-Uni
[2]Cranfield University – Royaume-Uni

**Résumé**

This talk will be split into two distinct parts. Firstly, the use of a plasma transferred arc (PTA) as a thermal power source for wire based additive manufacture (WAM) of metre scale engineering structural parts will be described. The PTA source is very beneficial as a power source for the WAM process and its advantages compared to other power sources such as lasers or conventional welding arcs will be highlighted. Indeed examples of components made successfully in WAM using the PTA source will be shown. However, there are potential issues when using PTA, typically related to high arc pressure, which could cause defects in the deposited material. Therefore, the arc pressure of a PTA source has been characterised experimentally. Operational regimes that avoid defects related to arc pressure have been identified and provided. The second part of the talk will illustrate how the WAM process has been used to produce large structures in tungsten, tantalum and molybdenum for application in plasma-confined fusion-reactor systems. The details of this process will be highlighted along with microstructural analysis and material properties. The production of a graded structure between these materials will also be discussed.

*Intervenant

# Treatment of graphene films in the early and late afterglows of N2 plasmas: comparison of the defect generation and N-incorporation dynamics

Germain Robert Bigras[1], Xavier Glad[1], Richard Martel[2], Andranik Sarkissian[3], and Luc Stafford*[1]

[1]Université de Montréal - Physique – Canada
[2]Université de Montréal - Chimie – Canada
[3]Plasmionique Inc. – Canada

**Résumé**

Graphene films grown on copper substrate by chemical vapor deposition were exposed to the flowing afterglow of a reduced-pressure N2 plasma sustained by microwave electromagnetic fields (surface-wave plasma). Two set of conditions were examined by controlling the gas flow rate: the late afterglow (LA) characterized by high number densities of reactive N atoms and the early afterglow (EA) in which significant populations of metastable N2(A) states and positive ions (N2+ and N4+) coexist with plasma-generated N atoms. LA treatments of graphene films show monotonous and steady incorporation of nitrogen atoms along with very low damage. However, given the very mild LA treatment conditions, a large part of the N atoms remains weakly bonded to the graphene surface; a feature ascribed to the plasma-induced functionalization of airborne hydrocarbon contaminants. In such conditions, graphitic inclusion of plasma-generated N atoms is limited to native defect sites. On the other hand, the presence of highly energetic species in the EA induces significant damage combined with much higher N-incorporation. Detailed Raman analysis of EA-treated samples further reveals a transition from vacancy-type defects to much larger multi-vacancies with increasing treatment time. This complete set of data indicates that through a judicious control of the populations of reactive N atoms, metastable N2(A) states, and positive ions (N2+ and N4+), the flowing afterglow of microwave N2 plasmas represents a highly promising tool for precise, post-growth tuning of the defect generation and N-incorporation dynamics in graphene films.

*Intervenant

# Determination of faults arc energy ignited between aeronautic cables

Thomas Vazquez*[1,2], Philippe Teulet*[3], Flavien Valensi*[4], Aurore Risacher*[5], Loïc Hermette*[6], and Vincent Casanovas

[1]IRT Saint Exupéry - Institut de Recherche Technologique – IRT Saint Exupéry - Institut de Recherche Technologique – France

[2]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

[3]Laboratoire Plasma et Conversion d'Energie [Toulouse] (LAPLACE) – Université Paul Sabatier (UPS) - Toulouse III, CNRS : UMR5213, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[4]Université de Toulouse, UPS, INPT, Laboratoire Plasma et Conversion d'Energie (LAPLACE) – Université Paul Sabatier (UPS) - Toulouse III, CNRS : UMR5213, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[5]IRT Saint exupéry (IRT AESE) – IRT Saint exupéry – 118 route de Narbonne, CS 44248 31432 Toulouse cedex 4, France

[6]IRT Saint Exupéry – IRT Saint exupéry, IRT Saint-Exupéry – France

**Résumé**

The risk to initiate a fault arc between two adjacent cables becomes greater for the new generation of civil airplanes, since the embedded power increases constantly. This is mainly due to the use of higher voltage. Therefore, even if the protection devices can detect these types of short circuit and cut the current, electric arcs can last long enough (of the order of hundreds of milliseconds) to propagate and induce important damage, compromising the safety of the flight. Besides, the use of new material for the wires and the structure leads to new arcing conditions. To get a better comprehension of this phenomenon and being able to limit its consequences, this work aims to study parallel arcs, initiated between two cables, and to make a power balance of this type of discharge.

Aeronautic cables made of copper or aluminium have been subjected to short circuits at 230 V and up to 125 A, both in direct and alternative current. A procedure is carried out to allow a systematic initiation of the arc: two cable samples are bond together, and a small part of the insulation is removed beforehand. The discharge is thus ignited between the two bared parts of the cables. It results in a propagation of the arc along the cables, causing an important erosion and hot metallic droplets ejection. The shape of the arc, recorded a high speed imaging camera, seems to be guided by the metallic vapour jets coming out from the electrodes. These images are correlated with the voltage and current of the discharge. A heat flux sensor is used to estimate the radiation power spread by the arc. The tests are performed in a chamber allowing to work at reduced pressure in order to reproduce the conditions occurring at various altitudes. A comparison is made between pressure at ground level and

*Intervenant

at certification altitude (15 000 m) corresponding to 100 kPa and 9,5 kPa, respectively. A power balance of the arc is made, considering the part of the total power deposited in the arc column and the part responsible to the degradation of the electrodes. The latter is deduced from mass loss measurement and thermodynamic calculation of the melting and vaporization energy of the electrodes, to estimate the energy proportion needed to deteriorate the cables. Particular attention was paid to measurement uncertainties limitation, concerning the heat flux determination and the ablated mass estimation.

Results show that the average power deposited in the discharge is slightly the same in AC than in DC for 100 kPa. The repartition of the energy is different yet, with around 50% of the total energy transferred to the electrodes and 50% deployed in the arc column in AC, whereas this ratio is 70% / 30% in DC. At 9,5 kPa the arc voltage is less high compared to atmospheric pressure; it implies a lessening of the power at low pressure, that we quantified for around 20% less in AC and 30% in DC.
For aluminium cables, an exothermic reaction takes place and gives rise to the formation of alumina (Al2O3) on the surface of the melted aluminium. It is therefore an additive component of energy that we estimated for the energy balance.

# HVDC Networks and the Aircraft Electrical Installation

Roland Causse*[1] and David Rousset*[1]

[1]AIRBUS – Airbus Group [Madrid] – France

**Résumé**

The new generations of aircrafts are introducing more and more electric actuators at the expense of hydraulic, pneumatic energies. This implies higher and higher voltages in order to minimize the consequences on the aircraft's weight. For non-propulsive systems, +/-270Vdc networks are envisaged while +/-1.5 kVdc voltages are mentioned for propulsion systems. The EWIS "Electrical Wiring Interconnection Systems" must adapt to the new constraints of these high voltage DC networks and in particular with regard to the phenomena of electric arcs caused by the damage of the insulators of the cables likely to arrive during the life of the plane. These parallel or serial arcing phenomena must be controlled so that the consequences remain acceptable from a safety and airworthiness point of view but also so as not to penalize operators in the case of long and costly repairs. A well-known phenomenon such as arc tracking was associated to the presence of aromatic polymer insulation. A simple protection principle was to design cables with materials not propagating the phenomena. Considering the new constraints imposed by HV, it is necessary to prepare a move from a protection based on material performances only, to a protection relying more on active means. Current protections based essentially on $I^2t$ type curves do not allow a satisfactory response. Indeed, increasing the wiring installation clearances or putting additional protections around the electrical harnesses are very penalizing from a mass point of view. The circuit protection devices initially designed to limit cable damage during a short circuit must now incorporate other functions designed to detect arcing phenomena as early as possible in their occurrence in order to limit the consequences for the environment.

*Intervenant

# Setting for defined fume particle generation and observation using a TIG welding torch

Stefan Eichler*[1], Erwan Siewert[2], and Jochen Schein[1]

[1]Universitaet der Bundeswehr Muenchen – Allemagne
[2]Linde AG – Allemagne

**Résumé**

Fumes generated by welding processes range from ultra-fine particles (diameter below 100 nm) to fine particles (a couple microns). The mass fume formation rate is much higher using GMAW compare to GTAW processes. Never the less, the particle size distribution of the GTAW process is nearly completely in the range of the UFP - above 90 % -. Those are considered much more hazardous due to the fact, that they pass the epithelial barrier inside the human lung.
For the observation of possible ways to influence the PSD of the GTAW process and its interactions the following setup has been designed and tested using a pure iron disc in a water cooled copper bed as an anode and particle source. Meanwhile voltage, current as well as calorimetric data of the torch and copper anode is recorded. For gas flow observation the setting is implemented into a Schlieren setting combined with 2 spectral selective cameras recording the shape of the arc in an 60○ angle. The temperature surrounding the arc region are monitored using thermocouples.

The particles are extracted with a defined flow rate using an adjustable mobile exhaust system with flow speed measurement. The particle size distribution is measured online by an Industrial scanning mobility particle sizer TSI 3936. The generated particles can be directly measured or be transferred to a second volume to observe various interactions.

First results show a good reproducibility of the PSD. A measuring error of the particle size distribution due to a high argon content in the carrier gas can be ruled out and is monitored online by measuring the oxygen concentration in sample flow.

*Intervenant

# Atmospheric pressure plasma modification of powder dispersions using RF jet and RF slit nozzle

Barbora Pijáková*[1] and Jozef Ráhel̆[1]

[1]Department of Physical Electronics; Masaryk University, Kotlářská 2, CZ-611 37 Brno – République tchèque

**Résumé**

Paint coating systems use numerous organic and inorganic powder components and additives. This fact introduces the problem of mixture homogeneity directly connected to the dispersion stability as well as miscibility of powders in liquids and solvents.
In this work, we investigated RF plasma modification of dispersed powders and its effect on powder wettability and dispersion sedimentation. The behaviour of fine powders of titanium dioxide, zirconium dioxide, aluminium dioxide and paint pigments was tested in deionized water and isopropanol (0.2 g/10ml). Plasma activation was made in so-called submersed regime, i.e. that plasma plume was in direct contact with the dispersion level. The motivation for testing both types of RF devices was to compare the efficiency of technologically more feasible 4 cm slit nozzle with the standard single channel RF jet. Both sources were operated at 150 W power and frequency of 13.56 MHz, using 1min treatment time. Effect of gas admixtures N2, O2, C4F8 in carrier Ar gas was observed.

Surface morphology, bulk chemical composition and contact angles of dried filtrates of pristine and modified powders were observed using scanning electron microscopy with energy dispersive spectroscopy and sessile drop contact angle evaluation. Time lapse camera recording of dispersion sedimentation rate was used.
The results showed conclusively the positive effect of RF plasma modification on both powder wettability improvement and the stability of final dispersion.

*Intervenant

# Arc electrode interaction in thermal plasma applications

Dirk Uhrlandt*[1], Guokai Zhang[1], Gregor Gött[1], Margarita Baeva[1], and Sergey Gortschakow[1]

[1]Leibniz Institute for Plasma Science and Technology – Allemagne

**Résumé**

The attachment of the arc at the electrodes and their interaction are of particular importance in all applications of transferred and non-transferred arcs. This is because the current distribution, the energy transfer to the electrodes and often also the main shape of the arc are mainly determined by the processes at and near the electrode surfaces. At the beginning, a rough overview about theoretical concepts to describe the arc-electrode interaction will be given.
It will be demonstrated in a second part that a model based on a non-equilibrium plasma description is able to provide a far-reaching understanding of the simplest case; the free-burning arc in argon with a tungsten cathode. The self-consistent description yields not only the sheath voltages but the complete electric potential structure including the pre-sheath regions. The energy balance of tungsten inert gas welding processes becomes explainable including questions like the energy transfer from sheath regions to the electrodes and to the plasma.

The limitations of existing models to describe an arc between non-refractory electrodes at the same level of detail will be discussed in a third part. Magneto-hydrodynamic models of gas metal arc welding including the description of metal vapor and sheath establishment will be considered as examples.

Recent findings of experimental studies for the sheath voltage in gas metal arc welding will be shown in a fourth part also to demonstrate future needs in modelling. In particular, the current dependence of the sheath voltage and voltage drops in the parts of the electrodes will be discussed.
Finally, a conclusion will be given with the focus on future needs in modelling and possible approaches in particular to treat arcs between non-refractory electrodes as in gas metal arc welding, for example.

*Intervenant

# Analysis of the electron population in non-equilibrium plasmas sustained by low-frequency, RF, and microwave electric fields

Luc Stafford*[1]

[1]Université de Montréal - UdeM (CANADA) – Canada

**Résumé**

The electron temperature, Te, is one of the most fundamental parameter of non-equilibrium plasmas and is a crucial feature to understand the electron heating dynamics and to control the plasma chemistry in many technological applications. In low-pressure plasmas, Te is usually analyzed by Langmuir probes. However, such measurements are difficult in reactive plasmas due to inherent probe contamination. In addition, analysis of the high-energy electrons are difficult due to their low density and the presence of an ion current that needs to be subtracted from the total measured current. In non-thermal plasmas at atmospheric pressure, Te values have been mostly determined from the neutral bremsstrahlung emission and Thomson scattering. However, such measurements are difficult or even impossible in low-density plasmas, for example, dielectric barrier dicharges (DBDs). In this work, a combination of optical emission spectroscopy (OES) and collisional-radiative modeling (CRM) is used to analyze the electron temperature in various non-equilibrium plasmas sustained by low-frequency, RF, and microwave electromagnetic fields. In low-pressure plasmas, this OES-CRM approach was used to analyze wave-particle interactions and collisionless electron heating in surface-wave argon-based plasma columns. In such microwave plasmas, a resonance can be excited close to the tube walls where the electron plasma frequency in the radially-inhomogeneous plasma column reaches the wave frequency. Through detailed analysis of the 2p-to-1s emission lines from Ar but also Ne, Xe, and Kr injected in trace amounts, the EEDF is found to depart from a Maxwellian with the presence of a high-energy tail. In addition, the relative population of high-energy electrons increases with the axial distance towards the end of the plasma column where the electron density decreases and the resonance point becomes closer to the discharge axis. The OES-CRM method was also used to perform a multi-scale investigation in the frequency domain of dusty argon RF plasmas with pulsed injection of organosilicon precursors (HMDSO). Variations of the electron temperature obtained by analysis of Ar 2p lines were observed over both the precursor injection cycles and the repetitive formation and loss dynamics of dust inside Ar-HMDSO plasmas. Finally, the CRM was recently updated to describe non-thermal plasmas at atmospheric pressure operated in He and Ar gas mixtures. In the case of He DBD, the values of Te were relatively high early in the discharge cycle (around 1.0–1.4 eV) and then much lower near discharge extinction (around 0.15 eV). For analysis of time-integrated (or cycle-averaged) OES measurements, Te was closer to the 0.15 eV values near the end of the discharge cycle, in good agreement with the values expected from theoretical predictions in the positive columns of He glow discharges at atmospheric pressure. More recently, similar experiments were performed in the $\gamma$ and $\Omega$ modes of capacitively coupled He plasmas. When the discharge is

*Intervenant

sustained in the $\gamma$ mode, Te is found to vary from 0.2 to 7.2 eV. In this case, high values of Te ($>$ 5 eV) occur only during a brief instant ($<$ 10 ns) in the high-voltage sheath. When the discharge is sustained in the $\Omega$ mode, Te is found to vary from 0.3 to 0.4 eV during the complete cycle.

# Microwave Plasma Reactor for Atmospheric-Pressure Carbon Dioxide Decomposition

Sina Mohsenian[1] and Juan Trelles*[1]

[1]University of Massachusetts at Lowell – États-Unis

**Résumé**

Nonequilibrium atmospheric-pressure plasmas are ideal for the conversion of renewable electricity into gas-phase reactivity, such as the synthesis of high-value chemicals from low-value feedstock. Due to greater selectivity, energy efficiency, and operational convenience of these plasmas, they are appealing for the direct decomposition of carbon dioxide to mitigate its emission into the atmosphere while creating carbon monoxide as a valuable industrial chemical. Particularly, microwave plasma processes can have high energetic efficiency for molecular dissociation via effective vibrational excitation of molecular species. The design, development, and characterization of a microwave plasma reactor for atmospheric pressure undiluted carbon dioxide decomposition are presented. The geometric configuration for the plasma reactor leads to the formation of a plasma bulb stabilized by tangentially-injected processing gas and a stable plasma jet attached to a converging-diverging nozzle. The plasma can be ignited and operated with undiluted CO2 gas, which has the potential for greater specific energy deposition, and therefore for higher efficiency for chemical synthesis. Electromagnetic wave confinement, residence time, and critical gas vorticity constitute fundamental reactor sizing and operation parameters. Fluid flow simulations show that vortex flow around the plasma is stronger than in other parts of the reactor, resulting in more confinement and stabilization of the plasma bulb. Fast imaging of the plasma bulb proves that the gas flow rate has a significant effect on the plasma stability. The electron temperature in the plasma bulb was estimated through optical emission spectroscopy (OES) for power levels up to 1000 W and flow rates up to 10 slpm. In addition, OES analyses revealed that the excitation mode of Swan bands is the most dominant mode in this microwave plasma source for both CO2 and CH4, indicating that the reactor is effective for CO2 or CH4 decomposition. Experimental results show that emission line intensities increase and jet temperature decreases with increasing flow rate; whereas line intensities, jet temperature, and jet length increase with increasing deposited power, indicating that flow rate plays a dual role in plasma stabilization and process performance. The slight increase of CO2 spectrum intensities with increasing deposited power indicates the latter has a minor role in CO2 decomposition. This may be due to lack of penetration of electromagnetic power into the plasma due to increased absorption at skin depth.

*Intervenant

# Cold Atmospheric Pressure Plasma applied for Aeronautical Polyurethane surface activation: preliminaries characterizations

Audrey Sanchot*[1], Vivien Murat[1], Nicolas Naude[2], Bertrand Rives[3], Laurent Guerre-Chaley[4], and Thomas Delsol[1]

[1]IRT Saint Exupéry - Institut de Recherche Technologique – IRT Saint Exupéry - Institut de Recherche Technologique – France

[2]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

[3]STELIA AEROSPACE – Stelia Aerospace group – France

[4]SATYS – SATYS – France

**Résumé**

Increasingly strict environmental standards and constraining security rules have led to new technologies development for a "greener" surface preparation, that is to say industrial solutions which do not impact or little the environment[i]. Plasma processes are particularly promising in that context.
Surface activation by cold atmospheric plasma is a method which consists in modifying free surface energy, in order to improve adhesion properties, before a coating step[ii]. One of the strengths of atmospheric plasma process is the absence of dust and degradation at a large scale. Considering its partial automation, the technique is reproducible, inducing less error and requesting less repairs compared to a manual one. The state of the art concerning this technology has shown that numerous fittings were developed towards important industrial groups[iii].

The aim of this project is to develop an automated surface activation before painting using an atmospheric cold plasma solution from AcXys Technologies. In order to facilitate industrialization of this kind of atmospheric pressure remote plasma for surface activation, a new approach has been proposed: the "plasma dose". This concept is already commonly used in Corona process. Mechanisms assigned to durable improvement of adhesion will be more appreciated and their characterization will contribute to a greater definition of surface preparation range by remote cold plasma. In this perspective, the influence of the plasma dose - directly linked to plasma process parameters (gas process, gas flow rate, discharge power, distance between nozzle and substrate, scanning speed...) - on the surface properties is investigated. Chemical bindings analyzed by ATR-FTIR, as morphology and roughness characterized by AFM are discussed with respect to surface energies obtained by contact angle measurements. Aging of the surface has also been considered. Finally, adherence tests (cross cut) provide the final approval.

*Intervenant

i

Document de référence sur les meilleures techniques disponibles - Traitement de surface des métaux et matières plastiques, Rapport de la Commission Européenne, 2006.

Circulaire DGT 2010/03 relative au contrôle du risque chimique sur les lieux de travail, Ministère du travail, de la solidarité et de la fonction publique, 2010.

ii

C. Tendero et al, Atmospheric pressure plasmas: A review, Spectrochimica Acta Part B, 61, 2 – 30, 2006.

L. Bárdos et al, Cold atmospheric plasma: Sources, processes, and applications, Thin Solid Films, 518, 6705–6713, 2010.

M. J. Shenton et al, Adhesion enhancement of polymer surfaces by atmospheric plasma treatment, J. Phys. D: Appl. Phys., 34, 2754–2760, 2001.

C. Sperandio et al, Influence of plasma surface treatment on bond strength behavior of an adhesively bonded aluminium-epoxy system, International Journal of Adhesion & Adhesives, 30, 20–728, 2010.

J. C. S. Fernandes et al, Plasma-polymerised coatings used as pre-treatment for aluminium alloys, Surface and Coatings Technology, 154, 8–13, 2002.

I. De Iorio et al, Plasma treatments of polymeric materials and A1 alloy for adhesive bonding, Journal of Materials Processing Technology 68, 179-183, 1997.

iii

C. Tendero et al, Atmospheric pressure plasmas: A review, Spectrochimica Acta Part B, 61, 2 – 30, 2006.

L. Bárdos et al, Cold atmospheric plasma: Sources, processes, and applications, Thin Solid Films, 518, 6705–6713, 2010.

# Study on reaction rates for 2T SF6 plasma: application to chemical kinetics of a decaying arc in high voltage circuit breakers

Xavier Baumann*[1], Philippe Teulet[2], Yann Cressault[3], and Arnaud Bultel[4]

[1]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

[2]Laboratoire Plasma et Conversion d'Energie [Toulouse] (LAPLACE) – Université Paul Sabatier (UPS) - Toulouse III, CNRS : UMR5213, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[3]Université de Toulouse, UPS, INPT, Laboratoire Plasma et Conversion d'Energie (Université de Toulouse, UPS, INPT, LAPLACE) – Université de Toulouse, UPS, INPT – 118 route de Narbonne, F-31062 Toulouse Cedex 9, France

[4]COmplexe de Recherche Interprofessionnel en Aérothermochimie CORIA – Université de Rouen, CNRS : UMR6614 – France

**Résumé**

Design and improvement of High-Voltage Circuit Breakers (HVCB) need magneto-hydrodynamic model to understand the properties of electrical arc. However, these models are dependent of fundamental properties such as thermodynamic properties, transport coefficients and radiative properties. In the present work, the studied gas is SF6 (gas most commonly used in HVCB). The determination of these parameters is well known in the scientific community in the assumption of chemical and thermal equilibrium but the Local Thermodynamic Equilibrium (LTE) hypothesis is not valid in some areas of the plasma: near the electrodes, near the walls and in peripheral areas of the arc where turbulence and pumping phenomena are significant. Moreover, the LTE hypothesis is not sure during the arc decay. The temperature is not high enough so that scattering develops an equilibrium state. In consequence, free electrons have a kinetic temperature higher than that of heavy particles. To study this type of discharge, the first step is to determine the particle densities which are necessary to obtain the other properties. The literature proposes several theoretical methods to calculate them: the minimization of a thermodynamic function, the law of mass action and the collisional-radiative or kinetic model. To our point of view, the technique based on the minimization of a thermodynamic function is unusable in non-thermal equilibrium conditions. The law of mass action is convenient but its extension to non-thermal equilibrium plasma is not fully rigorous because this technique is based on thermodynamic laws. The collisional radiative model and the kinetic model are consequently the best approaches to determine the plasma composition in non-thermal equilibrium conditions. These techniques are based on balance equations that are valid in all conditions of disequilibrium but they depend on the reaction rates. Most of the time, only the forward reaction rates are available. Thus, a relation between forward and reverse reactions rates is necessary. In the LTE, these relations are

*Intervenant

reduced to a combination between Saha-Eggert or Guldberg-Waage relations which are not useful for non LTE plasma. In this work, we study the forward and reverse reaction rates and their relation in the case of a non LTE plasma. The influence of the assumptions done on these reactions rate is discussed regarding the particle densities obtained in the case of a non LTE SF6 plasma at atmospheric pressure.

# Laser-aided diagnostics applied to ion thrusters

Stéphane Mazouffre*[1]

[1]Institut de Combustion, Aérothermique, Réactivité et Environnement (ICARE) – CNRS : UPR3021 – 1c Avenue de la Recherche Scientifique 45071 Orléans, France

**Résumé**

Ion Thrusters (ITs), also termed electric or plasma thrusters, are efficient ion accelerators used to propel satellites and space probes. Contrary to chemical thrusters, ion thrusters eject the propellant at very high speed, which directly translates into a low propellant mass consumption for a given maneuver or mission. ITs therefore allow either to drastically reduce the spacecraft mass or to extend the mission capabilities. There is a wide variety of IT technologies, all devices nevertheless rest upon a low-pressure plasma discharge. Among all existing thrusters, the Hall thruster is currently the most popular for satellite station-keeping, attitude control and orbit transfer owing to its large thrust-to-power ratio. Even though Hall thrusters are very simple on a technological standpoint, physical processes that govern their magnetized discharge properties, and in fine performances, are complex and still ill-understood. As a consequence, optimization of existing devices and development of new architectures is still very empirical, hence lengthy and expensive. A better understanding of phenomena such as electron cross-field transport and plasma-wall interactions in HTs requires a comparison between numerical simulation outcomes and data about electron and ion properties and dynamics. In this contribution, we will show advantages and interests in employing laser-aided diagnostics to probe the discharge and the beam of HTs. Three types of laser technique will be presented along with experimental results. Laser-Induced Fluorescence (LIF) spectroscopy allows to measure the atom and ion velocity distribution from which particle temperature and mean velocity can be extracted. Incoherent Thomson Scattering (ITS) gives access to the electron energy distribution function, a fundamental quantity in low-temperature low-pressure plasmas. Finally, Coherent Thomson Scattering (CTS) provides information about low-scale turbulence that plays a key role in particle transport, acceleration and energization.

*Intervenant

# Spherical powders manufacturing by Induction Plasma technology

Romain Vert*[1] and Alexandre Vassa[1]

[1]Tekna – - – France

**Résumé**

Metal-based Powder Metallurgy (PM) technologies requires satellites-free powders having a spherical shape ensuring the highest packing density achievable, a specific particles size distribution, high flow ability as well as an internal particle structure which is free of pores. Despite the various advantages that commercially available powders can offer in terms of affordability and/or ease of availability, they rarely meet all the requirements listed above.
Developing, industrializing and producing a high-performance powder can be achieved using the Inductively-Coupled Plasma (ICP) process developed by Tekna Plasma Systems Inc.. The ICP process is based on the in-flight heating and melting of the individual particles of the feed material, followed by their gradual cooling and solidification before reaching the bottom of the powder processing chamber. The technology allows for operation using a wide range of plasma gas mixtures at atmosphere pressure or soft vacuum. The plasma can be used as a chemical reactor as well as an enthalpy source.
Different case studies are presented regarding the manufacturing of titanium-based, nickel-based and aluminium based alloys and their recycling.

*Intervenant

# In-liquid synthesis of CuO nanoparticles by bipolar pulsed microplasma

Dong-Wook Kim*[1] and Dong-Wha Park[1]

[1]Inha University – Corée du Sud

**Résumé**

Cupric oxide (CuO) nanoparticles were synthesized in liquid media using microplasma without any electrolyte. In-liquid synthesis of nanomaterials by non-thermal plasma has been attracting attention since it doesn't require an additional reducing agent. Among them, particle synthesis during plasma electrolysis using a metal electrode as a metal ion source is one of the promising method due to its simplicity and absence of precursor, which enables to obtain clean product. Nevertheless, the existing researches have shown that electrolyte is still required to make dielectric liquid be conductive. In this study, the particle synthesis from dissolution of copper foil electrode was performed without electrolyte by assist of microplasma induced by high voltage. Moreover, the microplasma discharge was conducted with bipolar pulse power supply while similar processes are conducted with unipolar power supply. The experimental results showed the unique particle synthesis mechanism that is distinguishable from the existing methods. The synthesized particles were identified as CuO nanocrystals having particle size below 10nm. It is interesting to note that the surface morphology of electrode after the particle synthesis was similar with the synthesized particles. It seems that the obtained particles were generated through the detachment of oxide layer on the surface of electrode while successive dissolution-reduction of metal ions is main particle generation phenomena in typical plasma electrolysis. It is considered that alternate anodic and cathodic reaction by bipolar power supply induced the formation of nanostructured oxide layer on the electrode which are detached to generate the nanoparticles. Here, the particle generation mechanism will be investigated with the effect of discharge voltage on the particle generation and the measurement of pH variation during the discharge.

*Intervenant

# A novel approach for the estimation of nanoparticle evaporation through the Method of Moments.

Francesco Galleni*[1], Francesco Strappaveccia[2], and Emanuele Ghedini[3,4]

[1]Alma Mater Studiorum University of Bologna – Italie
[2]Department of Industrial Engineering - Alma Mater Studiorum - Università di Bologna (DIN) – Italie
[3]Industrial Research Center for Advanced Mechanics and Materials (C.I.R.I.-M.A.M.) – Italie
[4]Department of mechanical engineering (D.I.E.M.) – Alma Mater Studiorum – Università di Bologna, Via Saragozza 8, 40123 Bologna, Italy, Italie

**Résumé**

The synthesis of nanoparticles is of high importance for the industrial production of metallic and ceramic materials as well as in biomedical and environmental industry. Particularly, the processes involving ICTP plasma torches were found to be notably apt to the task, because of their high standards in process purity and the capability of achieving decidedly controlled mass production, since these reactors can run continuously.

Nevertheless the ICTP reactors are characterised by highly non-uniform and non-isothermal fields - due to the plasma environment - and, hence, by extremely high heating and cooling rates (up to ±107 K/s). These characteristics can certainly be considered as an asset for the process, but they also have the effect of rendering the modelling (physical and computational) of the entire process extremely challenging: a complete simulation should consider models to take into account the phenomena of nucleation, condensation, evaporation and coagulation and be sufficiently stable in order to be able to handle the high gradients of the plasma environment.

Several methods were established in the past to model the synthesis of nanoparticles, with the method of moments (MoM) and the nodal method (NM – a simplified form of the sectional method) being among the most used, chiefly because of their simplicity. In the MoM a distribution of the particle size (in volume or diameter) is assumed to solve the aerosol general dynamic equation (GDE). Commonly, the assumption of a unimodal lognormal profile for the PSD is done, so that the model becomes extremely simple, computationally fast and easy to implement; for these reasons, it was used in the past in numerous works at different degrees of complexity. However, the postulation of a static distribution remains a critical drawback especially in a plasma environment, since the model is not capable of properly predict phenomena such as recirculation or evaporation which have the effect of non-uniformly modifying the distribution and therefore tend to change its form. The poor results of the MoM in simulating evaporation phenomena in even less severe environments than those of plasma reactors have already been studied in the past. On the other hand, the discrete NM does not assume any fixed distribution and it is therefore more suited to model the whole synthesis; nonetheless the required computational effort is considerably higher than with the MoM.

*Intervenant

In this work the results of the application of the zero-dimensional form of the two approaches ( that is, the method of moments and the nodal method) are compared for the prediction of the evaporation processes, in order to understand and highlight the limits of the moment methods and to determine the usability of the method in plasma environments (i.e. high temperatures and steep gradients); in particular, the NM, is used as a benchmark for the MoM. Furthermore, a closure term is proposed for the method of moments, in order to take into account the disappearance of the particles due to the evaporation process.

# H2020 NanoDome project: a comprehensive multiscale approach to the modelling of nanoparticle synthesis in gas phase.

Francesco Strappaveccia*[1], Francesco Galleni[2], and Emanuele Ghedini[3,4]

[1]Department of Industrial Engineering - Alma Mater Studiorum - Università di Bologna (DIN) – Italie
[2]Alma Mater Studiorum University of Bologna – Italie
[3]Industrial Research Center for Advanced Mechanics and Materials (C.I.R.I.-M.A.M.) – Italie
[4]Department of mechanical engineering (D.I.E.M.) – Alma Mater Studiorum – Università di Bologna, Via Saragozza 8, 40123 Bologna, Italy, Italie

**Résumé**

Nanoparticle synthesis processes were developed for an extensive variety of materials such as pure metals, oxides or alloys. Nevertheless, accurate control of properties such as particle size distribution, composition, purity and dispersibility in a reliable and reproducible way, and at the same time guarantee a high-volume, continuous production at attractive cost/benefit ratios remains an issue. GP synthesis processes, such as plasma processes, provide a good balance between precision synthesis and production scale. This kind of processes enable the production of conspicuous quantities of nanoparticles, leading to an attractive cost/benefit ratio. However, the main problem affecting GPC processes is the difficulty of obtaining a precise control of the synthesis and to predict which process conditions can lead to products with specific characteristics. Moreover, a better understanding of the link between process conditions and nanoparticle features is also relevant for the estimation and regulation of the environmental impact of processes where nanoparticles are an undesired side effect and not the main product. These considerations strongly motivate an increase in theoretical and applied research to understand and predict the mechanisms of nanoparticles and nanostructures formation.
The H2020 NanoDome project has the aim of solving some of these issues by providing an open source modelling tool to improve existing nanoparticle gas phase synthesis process design capabilities, at research and industrial level.

From the mesoscale point of view, it is significant that each model presented until now has its own definitions and in literature a univocal physical description of the objects involved in such processes is not present. Therefore the aim of our work is to provide a common model for describing mesoscale systems and entities with a clear and precise mathematical notation, classifying the different structures that can occur during a coarse-grained simulation and, finally, propose a framework based on these definitions.

Furthermore, once the mesoscopic framework has been assessed, the novel approach proposed by the project is to provide a complete tool for simulating nanoparticles dynamics at mesoscopic scale and couple this simulation with data provided by the atomistic level for

*Intervenant

describing the behaviour of different species in the GP and on the other hand, elaborate the data provided by the CFD simulating the reactor, covering the complete processing route, in fact proposing a full multiscale model.
The preliminary results presented here are promising, not only regarding the mesoscopic simulation itself but also for the linking process with the CFD. In this poster, we present the results obtained for Si nanoparticles synthesis in a plasma reactor.

# Calculation of electron-impact excitation and ionisation cross sections and reaction rate coefficients for C, N and O atoms

Ali Hleli*[1], Philippe Teulet[2], Yann Cressault[3], Riahi Riadh , and Ghalila Hassen

[1]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France
[2]Laboratoire Plasma et Conversion d'Energie [Toulouse] (LAPLACE) – Université Paul Sabatier (UPS) - Toulouse III, CNRS : UMR5213, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France
[3]Université de Toulouse, UPS, INPT, Laboratoire Plasma et Conversion d'Energie (Université de Toulouse, UPS, INPT, LAPLACE) – Université de Toulouse, UPS, INPT – 118 route de Narbonne, F-31062 Toulouse Cedex 9, France

**Résumé**

Most of theoretical studies regarding electric arcs or thermal plasma processes and applications are achieved assuming the Local Thermodynamic Equilibrium (LTE) assumption with the development of Magneto-Hydrodynamic (MHD) models.
However, the LTE assumption is not effective in some particular regions of the plasma: in the vicinity of the electrodes and the walls and in the external areas of the arc where the pumping of contiguous cold gas has a significant effect. The LTE hypothesis is also unclear during arc decay or for low power arcs. In this last case, the temperature and the electron number density remain relatively low, even on the axis of the plasma. Thus the energy transfer between the electrons and heavy particles is not efficient enough to preserve the equal distribution of energy between the various chemical species. The consequence is that the electrons have a kinetic temperature Te higher than that of the heavy species Th.

To study theoretically this kind of discharge, taking into account the possible occurrence of departures from thermal equilibrium, it is necessary to develop multi-temperature MHD models. The implementation of these multi-T models is based upon 2T thermodynamic and transport property databases and the first and unavoidable step in obtaining these 2T properties is the calculation of the plasma composition. Several methods are available in the literature for the calculation of multi-T plasma compositions: the minimization of a thermodynamic function, the law of mass action or a kinetic or collisional-radiative (CR) model. However, it is now clearly established that the best and more accurate way to obtain the plasma composition under thermal non equilibrium conditions is the CR model. Indeed, compared to the other techniques, this kind of approach allows the avoidance of the simplifying assumptions associated with the internal excitation modes (electronic, vibrational and rotational). On the other hand, CR models are more complex to develop because they require the realisation of an extended cross sections or reaction rate coefficients database for all

*Intervenant

inelastic collisional processes between the chemical species (or internal levels) of the plasma. Moreover, the population number densities obtained from CR models in non-thermal equilibrium conditions are highly dependent of the accuracy of the cross section or reaction rate databases injected in the CR model. As a consequence, it is very important to ensure that cross-sections or reaction rates used in a CR model are accurate in order to obtain exact values of population number densities.
This work falls under these considerations as it concerns the calculation of electron-impact excitation and ionisation cross sections and reaction rate coefficients for carbon, nitrogen and oxygen atoms. Several theoretical formalisms proposed in the literature are used to calculate cross sections and rate coefficients for excitation of optically allowed and forbidden electronic transitions and for ionisation from electronic levels of the atoms. These theoretical data are then compared with each other and confronted to available experimental cross sections and rate coefficients in order to determine the most accurate formalism to be used in the implementation of CR model for C-N-O-containing plasmas. The cross section and reaction rate database finally created will be used in the development a multi-T CR model allowing the determination of the population number densities inside an electric arc generated between two graphite electrodes and dedicated to the synthesis of carbon nanoparticles.

# Degradation of phenol aqueous solution using submerged arc plasma

Eun Seo Jo*[1], Dong-Wook Kim[1], and Dong-Wha Park[1]

[1]Inha University – Corée du Sud

**Résumé**

Degradation of phenol aqueous solution was conducted using submerged arc plasma. A non-transferred arc plasma torch was located at the bottom of a reactor. Phenol aqueous solution was poured into the reactor and then was treated by discharging arc plasma jet. The plasma was generated as submerged in the solution, providing high enthalpy and active species such as hydroxyl radical (OH) for degradation of phenol. The experiments were conducted with various initial concentration of phenol, and treatment solution volumes and plasma current. The decomposition rate of phenol and the chemical oxygen demand (COD) were analyzed to evaluate the performance of phenol degradation. The experimental results showed the phenol decomposition rate above 97% when the 500mL aqueous solution with the phenol concentration of 1000mg/L was treated with the plasma jet operating at 2.6 kW for 20 min. In this study, the phenol degradation is considered to be conducted through both oxidation of organic compounds by hydroxyl radical and thermal decomposition occurring at the interface between plasma jet and phenol. The direct contact between the phenol molecule and the arc plasma led to the formation of carbon particles through simultaneous pyrolysis of the phenol molecule. Meanwhile, the hydroxyl radicals could degrade the phenol molecule through sequential oxidation. In addition, Fenton-like reaction was combined with our submerged arc plasma system for further improvement of phenol degradation. Because hydroxyl radical is considered to have a limited effect on the phenol degradation because of its short lifetime and recombination to form hydrogen peroxide, introducing catalyst was expected to improve the system efficiency. Magnetic Fe3O4 nanoparticles were used as a heterogeneous Fenton-like catalyst and led to the improved phenol degradation.

*Intervenant

# Decomposition of ceramic inks by an arc plasma jet operating in a pulsed mode and coating deposition

Fabrice Mavier[1], Fadi Zoubian[1], Pascal André[2], Marguerite Bienia[1], Martine Lejeune[1], and Vincent Rat*[3]

[1]Institut de Recherche sur les CERamiques – Université de Limoges, CNRS : UMR7315 – France
[2]Laboratoire de Physique de Clermont – Université de Clermont-Ferrand, CNRS : UMR6533 – France
[3]Institut de Recherche sur les CERamiques – Centre National de la Recherche Scientifique, Université de Limoges – France

**Résumé**

Coatings with nanostructured architectures can be obtained by plasma spraying technologies involving liquid feedstock. Suspension and Solution Precursor Plasma Spraying are of interest provided efforts must be developed to reach a proper control of heat and momentum transfers during the interaction steps between liquid and plasma. This results that arc instabilities in dc plasma spray torches must be compelled to improve the plasma properties either by limiting the arc motion or by strengthening the arc oscillations in controlled fashion.
The time-modulation of the arc current was shown to influence and promote the arc reattachment following the restrike mode in a low-powered dc plasma torch so that plasma properties, namely plasma enthalpy and speed, are strongly modulated at nozzle exit. A piezoelectric printhead for liquid injection was then synchronized with the plasma modulation to reach a better control of plasma/material interaction.

An aluminum nitrate ink and a ceramic ink composed of titanium dioxide nanoparticles were formulated to fit the technical requirements of the drop-on-demand printhead dispenser.
The thermal decomposition of the aluminum nitrate in pure nitrogen plasma at atmospheric pressure was first theoretically investigated by calculating the plasma composition at local thermodynamic equilibrium by using by the Gibbs free energy minimization method. At low temperature, the thermal decomposition was also studied by differential thermal and thermogravimetry analysis. Time-resolved imaging and Optical Emission Spectroscopy (OES) were used to describe the decomposition mechanisms. It was shown that the primary fragmentation of liquid droplets at the early stages of interaction with the plasma entailed the formation of in-flight solid fragments possibly leading to micro-sized oxide particles in the coating. OES measurements also highlighted metallic and molecular vapors (Al(I), AlO) seeded in the plasma which the trajectories depended on the injection timing with respect to plasma modulation. Amorphous alumina coatings with inclusions of $\gamma$-alumina micro-sized particles were obtained. Similar observations were carried out in the case of TiO2 ceramic ink. The controlled injection leaded to more homogeneous coatings of nanostructured cauliflowers shapes formed by titanium oxide vapors. The coatings contained a mixture of anatase and rutile phases.

*Intervenant

# Influence of current modulation on arc instabilities in dc plasma spray torch

Fabrice Mavier[1], Fadi Zoubian[1], and Vincent Rat*[1]

[1]Institut de Recherche sur les CERamiques – Centre National de la Recherche Scientifique, Université de Limoges – France

**Résumé**

Arc instabilities in dc plasma spray torches have evident pernicious influences on plasma jet properties, especially when injection liquid droplets for the deposition of finely structured coatings. Their control remains a challenging task in terms of basic understanding and technological improvement of dc torches. Segmented torches are now widely developed with configurations involving complex multi-electrode arrangements resulting in the use of several associated power supplied. In conventional torch with single cathode and anode electrodes, the arc fluctuations obey different modes of instabilities, mainly the restrike and Helmholtz modes. In low-powered dc torch operating with pure nitrogen and constant arc current, it was shown that the arc dynamics closely followed the restrike mode, i.e. it was governed by a stick and slip motion interrupted by the arc reattachment upstream the anode nozzle at a frequency of about 1400 Hz. The restrike mode being known to be influenced by the arc current value, it was investigated the influence of the time-modulation of the arc current amplitude on the arc dynamics. The electrical features of the dc torch were analyzed as function of the current amplitude. Plasma speed and temperature were also measured. Time-resolved end-on imaging of the arc was carried out following the voltage and current time-dependences. A simplified model of fluctuating plasma properties at nozzle exit was compared to the measurements. It was observed that the arc current modulation influenced the restrike mode by modulating the arc radius and probably also the electric field strength of the arc column.

*Intervenant

# Experimental characterization of a surface-wave sustained Argon-N2-H2 mixture plasma column at atmospheric pressure

Jong Hern Mun*[1], Mathieu Masquère[1], Philippe Teulet[1], Yann Cressault[1], and Abdel Majid Kassir[1]

[1]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

**Résumé**

Microwave plasma jets at atmospheric pressure have been generating increasing interest in terms of plasma processes for material synthesis, deposition and gas depollution. They combine many advantages such as low cost, simple design and easy handling, but since the thermal equilibrium is hard to reach with this architecture [1], optimizing the process is rather a delicate task. Nevertheless, MW plasma for its stability is suited to validate transfer properties or spectrum simulation data comprising thermal nonequilibrium one can observe in peripheral area of a thermal plasma.
This study aims at validating the plasma spectrum simulation code that is under development by our team in LAPLACE [2] with a surfatron powered atmospheric pressure microwave plasma jet using different gases. This paper contains first results of Ar - N2/H2 mixture plasma diagnostics including excitation and rotational temperature of the plasma obtained by Boltzmann plot on argon lines and the first negative system of N2+, and the electron density given by Stark broadening of H alpha line. Spline interpolation based Abel inversion was applied to the molecular band of N2+ for the Boltzmann plot and LIFBASE was used to compare the spectrum.

The gas is tangentially injected in a 11/16mm diameter quartz tube, increasing the tube's stability under plasma load by preventing its wall from being damaged by overheating or pierced/broken by the sticking of the plasma at a fixed position along it [3]. The outer tube wall is air-cooled. Electromagnetic surface wave at 2.45Ghz@800W was used to sustain the plasma. Spectroscopic emission data was acquired 6cm over from the surfaguide center through the tube.

**References**

Jasiński, Mariusz, et al. "CFC-11 destruction by microwave torch generated atmospheric-pressure nitrogen discharge." *Journal of Physics D: Applied Physics* 35.18 (2002): 2274.

T Billoux, " Élaboration d'une base de données radiatives pour des plasmas de type CwHxOyNz et application au transfert radiatif pour des mélanges air, CO2 et CO-H2 " (2013). PhD Thesis. Université de Toulouse.

Y. Kabouzi et al, French patent application (2004) FR 04 51527

*Intervenant

# Experimental Study on insulation properties of C4F7N/N2 mixture substituting SF6 in insulation

Tian Shuangshaung*[1,2], Cressault Yann[2], Zhang Xiaoxing[1], Xiao Song[1], Li Yi[1], Zhang Ji[1], and Chen Qi[1]

[1]School of Electrical Engineering, Wuhan University – Chine
[2]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

**Résumé**

The research of new insulating gas is to substitute SF6 in gas-insulated equipment because of the higher global warming potential of SF6. The breakdown voltage and partial discharge initial voltage of C4F7N/N2 mixture are explored at the power frequency voltage under the different mixing ratios at 0.1-0.6MPa. The experimental results show that the increase of pressure and mixing ratio can effectively improve the insulation performance of C4F7N/N2 mixture gas. The breakdown performance of C4F7N/N2 mixed gas at 0.3MPa, 0.4MPa, 0.5MPa and 0.6MPa can reach 63.4%, 54.6%, 49% and 56.4% of pure SF6. Considering the liquefaction temperature characteristics of the mixed gas, if the mixed gas is used in high-voltage electrical insulation equipment, it should meet the minimum operating temperature of -25 ◦C. The content of C4F7N should be less than 6% at 0.6MPa and be less than 12% 0.3MPa. The experimental results can provide support for the use of new gases in equipment.
The breakdown voltage and partial discharge initial voltage of 0.1% to 0.6MPa and C4F7N content of 2% to 12% are studied under AC voltage (50Hz). The C4F7N gas used NOVEC 4710) is of 99 % purity. Experiments are performed using a step-up method on the needle-plate electrode. The power frequency voltage is applied to cause PD, and the waveform of the PD signal is obtained by a pulse current method and a high-speed digital acquisition system. The voltage is gradually increased until the breakdown of the gas, the applied voltage as the breakdown voltage value. The partial discharge characteristics and the power frequency breakdown characteristics of C4F7N/N2 mixed gas in the non-uniform field are systematically evaluated using the gas insulated dielectric test platform. The effect of gas pressure and mixing ratio on the insulation performance is analyzed. The research results can provide an important basis for its engineering application.

We discussed that:

(1) the insulation performance of C4F7N/N2 mixture gas increases at the same pressure as the mixing ratio increases. The relative insulation performance of mixed gas at high pressure (0.5-0.6 MPa) shows a trend of saturation growth with increasing mixing ratio. Increasing the mixing ratio at low pressure can significantly increase the insulating properties of the gas mixture.

*Intervenant

(2) the breakdown performance of C4F7N/N2 mixed gas at 0.3MPa, 0.4MPa, 0.5MPa and 0.6MPa (very uneven electric field) can reach 63.4%, 54.6%, 49% and 56.4% of pure SF6; PDIV- 80.4%, 66.9%, 62.8% and 68.8% of the pure SF6 under the same conditions can be achieved.

(3) the C4F7N/N2 mixture gas has the potential to completely replace SF6 in low voltage electrical equipment. Due to the limitation of the liquefaction temperature under high pressure, the insulating properties of the mixed gas cannot reach the level of that of pure SF6 .

# Study of underwater pulsed electric discharge plasma for synthesis of metal colloidal solutions

Tetiana Tmenova*[1,2], Yann Cressault[3], Valensi Flavien[4], Anatoly Veklich[2], Viatcheslav Boretskij[2], and Konstantin Lopatko[5]

[1]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – Université Paul Sabatier - Toulouse III – France

[2]Taras Shevchenko National University of Kyiv – Ukraine

[3]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – Université Paul Sabatier - Toulouse III – France

[4]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – CNRS : UMR5213, Université Paul Sabatier [UPS] - Toulouse III, Institut National Polytechnique de Toulouse, Université Paul Sabatier (UPS) - Toulouse III – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[5]National University of Life and Environmental Sciences of Ukraine – Ukraine

**Résumé**

Studies of electric discharge plasma in liquids attract attention of researchers both from the point of view of scientific challenges and its numerous applications in such fields as biology, medicine, chemistry, electrochemistry, etc. Over the past few decades, a new branch of plasma research, nanomaterial synthesis through plasma-liquid interactions [1], has been developing rapidly, mainly due to the various, recently developed plasma sources operating at low and atmospheric pressures.
The nature of the discharges in liquids is much less understood and may be completely different from those in gases. Unfortunately, until now there are no complete physical models of such discharges, which makes them of a great scientific interest.

In this work, studies of underwater pulsed electric discharge were implemented using two experimental setups. The first one is a technological unit for synthesis of metal colloidal solutions by means of underwater electrospark erosion of metal granules [2]. During each pulse, several arcs ignite between granules in a stochastic mode. These sub-pulses that cause actual erosion can be shorter than the pulses delivered by the power supply. High-speed imaging allowed us to visually distinguish individual spark pulses occurring between granules and estimate their average duration. This arcing time was used for the second setup that allows creating arcs in a simplified configuration (single-pulse discharge between two cylindrical tapered electrodes) [3]. The reference configuration is for copper electrodes (6 mm diameter) with tip at a depths of 5 mm in tap water, maximal current of 600 A and an arc duration of 150 $\mu$s. Additional tests were performed to study the influence of arc power, electrode material (molybdenum instead of copper), water depth and properties (use of deionize water).

In the case of the operational unit, the spatial and temporal lack of reproducibility presents a challenge for optical emission spectroscopy (OES) diagnostics. Consequently, only qualitative

*Intervenant

study (spectra recording for emission lines identification) has been performed, with a four-grating SDH-IV spectrometer (Solar Laser Systems). More thorough spectroscopic diagnostic has been performed using the second setup. An Acton SpectraPro SP-2750 monochromator equipped with EMCCD camera (Princeton Instruments) was used to get spectra during the high-current part (50ms) of the pulse.

Spectra analysis and estimation of plasma parameters were performed with respect to electric characteristics of the experimental arrangements and, correspondingly, different values of the power input in two studied systems. High-speed imaging was also used with the second setup to study the geometry of plasma channel and bubble as a function of experimental conditions. Estimation of erosion rates (from mass loss measurement) shows that anode erosion is greater than that of cathode.

**References**

Chen Q., Li J., Li Y. A review of plasma–liquid interactions for nanomaterial synthesis // J. Phys. D: Appl. Phys.– 2015. – V.48. – P. 424005.

Tmenova T.A., Veklich A.N., Boretskij V.F., Cressault Y., Valensi F., Lopatko K.G., Aftandilyants Y.G. Optical emission spectroscopy of plasma of underwater electric spark discharges between metal granules // Problems of Atomic Science and Technology. – 2017 – V.1. – P.132-135.

Venger R.O., Tmenova T.A., Veklich A.N., Boretskij V.F., Cressault Y., Valensi F. Detailed Investigation of the Electric Discharge Plasma between Copper Electrodes Immersed into Water // Atoms. – 2017. – V. 5. – 17 p.

# Development and characterization of a 3D-printed compact atmospheric plasma reactor

Fadi Zoubian , Hervé Rabat , Olivier Aubry , Nicolas Dumuis , Sebastien Dozias , and Dunpin Hong*[1]

[1]Groupe de recherches sur l'énergétique des milieux ionisés – Université d'Orléans : UMR7344, CNRS : UMRUMR7344 – France

**Résumé**

The increasing use of high quality thin films in many technological applications such as photovoltaics and microelectronics has prompted the need to improve the deposition processes. New processes should be able to run in less constrained conditions such as atmospheric pressure rather than vacuum and to have faster deposition rates while respecting the same high quality of deposited films. Recent works have shown the significant benefit of Atmospheric Spatial Atomic Layer Deposition (SALD) avoiding the traditional purging and injection cycles needed to a time separated injection of reaction species, and a more significant benefit thanks to the coupling of an atmospheric plasma to SALD. In this context, we developed a compact atmospheric dielectric discharge barrier (DBD) plasma reactor to assist an atomic layer deposition SALD process. Additive fabrication, also known as 3D printing, was used to realize the plasma reactor. This reactor was designed to be compatible with the SALD head. A High Voltage generator delivering up to 25 kV in amplitude supplied the plasma source. The influences of the shape and thickness of the DBD arrangement on the morphology of the discharges were analyzed by imaging measurements. A curved shape allows having a plasma closer to the exit of the reactor to deliver short-life species to the reaction zone. The electrical properties of the discharges were measured as functions of applied voltage and frequency showed for instance that the active power varies between 0.2 W and 3.3 W with the increasing of the frequency from 1 to 10kHz. Finally, the exit gas was analyzed by using chemical methods such as FTIR spectroscopy and micro gas chromatography.

*Intervenant

# Synthesis of Tungsten Carbide Nanoparticles using Triple Thermal Plasma Jet System

Jeong-Hwan Oh*[1], Minseok Kim[1], Young Hee Lee[1], Seung-Hyun Hong[1], Tae-Hee Kim[2], and Sooseok Choi[1,2]

[1]Department of Nuclear and Energy Engineering, Jeju National University – Corée du Sud
[2]Institute for Nuclear Science and Technology, Jeju National University – Corée du Sud

**Résumé**

Tungsten is widely used for the high temperature application such as filaments, electrodes, rocket nozzles, etc. The tungsten carbide is difficult to be synthesized as nanoparticles due to extreme high melting and boiling point of tungsten as 3.695 and 6.230 K, respectively. Triple thermal plasma jet system was newly developed for the synthesis of promising nanomaterial by vaporization of raw material. In the traditional singular thermal plasma jet system, the vaporization of injected raw material is incomplete by the high velocity of viscous plasma jet. Therefore, the injection of the raw material into the central jet is important. In the triple thermal plasma jet system, three thermal plasma jets are encountered at the center axis of the reactor and form an extended flame. The starting material is injected into the central flame and goes through the central high temperature region of the flame.

In this work, tungsten carbide (WC) nanoparticles were synthesized from refractory tungsten powder having micron size and different carbon sources of amorphous carbon and carbon nanotubes. In order to evaporate refractory tungsten and carbon, the input power was set highly as 20_˜30 kW by Ar-N2 mixed plasma forming gas. Mixed tungsten and carbon powder was fed at 0.2_˜0.5 g/min with Ar carrier gas of 5 L/min.
The produced particles were analyzed as crystal W, WC and W2C from X-ray diffraction (XRD) measurement. The tungsten crystal peaks were detected from the un-vaporized raw tungsten powder in SEM analysis. Tungsten carbide nanoparticles were synthesized in a small size under 40 nanometers with angular morphology. In the transmission electron microscope (TEM) measurement, on the other hand, it was observed that the synthesized nanoparticles were crystal WC and W2C by analyzing the lattice structure of HR-TEM images.

*Intervenant

# Synthesis of Metal Boride Nanoparticles in Triple Thermal Plasma Jet System

Minseok Kim*[1], Jeong-Hwan Oh[1], Tae-Hee Kim[2], Yong Hee Lee[1], Seung-Hyun Hong[1], and Sooseok Choi[1,2]

[1]Department of Nuclear and Energy Engineering, Jeju National University, Jeju 63243, Republic of Korea – Corée du Sud

[2]Institute for Nuclear Science and Technology, Jeju National University, Jeju 63243, Republic of Korea – Corée du Sud

**Résumé**

Titanium, nickel, and tungsten boride nanoparticles were synthesized from metal and boron powder as starting materials in triple thermal plasma jet system. The coalesced high-enthalpy thermal plasma jet not only generates an extensive high temperature region but also allows the penetration of starting materials into the center of high temperature region effectively. Accordingly, it was greatly improved to evaporate for micro-sized Ti, Ni, W, and B powders which have high vaporization temperature above 3,000 K. The triple thermal plasma jet was generated by 14 L/min of Ar and 14 L/min of N2 mixed gases. The current of each torch was fixed at about 90 to 100 A, and then each voltage of them was 90 to 100 V. Three kinds of starting material were respectively injected to the synthesis system which consists of filter and 7 reactor sections as mixture of Ti and B (1:2 mol %), Ni and B (1:1 mol %), and W and B (1:2 mol %) with Ar carrier gas of 5 L/min.

The characteristics of nanoparticles were observed from TEM images. Since the synthesized particles size was 50_˜100 nm, it was confirmed that starting materials were completely evaporated in the triple thermal plasma jet system. In XRD analysis, TiB was dominant in the reactor which is located near the plasma flame, while TiB2 was mainly found in the backside reactor and the filter. It means the titanium boride nanoparticles have two phase structures simultaneously as well as the synthesis mechanism differed according to the reactor region. In the case of Ni and B starting material, NiB was more dominant than Ni2B and Ni4B3 in the whole reactors. The crystallinity of the synthesized nickel boride was lower than the synthesized titanium boride. In W and B starting material, W2B was more dominant than WB and WB4 in the all reactor from XRD analysis.

*Intervenant

# Numerical Simulation of Triple DC Plasma Torch System

Lee Yong Hee*[1], Kim Tae-Hee[2], and Choi Sooseok[1]

[1]Department of Nuclear and Energy Engineering, Jeju National University, Jeju 63243, Republic of Korea – Corée du Sud

[2]Institute for Nuclear Science and Technology, Jeju National University, Jeju 63243, Republic of Korea – Corée du Sud

**Résumé**

DC thermal plasma is widely used to synthesize various nanoparticles as an excellent medium with high temperature and velocity. Although the temperature of thermal plasma jet is increased up to above 10,000 K, general single DC thermal plasma has a limitation to evaporate the refractory raw material. Because the velocity of plasma jet is extremely rapid in the center of the flame, the injected raw material is difficult to flow into the higher temperature region. The triple DC plasma torch system has been suggested to overcome this limitation [1]. The three plasma jets generated by each torch converge toward to the center point, and it forms a large flame in the reactor. The raw materials are injected into the interspace of the jets. It is supplied more effectively to exposure high enthalpy environment. In experiments, nanoparticles which requires high enthalpy medium such as borides, carbides, non-equilibrium condensed oxides were successfully synthesized in the triple DC plasma torch system.

The three plasma torches were supplied at a fixed current of 100 A, and the input power was controlled by the determined arc voltage according to the kind of discharging gases; Ar, Ar-N2, Ar-H2 gases. The flow rate of Ar was fixed at 14 slpm and N2 and H2 were added at 14 slpm. The input power was determined as about 7 kW by Ar discharging gas. The high temperature region that is able to evaporate the raw material is not formed sufficiently in the reactor region in pure Ar discharge. The total input power rose up to about 25 kW with the injection of the additional N2 and H2 gases with Ar discharging gas. In both cases, the temperature at the central area that the plasma jets are converged was calculated from 6,000 to 6,300 K. The volume of this high temperature region was broaden and elongated as N2 and H2 gases, respectively. It describes the resulting situation in the actual experiments that the characteristic of nanoparticles are different depends on the collection position due to the residence time of the vaporized raw material in the high temperature region.

Z. P. Lu, J. Heberlein and E. Pfender, *Plasma Chem. Plasma Process.* 12, 55, (1992)

*Intervenant

# Impact of the substrate on the discharge characteristics in an atmospheric-pressure helium plasma jet: Optical diagnostics

Julien Cosimi* , Frédéric Marchal*[1], Nofel Merbahi[2], and Mohammed Yousfi

[1]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – CNRS : UMR5213, Université Paul Sabatier - Toulouse III, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[2]LAPLACE-CNRS University of Toulouse (LAPLACE-CNRS Toulouse) – CNRS : UMR5213, Université Paul Sabatier - Toulouse III – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

**Résumé**

Low-temperature atmospheric pressure plasma jets can generate reactive species without heating and are very attractive for medical applications as for example chronic wounds treatment. The plasma jet, driving by an impulse high voltage supply, produces a succession of fast ionisation waves launched from the jet through a gas helium gas flow. The characteristics of the plasma jet have a strong dependence with parameters like electrical conductivity of the surface treated and the gas flow rate. To have a better understanding of the propagation and interaction mechanisms of ionisation waves produced by plasma jet with a surface, special, temporal and spectral resolved optical analysis and fast imaging are employed.

Plasma jet used in this study is made of two aluminum electrodes wrapped around a quartz tube of 6 mm outer diameter. The upper electrode is linked to the high potential of a pulsed high voltage generator and the lower electrode to the ground. For the present study high voltage parameters are fixed at 10 kV amplitude, 10 kHz frequency and 1 $\mu$s pulse width. Helium (99,999%) is injected throw the tube and the gas flow rate is controlled by a flow meter. Optical emission of OH (306 to 310 nm), N2 (SPS 337 nm) and O (triplet around 777 nm) are monitored over time along two axes (axial and radial) of the plasma jet using a photomultiplier and a photon counter with a time resolution of 5 ns. To reconstruct the spatial distribution of the plasma properties, a filtered Abel transform is implemented. Fast imaging is performed with an ICCD camera synchronised with the discharge generation with a delay generator. Influence of the nature of the exposed substrates is studied by using three substrates with different electrical conductivity: glass, metal and deionized water.

Our results show that the nature of the exposed substrates can induce change in the propagation of the plasma jet. For materials with low electrical conductivity, ionization wave reaches substrate surface and propagates on the dielectric surface tangentially to the horizontal component of the electric field produces by surface charging. In the case of metal exposition, a conductive channel between the substrate and helium plasma jet is observed. The channel is characterized by high photon emission and a larger number of excited species than for low conductive material. Furthermore, the presence of a second discharge which propagates from the substrate toward the jet outlet is highlighted.

*Intervenant

With deionized water, which has an average conductivity between glass and metal, an association of the two phenomena with the splitting of the ionization wave in a surface ionisation wave and the formation of a conductive channel with the presence of the second discharge which propagates from the surface to the jet are observed.

# Suspension Plasma Spraying

Christian Moreau*[1]

[1]Concordia University [Montreal, Canada] – Canada

**Résumé**

Over the last decade, extensive research and development efforts have been dedicated to the emerging technology of suspension plasma spray (SPS). In this process, the feedstock material to be deposited consists of nano- or submicron-sized particles in suspension in a liquid (commonly ethanol or water). This suspension is injected in a plasma jet to produce coatings with unique microstructures, one or two orders of magnitude finer than those achieved normally in air plasma spray (APS). This emerging technology has attracted much attention over the last 20 years as it opens up a series of new research challenges as well as emerging industrial coating applications. In this presentation, an overview of the SPS technology will be provided with a focus on key challenges that must be addressed to improve our understanding and control of this innovative coating process. In particular, the injection of the suspension in the high speed thermal plasma jet and the trajectory of the impinging micron-size droplets close to the substrate at the stagnation point will be discussed. Finally a few examples of emerging applications of the SPS technology will be introduced.

*Intervenant

# Direct decarbonization of methane by thermal plasma for the co-production of hydrogen and carbon nanostructures

Laurent Fulcheri*[1]

[1]Centre Procédés, Énergies Renouvelables, Systèmes Énergétiques – MINES ParisTech - École nationale supérieure des mines de Paris, Université de recherche Paris Sciences Lettres (PSL) – France

**Résumé**

In the context of the large scale deployment of Renewable Energy for green electricity production, plasma processes present a formidable alternative to many high-temperature highly CO2-emitting processes based on hydrocarbons combustion. In this paper, we discuss the development of a new breakthrough process for the co-production of hydrogen and carbon nanostructures by direct cracking of methane at very high temperatures without direct CO2 emissions. We first begin with a state of the art review of the plasma development, then we focus our attention on the main scientific stakes and challenges associated with this development, including gas phase particles nucleation and growth, nanosecond mixing, reactive plasma flows and CFD and MHD modelling.

*Intervenant

# Model of the cathode region of plasma photoelectric converter of concentrated solar radiation.

Nikolay Gorbunov*[1] and Gilles Flamant

[1]Admiral Makarov State University of Maritime and Inland Shipping, 198035, Dvinskaya st. 5/7, St. Petersburg – Russie

**Résumé**

In this study, we consider a model of the cathode region of a plasma photoelectric converter of concentrated solar radiation in the regime of an open external circuit. Plasma is analyzed in sodium vapor at a pressure of (1E4 -1E5) Pa, which ensures effective absorption of the entire spectrum of solar radiation. The necessary optical power is calculated for creating a plasma in the state of Local Thermodynamic Equilibrium (LTE), whose temperature is in the range 4000-4500 K. This temperature provides a small internal resistance of the plasma voltage source, which is a necessary condition for effective direct photoelectric conversion.
To solve the problem, the radial distribution of the plasma parameters was analyzed on the basis of the energy balance equation. We found that the transfer of energy by radiation plays an important role in the formation of the radial distribution of the LTE plasma temperature. A large value of thermal conductivity ensures a small temperature drop between the central part and the plasma LTE boundary near the walls of the converter.

To specify the boundary conditions in the energy balance equation at the plasma LTE boundary, we considered the hydrodynamic model of an expansion zone near the wall of the cathode. In this zone, there is a sharp decrease in the thermal conductivity due to radiative energy transfer, and the temperatures of electrons and heavy particles are different. Our estimates show the important effect of the cathode temperature on the radiation transfer of energy. A large number of alkali molecules are formed at a sufficiently low wall temperature. The absorption spectrum of the molecules prevents the radiation from leaving the plasma. The alkali molecules dissociate effectively into atoms at a high wall temperature and the role of radiative energy transfer increases. Similarly, a significant effect of the wall temperature on the radiation yield is observed experimentally for gas-discharge light sources.

The thermal non-equilibrium plasma model resulted in calculating the spatial distribution of the electron temperature up to the boundary of the ionization layer and the energy flux carried away to the cathode wall by charged particles. An electron temperature gradient is formed in the expansion zone. The energy losses of electrons in the ionization layer near the cathode are compensated by the thermal conductivity of the electron gas. Thus, the energy balance for the cathode region in a photoplasma differs significantly from the local energy balance of arc discharge at atmospheric pressure. The specificity of the conditions under consideration consists in the non-local nature of the balance of the electron temperature in the expansion zone.

*Intervenant

Acknowledgements: This work was supported by French "Investments for the future" programme managed by the National Agency for Research under contract ANR-10-LABX-22-01 (labex SOLSTICE).

# Numerical optimization of Mean Absorption Coefficient in Air using Planck Modified Mean Function

Narjisse Kabbaj*[1], Yann Cressault[1], Philippe Teulet[1], and Frank Reichert[2]

[1]Université de Toulouse, UPS, INPT, Laboratoire Plasma et Conversion d'Energie – Université Paul Sabatier-Toulouse III - UPS – France

[2]Siemens AG, E T HP CB RD ENG 1 – Allemagne

**Résumé**

The prediction of the radiative contribution in the energy balance of the plasma is essential to provide for a satisfactory description of the thermal behavior of electric arc.
The accurate estimation of the divergence of radiative flux (DRF) is necessary to describe the temperature evolution within the arc. The DRF is obtained by the resolution of the Radiative Transfer Equation (RTE). Unfortunately, this equation is complex to solve and demands a high computational effort because of its dependence on temperature, pressure, wavelength, and the geometry. In fact, the complexity of the spectrum of absorption coefficient makes the resolution of RTE very challenging.

Many approximate methods were developed to simplify the problem in term of computational time. The first one concerns the Net Emission Coefficient (NEC)[1-2]. This property is a geometrical simplification. It allows a good prediction in the hottest regions of the plasma. The second approximation is a spectral simplification: Mean Absorption Coefficient (MAC). This property is characterized to induce less error on the radiative transfer in the medium and cold regions of the plasma. However, this method requires having a good definition of both spectral intervals and mean functions (classic, Rosseland, Planck, Planck modified (PMMF), ...) to determine an accurate divergence of radiative flux in numerical methods. For this approximate method, the spectral range is defined according to the continuum of absorption coefficient and we use the Planck modified mean function to calculate MACs. This mean function requires a good definition of the characteristic absorption length. In fact, in the presence of strong broadening lines and molecular emission, the characteristic absoprtion length plays an important role for the accurate calculation of mean absorption coefficients. In this paper, we develop a methodology of optimization that allows to find the best absoprtion lenght in order to have an accurate divergence of radiative flux using MACs.

A detailed description of these approximate methods is developed in the case of Air plasma at P=1bar. To have an estimation about the accuracy of these methods, a 1D resolution the RTE for given temperature profiles is presented. Also a comparison of the exact DRF with DRF using NEC, MACs (PPMF) and MACs optimized is described.

*Intervenant

## References

J.J. Lowke, J. Quant. Spectrosc. Radiat. Transfer (1974), 14, 111

J.J. Lowke and E.R. Capriotti, J. Quant. Spectrosc. Radiat. Transfer (1969), 9, 207

# Numerical Analysis of SF6 Decomposition Process in a Cement Kiln Reactor Combined with Thermal Plasma

Juyoung Ko*[1], Sooseok Choi[1], and Tae-Hee Kim[2]

[1]Department of Nuclear and Energy Engineering, Jeju National University – Corée du Sud
[2]Institute for Nuclear Science and Technology, Jeju National University – Corée du Sud

**Résumé**

Perfluorocompound(PFC)gases have a very long life time in the atmosphere and a high global warming potential (GWP) which is thousands of times higher than those of carbon dioxide and hydrocarbons. Among PFCs, SF6 used in an insulation material manufacturing releases into the atmosphere, its decomposition requires a high enthalpy environment due to its chemical stability.
Calcium oxide (CaO) is produced by decarboxylation of limestone (CaCO3) which is the main ingredient of cement. CaO is reacted with other materials in the cement kiln and produced the clinker.The cement kiln, which has a temperature of above 1,000 K and contains a large amount of CaO as an effective reactant, is suitable environment for SF6 decomposition. However, a temperature in the kiln is nonuniform according to the position and time. Since high temperature source is able to decompose completely, thermal plasma is advantageous that provides high temperature above 10,000 K.

In order to investigate more efficient decomposition technique for high concentration of SF6, on a large scale, the numerical analysis was performed for the kiln combined with the thermal plasma torch. We carried out thermodynamics equilibrium calculations to analyze the potential of the decomposition and recombination of SF6 according to temperature based on the Gibbs free energy minimum. It was revealed that SF6 begins to decompose from 1,300 K and mostly disappear at 2,500 K. The decomposed SF6 molecules by thermal plasma react with CaO as a reactant to produce CaF2 and CaSO4. This reaction has the equilibrium constant above 1 (log k $>$ 0) at the room temperature. Even if the reaction rate in the actual process is decrease than the calculated result, it is expected to be sufficiently reacted at low temperatures. The produced CaF2 byproduct can be re-decomposed above 3,000 K in thermodynamic equilibrium calculation. Therefore, in order to prevent the re-decomposition of CaF2, it is necessary to simulate the temperature distribution inside of the Kiln.
In this study, a direct current (DC) non-transferred arc plasma torch was applied for generating nitrogen thermal plasma. It was applied that the flow rate of discharge gas (N2) was 150 L/min, and the input current was fixed at 100 A in the atmospheric pressure. The calculated results for thermal plasma jet were verified by comparing measured arc voltage and input power as experimental data. Numerical analysis was carried out to examine the heat flow characteristics in cement kiln. The complex flow in the kiln region are simulated by a commercial computational fluid dynamics(CFD) code, FLUNET. As a result, the temperature distribution inside the cement kiln was analyzed to establish the basis of the numerical analysis for the decomposition and conversion process of SF6.

*Intervenant

# Recent advances in the modelling of plasma-electrode interaction and electrode erosion in high- to low-pressure to vacuum arcs

Mikhail Benilov*[1,2]

[1]Departamento de Física, FCEE, Universidade da Madeira, Largo do Município, 9000-082 Funchal, Portugal – Largo do Municipio 9000-082 Funchal Portugal, Portugal
[2]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal – Portugal

**Résumé**

One-fluid MHD equations, which are widely used for arc modelling and rely on the assumption of LTE, lose their validity near electrodes, where LTE breaks down. Since regime of current transfer to electrodes is of critical importance to efficiency and lifetime of arc devices, there has been a surge of interest in the literature toward going beyond one-fluid models. This talk is concerned with advances achieved in the last couple of years due to efforts invested by various groups around the globe.
The work has continued on the unified modelling approach, which is a standard tool in simulations of cold plasmas. This approach employs the single set of equations, including the Poisson equation (as well as transport and conservation equations for each plasma species and the electron energy equation), in the whole interelectrode gap. New results have been published concerning application of this approach to model 1D problems. The unified modelling approach has been successfully applied for 2D simulations of low-current high-pressure arcs.

The work has continued on the numerical approach that relies on the assumption of quasi-neutrality in the bulk and boundary conditions describing the near-cathode space-charge sheath, and on the approach that relies on the assumptions of quasi-neutrality and ionization equilibrium in the bulk and boundary conditions describing the space-charge sheath and the ionization layer near the cathode. An approach has been developed that employs the assumptions of quasi-neutrality and ionization and thermal equilibrium in the bulk and boundary conditions describing the sheath, the ionization layer, and the layer of thermal non-equilibrium near the cathode. The latter approach is significantly simpler than the first and second ones, requires less work on evaluation of material functions, and is also much simpler for numerical realization and may be implemented by means of ready-to-use specialized software.

New results on near-anode layers have been reported. In particular, the modelling of near-anode layers in arc discharges in several gases, performed in a wide range of current densities, anode surface temperatures, and plasma pressures, has shown that the density of energy flux to the anode is only weakly affected by the anode surface temperature and varies approximately linearly with the current density. This allows one to interpret modelling results in

*Intervenant

terms of volt equivalent of the heat flux to the anode; the so-called anode heating voltage. The data computed have been used, in particular, for formulation of boundary conditions for the LTE arc plasma equations at the plasma-anode interface.

Significant advances have been achieved by workers from different countries in the first-principle modelling of erosion of volatile cathodes of vacuum and low-pressure arcs. A model of cathode spots in high-current vacuum arcs was developed with account of all the potentially relevant mechanisms: the bombardment of the cathode surface by ions coming from a pre-existing plasma cloud; vaporization of the cathode material in the spot, its ionization and the interaction of the produced plasma with the cathode; the Joule heat generation; melting of the cathode material and motion of the melt under the effect of the plasma pressure and the Lorentz force and related phenomena. It was found that a crater is formed on the cathode surface and a droplet is ejected without explosions; a result in stark contrast with the reigning paradigm of explosive emission. The same model was applied to investigation of unipolar arcs on tungsten tiles of plasma-facing components in fusion devices.
The work was supported by FCT of Portugal (project Pest-OE/UID/FIS/50010/2013).

# Reproduction of cosmic dust by non-equilibrium condensation in triple thermal plasma jet system

Tae-Hee Kim*[1], Jeong-Hwan Oh[2], Minseok Kim[2], Yong Hee Lee[2], Akira Tsuchiyama[3], Junya Matsuno[3], Aki Takigawa[3], and Sooseok Choi[1,2]

[1]Institute for Nuclear Science and Technology, Jeju National University – Corée du Sud

[2]Department of Nuclear and Energy Engineering, Jeju National University – Corée du Sud

[3]Mineralogical Laboratory, Division of Earth and Planetary Sciences, Kyoto University – Japon

**Résumé**

Cosmic dust analogue nanomaterial called as GEMS (glass with embedded metal and sulfides) was reproduced in triple thermal plasma jet system in this work. Chondritic porous interplanetary dust particles (CP IDPs) contain abundant amorphous silicate grains of ~100 nm in size with Fe-Ni and FeS nanoparticles known as GEMS (glass with embedded metal and sulfides). It is considered to be the most primitive materials of the solar system, and some of them originated from pre-solar environments. Since the origins of GEMS are still in controversy as non-equilibrium condensation in the early solar nebula and amorphization by irradiation in interstellar medium, the reproduction experiments of them is crucial for determination of the GEMS origin. Thermal plasma having high temperature and velocity characteristic is able to possible generates non-equilibrium condensation environment.

In previous studies, nanoparticles with very similar structures to GEMS were formed using the ITP (Induction thermal plasma) system at 6 kW in a limited parameter range of, which suggested that a high quenching rate is a key condition to reproduce GEMS-like textures. Subsequently, we performed same experiments with the single DC non-transferred thermal plasma jet to improve the quenching rate and offer higher temperature. However, it was a limitation that the vaporization of starting material was incomplete because some of the starting material could not pass through high temperature region efficiently due to extreme high velocity in central jet. Since the starting material have various atomic component and it was controlled in molar scale, the complete vaporization of them is important factor.

In order to improve the vaporization and provide higher quenching rates, we carried out the vaporization and condensation experiments in the triple thermal plasma jet system at the higher input power of 30 kW. A mixture of micron-sized metal and oxides powder was used as a starting material; Si, SiO2, MgO, Fe, Na2SiO3, CaO, and Ni under 10 $\mu$m. The chemical composition having the averaged composition of GEMS without sulfur was adopted as a starting material. The starting material was injected into the high temperature region of the merged thermal plasma jet and condensed nanoparticles were collected at the chamber wall. Most run product was analyzed as metal embedded amorphous silicate nanoparticles under 50 nm in the reactor which is located near the plasma flame. However, most run products were metal attached amorphous silicate in the further reactor from the plasma jet. The particle size was increased to few hundreds nanometers and a lot of amorphous silicate particles without the embedded metal was observed. It was described that the vaporized starting material had undergone different condensation process according to the condensed position as reactor.

*Intervenant

# A Multi-Stage approach for DBD modelling

Andrea Cristofolini*[1] and Arturo Popoli*[1]

[1]Department of Electrical, Electronic and Information Engineering, University of Bologna – Italie

**Résumé**

**A Multi-Stage approach for DBD modelling**
Andrea Cristofolini, Arturo Popoli

Department of Electrical, Electronic and Information Engineering "Guglielmo Marconi", University of Bologna

Cold plasmas combine the advantages of non-equilibrium plasma properties with the ease of atmospheric-pressure operation and with the flexibility in the choice of used materials. DBDs in air usually produce a number of chemical active species (ozone, OH radicals, etc.), which are the basis of many industrial applications aimed at the sterilization, the treatment of gas streams and combustion. The body force and the energy delivered to the discharge are exploited in applications related to flow control (delay of the transition from laminar to turbulent regime, stall delay).

One of the greatest difficulties in modeling the cold plasma produced by a Dielectric Barrier Discharge is to adequately represent the non-equilibrium regime. In particular, streamer dominated discharges are characterized by wide differences in time scales and characteristic lengths. The lifetime of a streamer in atmospheric air is typically in the range of some nanoseconds, while its characteristic transverse length is in the order of some tens of micrometers. It is clear that significant difficulties arise in modeling the effect of this mechanism on physical phenomena that have greater characteristic lengths and time scale.

Many detailed approaches have been proposed, where the discharge is modeled as a mixture of neutral molecules, electrons, and positive and negative ions. The governing equations of these models are often based on the drift diffusion equation coupled with the Poisson's equation for determining the electric field. Other approaches have been proposed, in which the action of the electric field on charges is described by an electrodynamic rather than an electrostatic model.

All the mentioned models are capable to capture many of the typical characteristics of cold electric discharges. However, the computational load that these codes require makes it difficult, if not impossible, to use them for the study of large scale applications of technological interest, in which the discharge interacts with flow fields with characteristic lengths of the order of some fraction of a meter and characteristic times of a few milliseconds or more.

In order to avoid these difficulties the proposed model of the discharge model will make use of a one-dimensional simplified description of the streamers, relying on lumped circuital

*Intervenant

elements: a non linear resistance take into account the motion of charge carries within the streamer, and a capacitance represents the ability of electric charge to distributie on the dielectric surfaces. The streamer interactions with the dielectric (secondary emission, surface charge deposition) will also be included in the model.

A multi-species transport model based on the drift-diffusion equation was also developed to study the evolution of the heavy species over time. The source term appearing in the governing equations will be derived by appropriately mediating the results obtained from the model of the streamer previously described. To decouple the model from the fast electron dynamics, electrons will be considered to instantaneously adapt to the Boltzmann distribution. As a result, the electric field acting on the calculation domain is evaluated by solving the non-linear Poisson equation.
The result of a 2-dimensional analysis of a DBD produced by a fluid dynamic actuator will be presented.

# Simulation of pre-breakdown discharges in air in a wide range of conditions

Nuno G. C. Ferreira[1,2], Diego Santos[1,2], Pedro G. C. Almeida[1,2], George Naidis[3], and Mikhail Benilov*[1,2]

[1]Departamento de Física, FCEE, Universidade da Madeira, Largo do Município, 9000-082 Funchal, Portugal – Portugal

[2]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal – Portugal

[3]Joint Institute for High Temperatures of RAS, 125412 Moscow, Russian Federation – Russie

**Résumé**

The physics of low-current discharges in high-pressure gases, such as corona, Townsend, and streamer discharges, has been understood reasonably well by now and a number of useful theoretical results, including analytical ones, have been obtained under various approximations. It is desirable to have also a unified method of numerical modelling, which would be fast, robust, and applicable to a wide range of conditions.
A method developed in this work employs, in the framework of a single code, stationary or time-dependent solvers, depending on the discharge being modelled being stationary (e.g., stable corona or Townsend discharge) or non-stationary (e.g., streamers). Note that stationary solvers offer important advantages in simulations of steady-state discharges compared to time-dependent solvers; in particular, they allow decoupling of physical and numerical stability and are not subject to the Courant–Friedrichs–Lewy criterion or analogous limitations on the mesh element size. The developed method allows investigating in a natural way steady-state discharges, their stability, and transition into other discharge forms, e.g., loss of stability of a glow corona and corona-to-streamer transitions.

The model comprises the conservation equations of species, transport equations of species, written in the drift-diffusion approximation, and the Poisson equation. Three negative ion species (O-, O2- and O3-) are considered and the conventional set of reactions: ionization by electron impact, photoionization, two-body (dissociative) attachment, three-body attachment, collisional detachment, associative detachment, charge transfer, electron-ion recombination, and ion-ion recombination. The rate of photoionization is evaluated by means of the three-exponential Helmholtz approximation.

Two examples are treated. In the first example, the inception voltage of positive glow corona discharge between concentric cylinders in air in a wide pressure range was computed. It was found that the boundary condition for the rate of photoionization at the surface of the corona electrode (anode) affects the corona inception voltage for lower values of $pr$ (here $r$ is the radius of the corona electrode), while the account of detachment affects the corona inception voltage for higher values of $pr$. The modelling was validated by comparison with standard experimental data and a very good agreement was found.

*Intervenant

In the second example, a pre-breakdown discharge in weakly non-uniform electric field between concentric cylinders in air in a wide pressure range was computed. The effect of microscopic non-uniformities on the positive (inner) electrode was studied by means of straightforward (multidimensional) modelling. The effect of field emission from non-uniformities on the negative electrode was studied with the use of the field enhancement factor and the Murphy-Good formalism, which is supposed to be more accurate than the Fowler-Nordheim formula. It was found that both effects play no role for lower values of air pressure and come into play for higher values, however field emission comes into play for values of pressure lower than those for which the effect of comparable non-uniformities on the positive electrode comes into play. The dependence of the inception voltage on the air pressure, computed with the account of field emission, reveals saturation with increasing pressure and conforms to the measured dependence of the breakdown voltage on pressure.

The work at UMa was supported by FCT of Portugal (project Pest-OE/UID/FIS/50010/2013).

# A robust method to compute the 2T reactive thermal conductivity of SF6 plasma

Gabriel Vanhulle*[1], Yann Cressault[2], and Ph Teulet[1]

[1]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France
[2]Université de Toulouse, UPS, INPT, Laboratoire Plasma et Conversion d'Energie (Université de Toulouse, UPS, INPT, LAPLACE) – Université de Toulouse, UPS, INPT – 118 route de Narbonne, F-31062 Toulouse Cedex 9, France

**Résumé**

Simulation of a high voltage circuit breaker is made using magneto-hydro-dynamic models (MHD). Those numeric simulations are dependent on databanks of fundamental properties such as thermodynamic properties, transport coefficients and radiative properties. The Local Thermodynamic Equilibrium (LTE) hypothesis is widely used in the calculation of these properties, but it is known that it is debatable where the energy is fairly less distributed such as areas near the electrodes, in the surrounding gases or during the cooling and the extinction of an electrical arc. Consequently, the numerical simulations have to be performed considering nonequilibrium phenomena, which are taken into account using the two-temperature assumption. In this we distinguish the electron kinetic temperature Te which characterizes the high temperatures area of the plasma, while the heavy particles kinetic temperature Tg describes low temperature regions.
The calculation of transport properties under 2T assumption is well described by the theory of Chapman and Enskog [1] extended by Muckenfuss [2] and the works of Rat et al. [3] Bonnefoi [4] and Devoto [5]. But because the Chapman-Enskog method is inefficient in treating the inelastic collisions, it treats poorly the reactive contribution to the thermal conductivity. The computation of the 2T reactive thermal conductivity at high pressure for complex gases such as SF6 using multi-temperature expressions from the literature (such as the one provided by Ghorui et al. [6]) showed limits in treating complex mixtures at high pressure. In order to obtain better results we had to devise our own formulation.

To achieve this, we have extended the expression from Butler and Brokaw [7] to 2T assumption using the two temperature Te and Tg. We divided the total reactive thermal conductivity into two contributions, one for the heavy particles (taking into account neutral atoms and molecules) and one for the electron part (taking into account electrons and ions). The temperature terms in each contribution were assigned to the electron temperature or the heavy particles temperature by comparing with results from the literature.

References

S. Chapman, "The kinetic theory of a gas constituted of spherically symmetrical molecules," *Philos. Trans. R. Soc. Lond. Ser. Contain. Pap. Math. Phys. Character*, vol. 211, pp.

*Intervenant

433–483, 1912.

C. Muckenfuss and C. F. Curtiss, "Thermal Conductivity of Multicomponent Gas Mixtures," *J. Chem. Phys.*, vol. 29, no. 6, pp. 1273–1277, 1958.

V. Rat, P. André, J. Aubreton, M. F. Elchinger, P. Fauchais, and A. Lefort, "Transport properties in a two-temperature plasma: Theory and application," *Phys. Rev. E*, vol. 64, no. 2, Jul. 2001.

C. Bonnefoi, "Contribution à l'étude des méthodes de résolution de l'équation de Boltzmann dans un plasma à deux températures: exemple le mélange argon-hydrogène," PhD Thesis, 1983.

R. S. Devoto, "Transport Properties of Ionized Monatomic Gases," *Phys. Fluids*, vol. 9, no. 6, p. 1230, 1966.

S. Ghorui, J. V. R. Heberlein, and E. Pfender, "Thermodynamic and Transport Properties of Two-temperature Oxygen Plasmas," *Plasma Chem. Plasma Process.*, vol. 27, no. 3, p. 267–291, May 2007.

J. Butler, R. Brokaw "Thermal conductivity of gas mixtures in chemical equilibrium", *The Journal of Chemical Physics*, vol. 26, no 6, p. 1636-1643, 1957.

# Synthesis of N-B substituted single wall carbon nanotubes by electric arc: plasma diagnostic

Soumaya Ben Nasr*[1,2], Gourari Djamel Eddine*[3,4], Valensi Flavien*[5], Yann Cressault*[6], Lotfi Beji*[2], Riadh Hannachi*[2], Manitra Razafinimanana*[1], Sébastien Joulie*[7], and Marc Monthioux*[8]

[1]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France
[2]Laboratoire des Energies et des Matériaux LABEM – Tunisie
[3]Centre d'élaboration de matériaux et d'études structurales (CEMES) – CNRS : UPR8011 – 29 Rue Jeanne Marvig - BP 4347 31055 TOULOUSE CEDEX 4, France
[4]Laboratoire Plasma et Conversion d'Energie [Toulouse] (LAPLACE) – Université Paul Sabatier (UPS) - Toulouse III, CNRS : UMR5213, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France
[5]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – CNRS : UMR5213, Université Paul Sabatier [UPS] - Toulouse III, Institut National Polytechnique de Toulouse, Université Paul Sabatier (UPS) - Toulouse III – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France
[6]Université de Toulouse, UPS, INPT, Laboratoire Plasma et Conversion d'Energie (Université de Toulouse, UPS, INPT, LAPLACE) – Université de Toulouse, UPS, INPT – 118 route de Narbonne, F-31062 Toulouse Cedex 9, France
[7]Centre d'élaboration de matériaux et d'études structurales – CNRS : UPR8011 – France
[8]Centre d'élaboration de matériaux et d'études structurales (CEMES) – CEMES – France

**Résumé**

The discovery of carbon nanotubes (CNTs) in 1991 by Ijima has opened up a new era in science and technology of nanostructures, and has attracted an enormous attention due to their excellent physical and chemical properties. However they present some constraints when practically applied in electronic industry since they have either metallic or semiconducting electronic properties. This behavior depends on the diameter and chirality that are difficult to control during synthesis.
Unlike pure carbon nanotubes (CNT), electrical and thermal properties of the doped carbon nanotubes (CNx/CxByNz/CBx), in which carbon atoms are partially substituted by boron and/or nitrogen atoms, are determined mainly by their atomic composition and configuration. This enables tuning their properties according to the intended application.

Despite the huge progress in CNT research over the years, we are still unable to produce CNTs of well-defined properties in large quantities by a cost-effective technique. The root cause of this problem is the lack of proper understanding of the CNTs growth mechanism that depends on the plasma temperatures. This makes the knowledge of radiation losses from the arc is indeed important to interpret the arc energy balance and heating of the

*Intervenant

surrounding gas, including the growth zone where nanotubes are formed. In addition, the composition of the plasma is a fundamental data for the study of its radiative properties. Hence this paper is devoted to work on the plasma diagnostic in order to study the correlation between plasma parameters and the synthesized doped CNTs properties.

The synthesis is carried out by arc discharge in a gaseous environment (various nitrogen/helium mixtures at 60kPa) inside an 18L cylindrical chamber. Under an applied current in the range of 50-80A, the arc is established and the plasma evaporates the heterogeneous anode (filled with graphite, catalysts, and boron). Depending on the experimental conditions, nanocarbons are formed when materials condensate.

This diagnostic was developed by optical spectroscopy (emission spectroscopy) applied to the C2 Swan 0-0 molecular band as well as to the atomic lines of nickel, resulting from the erosion of the anode, using the Boltzmann plot method.
In this work we present, the plasma parameters (density, electron temperature and rotational temperature profiles for different experimental conditions), and then, a comparison between the temperature profiles, obtained directly from the side-on integrated spectral line profiles emitted by the discharge, and the radial distribution of the temperature in the plasma. The latter is obtained by applying the Abel inversion on those spectral line profiles.

# Electric arc conductivity in a three-phase AC plasma torch operating on a mixture of air and methane

Viktor Popov*[1], Sergey Popov[1], Alexander Surov[1], Dmitry Subbotin[2,1], Eugeny Serba[1], and Nikita Obraztsov[3,1]

[1]Institute for Electrophysics and Electric Power of Russian Academy of Sciences – Russie
[2]St.-Petersburg State Technological Institute (Technical University) – Russie
[3]Saint Petersburg State Technical University – Russie

**Résumé**

Reforming methane to produce synthesis gas is an important part of the chemical industry. The main reforming method is the steam catalytic process. This method is limited by the temperature at which the catalyst remains active and hourly space velocity. In addition, the process proceeds with the absorption of heat, and the heating of steam to 800 ∘ C is very costly and dangerous. At the present time, the method of partial oxidation of methane has become very popular, but there are difficulties with the stability of the process (first of all, flame failure). There are a number of works devoted to plasma support of combustion. For this purpose, a barrier discharge, a spark discharge, a corona discharge and electric arc and microwave plasma torches are used. At the same time, electric arc plasma torches proved to be effective for igniting not only gaseous fuels, but also pulverized coal.
The report considers a high-voltage AC plasma torch operating on a mixture of air and methane for reforming. The plasma torch is powered by a power source consisting of a step-up transformer (380/10000V, 50Hz), current-limiting reactors and a reactive power compensator. The plasma torch consists of three electric arc channels with copper rod electrodes. Plasma-forming gas is supplied tangentially to the near-electrode zone. For the vortex stabilization of the arc, part of the air was supplied into the arc zone of the electric arc in addition. Gas supply mode: air flow rate into the near-electrode zone is 6 g/s, air flow rate into the arc zone is 6 g/s, methane flow rate into the electrode zone is 0...1 g/s.

With increasing methane flow rate, the voltage drop and the power of the plasma torch increased (500-1250 V and 41-94 kW, respectively). There are several reasons for this phenomenon. First of all, an endothermic chemical reaction proceeds in the electric arc:

CH4 + 0.5O2 = CO + 2H2

At the same time, part of the electrical energy is spent on the chemical process. In addition, the produced hydrogen has a high thermal conductivity and heat capacity, which leads to an increase in heat exchange between the electric arc and the cold stabilizing gas vortex. All these factors lead to a decrease in the electrical conductivity of the electric arc. As is known in the column of arcs of high pressure (˜ 1 Bar and higher), thermodynamic equilibrium is quite suitable. In this approximation, the conductivity of the discharge was

*Intervenant

estimated from data on the current density, the electric field strength, electron's concentration, electron charge and mass, the temperature, concentrations of uncharged spaces, cross-sections of collisions of uncharged spaces, cross-section of the Coulomb collisions and the ion's concentration.

# Measurement of the gas temperature of neutrals in reactive plasmas by moderate-resolution OES

Andrey Miakonkikh*[1] and Konstantin Rudenko[1]

[1]Institute of Physics and Technology RAS, Moscow – Russie

**Résumé**

Gas temperature is important parameter for isotropic plasma etching of submicron features in microelectronic technology (ULSIs, 3D-integration etc). Gas temperature of plasma determines the heat flow to processed wafer and influences on the parameters of etched silicon structures fabricated by cryogenic plasma etch process. The most simple and non-destructive way of measuring gas temperature under process conditions is spectral technique based on measuring of rotational structure of the molecular bands in emission spectra. It should be taken into account that the most common and commercially available compact tools for OES diagnostics normally have spectral range (250-1000 nm) but relatively low spectral resolution (_˜0.1 nm). That does not allow resolving rotational and vibrational lines of molecules.
In the present work, it has been proposed with the diagnostic purpose to use small addition of nitrogen as actinometer to the plasma of processing gas mixtures, with subsequent determination of the rotational and translational temperature of nitrogen molecules. The effective exchange of energy in intermolecular collisions in a gas and the principle of local thermodynamic equilibrium make it possible to spread the gas temperature of N2 on the whole gas mixture.

In this study, this method was used for measuring of gas temperature in ICP-plasma (SF6+O2) / (5% N2) and SF6 / (5% N2). The value of Trot of nitrogen molecules was determined from the partially resolved rotational structure of the 0-0 transition (337.13 nm) of the second positive system of N2. This strong transition is free from overlapping emission lines of other plasma components.

The experiments were performed in two different plasma tools: 1) the input plasma power PRF = 400-800 W at f=13.56 MHz, operative pressure p = 1.5-20 mTorr; 2) the input power PRF = 800-2500 W at f=2 MHz, the operative pressure p = 7-16 mTorr.

All experimental spectra were preliminarily normalized to the spectral sensitivity function of the spectrometer. The instrument broadening function of the spectrometer was well approximated by a Gaussian with half-width equal to $\lambda = 0.1258$ nm.

Acquired rotational spectra of N2 were corrected by subtracting a constant baseline, the wave numbers and intensities of the individual lines of the rotational structure of the transition were calculated *ab initio*, the output spectra were convoluted with instrument broadening function of spectrometer.

*Intervenant

Finally a procedure was performed to minimize standard deviation of the synthesized spectrum from the measured spectra; the value of the rotational temperature Trot is taken as the adjustable parameter.

With this method the estimated error in measuring the rotational temperature in the experiment was within ± 50 K. It was observed that the value of the gas temperature varies only slightly with operating pressure range, but increases linearly with input power. It should also be noted that the absolute values of gas temperatures are different for high RF and low RF tools (1 - 800K, 2 - 600K) with other conditions being equal.
Investigation was carried out under Program of FASO of Russia and was partially supported by RFBR, research project # 18-57-06001.

# In situ measurement of Silicon surface oxidation in low temperature oxygen plasma

Andrey Miakonkikh*[1], Iosif Clemente[1], Konstantin Rudenko*[1], and Sergey Averkin[1]

[1]Institute of Physics and Technology RAS, Moscow – Russie

**Résumé**

Precise and controllable modification of surface by oxygen plasma is becoming key step in atomic layer etching, selective atomic layer deposition, and advanced gas-chopping processes of plasma etching in microelectronic technology. These tasks focus the point of interest on problem of measurement of oxidation kinetics with sub-nanometer precision. This work is focused on initial stages of oxidation during formation of oxide films with thickness 0.5-1 nm within time of 2-10 sec.
Experiments were carried out in ICP etcher on (100) silicon wafers (n-type, 10-20 Ohm), previously dipped in 5% HF solution. The tool was equipped with ellipsometric windows, quartz OES window and Langmuir probe port. Plasma parameters were as follows: ICP power was 600W, pressure – 18-58 mTorr, oxygen flow – 80-150 sccm. Sample was chucked to the cooled table (18-20C) with helium backed pressure to improve thermal contact. Bias voltage was not applied during the experiment.

As an *in situ* measurement tool was the spectral ellipsometer Woollam M-2000X (246-998 nm spectral range, 73.2 incidence angle). Data acquisition takes about 0.5 sec with 1 sec time resolution. In all experiments silicon wafer temperature didn't exceed 100C.

Density of oxygen ions in plasma was measured by means of Langmuir probe with ESPion system. Parameters of plasma were estimated by using OML theory. EEDF were calculated by double differentiating of IV-curve with preliminary smoothing by Savitsky-Golay method.

Density of oxygen radicals O* in plasma were measured by OES actinometry using intensity of 750.39 nm line of Ar (gas-actinometr) and 777.74 nm line of O*.

Observed growth of SiO2 during plasma enhanced oxidation is saturated within 5-10 seconds. It was revealed that oxidation rate decreased with pressure and could not be described by Deal-Grove model. Simultaneously measured density of O* radicals in plasma shows that its concentration was increased with operative pressure almost linearly. Electron temperature and plasma potential measured by Langmuir probe gives negligible dependence on gas pressure under considered conditions, while the density of plasma (electron and positive ion concentrations) decreased with growth of pressure at constant discharge power. That correlation of plasma density and oxidation rate allows concluding that flux of oxygen ions to Silicon surface, accelerated by the plasma potential, is defining factor for plasma oxidation process of Silicon.
The reported study was carried out under Program of FASO of Russia and was partially supported by RFBR, research project # 18-37-00354.

*Intervenant

# Novel Distributed Air-Breathing Plasma Jet Propulsion Concept for All-Electric High-Altitude Flying Wings

Berkant Goeksel*[1]

[1]IB Goeksel Electrofluidsystems – Allemagne

**Résumé**

The paper describes a novel distributed air-breathing plasma jet propulsion concept for all-electric hybrid flying wings capable of reaching altitudes of 100,000 ft and subsonic speeds of 500 mph, Fig. 1. The new concept is based on the recently achieved first breakthrough for air-breathing high-thrust plasma jet engines [5]. Pulse operation with a few hundred Hertz will soon enable thrust levels of up to 5-10 N from each of the small trailing edge plasma thruster cells with one inch of core engine diameter and thrust-to-area ratios of modern fuel-powered jet engines.
An array of tens of thrusters with a magnetohydrodynamic (MHD) fast jet core and low speed electrohydrodynamic (EHD) fan engine based on sliding discharges on new ultra-lightweight structures will serve as a distributed plasma "rocket" booster for a short duration fast climb from 50,000 ft to stratospheric altitudes up to 100,000 ft, Fig. 2. Two electric aircraft engines with each 110 lb (50 kg) weight and 260 kW of power as recently developed by Siemens will make the main propulsion for take-off and landing and climb up to 50,000 ft [3], [4]. Especially for climbing up to 100,000 ft the propellers will apply sophisticated pulsed plasma separation flow control methods. The novel distributed air-breathing plasma engine will be only powered for a short duration to reach stratospheric altitudes with lowest possible power consumption from the high-density battery swap modules and special fuel cell systems with minimum 660 kW, all system optimized for a short one to two hours near-space tourism flight application [2].

The shining Plasma Stingray shown in Fig. 1 can bring up to six space tourists to the edge of near-space in less than an hour, switch-off the plasma pulse detonation engine at 100,000 ft and come back as a glider or lifting body aerospace shuttle. Advanced plasma flow control methods will be used to increase the glide ratio and flight time. Wing mounted flexible solar cells based on optical rectenna technology can provide additional 50 kW or at least 25 kW using state-of-the-art solar cells with 30% efficiency. Possible near infrared, terahertz or microwave power transmissions to flexible underwing rectannas are additional onboard lightweight power tools [1].

Electrofluidsystems announced the first breakthrough for future air-breathing magneto-plasma propulsion systems with the release of a new Star Wars movie in December 2015 and presented a first prototype at the ILA Berlin Air Show in June 2016. The first scientific paper was published in April 2017 discussing the working principle of the new pulsed plasma engine based on Lorentz forcing through a set of arc discharges with self-induced magnetic fields,

*Intervenant

Fig. 3-4 [5] The new paper will also discuss first high-speed camera recordings with a Photon FastCam SA-Z, Fig. 5-6.

Supplementary data with figures available at http://www.electrofluidsystems.com/Goeksel-HTPP15-Abstract1.pdf

Morris Jr., C. E. K., ”Microwave-Powered, Unmanned, High-Altitude Airplanes,” *AIAA Journal of Aircraftl*, Vol. 21, No. 12, 1984, pp. 966-970.

Kohout, L. L., and Schmitz, P. C., ”An Analysis of Fuel Cell Options for an All-Electric Unmanned Aerial Vehicle,” NASA TM-2007-214699, 2007.

Petermaier, K., ”Electric Propulsion Components with High Power Densities for Aviation,” Presentation at the Transformative Vertical Flight Workshop, 2015.

Anton, F., ”Elektrische Antriebssysteme für Luftfahrzeuge,” English presentation at the Bayerischer Fliegertag, 2017. URL:

Goeksel, B., Mashek, I. ”First Breakthrough for Future Air-Breathing Magneto-Plasma Propulsion Systems.” Journal of Physics: Conference Series, Vol. 825, 2017, 012005.

# LDA Electric Wind Velocity Measurements Behind Single Dielectric Barrier, Multi Dielectric Barrier and Sliding Discharge Plasma Actuators

Berkant Goeksel*[1]

[1]IB Goeksel Electrofluidsystems – Allemagne

**Résumé**

For plasma separation flow control applications on mini unmanned aerial vehicles (UAVs) it was envisioned to develop easy to built and effective plasma actuators for use with highly miniaturized plasma generators restricted to 12.5kVpp AC, 20.0kV DC and an overall power consumption of 30.0W for long time operations. For this purpose, we first aimed to compare the steady and unsteady wall jet velocities of three plasma actuator types with standard Kapton dielectrics and sinusoidal excitation: 1. SDBD, 2. MDBD (two unphased SDBDs) and 3. sliding discharge plasma actuators [1, 2, 3]. The main focus was on high unsteady wall jet velocities to attain as much flow control authority as possible at low Reynolds numbers relevant for small UAVs as discussed in [1].
The electric wind velocities were measured on different locations of a flat plate inside a smoke filled box using a 2-component LDA system in quiescent air (u=0 m/s). Fig. 1a and Fig. 1b show the steady wall jet velocities measured 5 mm downstream of the serrated last electrode on power. A sliding discharge actuator with moderate 8.0kVpp AC, 10.0kV DC and 30.4W can already induce peak velocities of 3.5 m/s. Two 30W generators powering a MDBD at 12.5kVpp can even induce velocities up to 5.5 m/s. This is quite effective and comparable to the results in [2, 3, 4].

Fig. 2 shows the unsteady velocities reached at a duty cycle of 50%. As already expected from the steady velocity distributions, the highest mean unsteady velocities are achieved by DBDs in series and sliding discharge plasma actuator. Shown are only the unsteady velocities for 50% duty cycle. Usually the peak unsteady momentum is reached at a duty cycle of approximately 10% [1].

MDBD plasma actuators [5] with moderate voltages of 8-12kV AC and sliding discharge actuators with voltages up to 20kV DC can be combined to further increase the control authority (Fig. 3) and thus efffectiveness of the plasma actuators to be used on small UAVs like the Plasma Flyer UAS of Electrofluidsystems with more sophisticated, doped flexible dielectric barrier materials (Fig. 4).

Supplementary data with figures available at http://www.electrofluidsystems.com/Goeksel-HTPP15-Abstract2.pdf

*Intervenant

*References*

Göksel B, Rechenberg I, Greenblatt D and Paschereit C O 2006 Steady and unsteady plasma wall jets for separation and circulation control *3rd AIAA Flow Control Conference 2006*, AIAA 2006-3686, San Francisco, California

Moreau E, Louste C and Touchard G 2008 Electric wind induced by sliding discharge in air at atmospheric pressure *J Electrostatics* **66** 107-114

Benard N and Moreau E 2014 Electrical and mechanicalcharacteristics of surface AC dielectric barrier discharge plasma actuators applied to airflow control *Exp. Fluids* **55** 1–43

Matsuno T, Fukuda A, Kawazoe H, Nakai K and Nishida H (2017) Parametric optimization of multi-electrode plasma actuator with serrated electrode *IOP Conf. Ser.: Mater. Sci. Eng.* **249** 012005

Asaumi N and Matsuno S 2017 Multi-electrode plasma actuator to improve performance of flow separation control *Int. J. Gas Turbine, Propulsion and Power Systems* **9** 1-8

# Lightning arc interaction with complex structure

Audrey Bigand*[1,2], Jean-Marc Bauchire*[2], Christine Espinosa[1], and Hervé Rabat[2]

[1]Institut Supérieur de lÁéronautique et de lÉspace – ICA (Institut Clément Ader) – France
[2]Groupe de recherches sur l´énergétique des milieux ionisés – Centre National de la Recherche Scientifique : UMR7344, Université d'Orléans : UMR7344 – France

**Résumé**

Lightning is a natural and unpredictable phenomenon due to charge generation in clouds producing intense electrical field leading to flashes of extremely high current and high voltage pulses of few microseconds to few milliseconds. In this context, aircrafts are subjected to the risk of being struck during flight. The lightning damage mechanism for carbon laminate aeronautical structure is a complex multi-physical phenomenon. In order to understand this phenomenon, it is of first importance to understand and predict the interaction of the lightning arc with the aircraft structure. This arc can be divided in 2 areas: a free arc area for which the expansion follows the rules of the magnetohydrodynamic equations with a quick pulse of current and an arc root area with an expansion depending on the properties of the metallic lightning strike protection and the confinement effect of the paint covering the structure. This theory has been studied through multiphysics models and lightning lab tests.

*Intervenant

# Lightning strike protection explosion and overpressure profile

Audrey Bigand*[1,2], Christine Espinosa[3], Jean-Marc Bauchire[4], and Hervé Rabat[4]

[1]Institut Supérieur de lÁéronautique et de lÉspace – ICA (Institut Clément Ader) – France
[2]Groupe de recherches sur l´énergétique des milieux ionisés – Centre National de la Recherche Scientifique : UMR7344, Université d'Orléans : UMR7344 – France
[3]institut clément ader (ICA) – Institut Supérieur de l'Aéronautique et de l'Espace (ISAE) – ICA Montaudran, France
[4]Groupe de recherches sur l'énergétique des milieux ionisés (GREMI) – CNRS : UMR7344, Université d'Orléans – 14 Rue d'Issoudun - BP 6744 45067 ORLEANS CEDEX 2, France

**Résumé**

Lightning is a natural and unpredictable phenomenon due to charge generation in clouds producing intense electrical field leading to flashes of extremely high current and high voltage pulses of few microseconds to few milliseconds. In this context, aircrafts are subjected to the risk of being struck during flight. The lightning damage mechanism for carbon laminate aeronautical structure is a complex multi-physical phenomenon. One of the main contributor is the overpressure generated by the quick vaporisation of the metallic lightning strike protection that covers the composite aircraft surface in order to divert lightning current. This metallic protection is a copper mesh that explodes in few microseconds with the lightning current flowing into it due to Joule heating. This quick elevation of temperature leads to a dilatation of copper and explosion which generates an important and sudden overpressure on the composite surface. In order to study this phenomenon, current density has been assessed in each wire of the mesh and joule heating computed to predict explosion time. This model, that will be used to build a pressure profile, is compared to the results of an innovative test approach in which lightning current pulse is injected into a wire, representing an elementary part of the mesh. During this test in which the wire will explode before entering into plasma state, high speed cameras are used in order to record metal expansion. This result is combined with a pressure sensor installed few centimeters away in order to measure the pressure amplitude and waveform. Thanks to this experiment, it will be possible to built a spatial and temporal dynamic profile of overpressure to apply on the aircraft composite structure and analyse the damage.

*Intervenant

# Temporal analysis of DC- and Microwave-driven plasma micro-discharges

Antoine Simon[1,2], Th. Callegari*[1], Romain Pascaud[2], Laurent Liard[1], and Olivier Pascal[1]

[1]Laboratoire Plasma et Conversion d'Energie (LAPLACE) – CNRS : UMR5213, Université Paul Sabatier - Toulouse III, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[2]Institut Supérieur de l'Aéronautique et de l'Espace (ISAE) – Ministère de la Défense – ISAE - 10 av. Edouard Belin - BP 54032 - 31055 TOULOUSE Cedex 4, France

**Résumé**

*This paper presents the work performed as part of the use of micro-discharge in planar circuits to design high microwave power limiting devices. Due to the multiplication of microwave communication systems, it is becoming increasingly important to develop efficient protection devices against high power microwave threats. One of the most critical features of microwave power limiters is the response time. PIN diodes are commonly involved due to their response time in the order of a few nanoseconds. However, their use is limited to low power threats (typically few Watts). For higher microwave power, plasma discharges offer an alternative solution. Transmit/Receive tubes with response time less than few nanoseconds have been widely used to protect RADAR receivers from high power microwave signals [1]. However, T/R tubes cannot be easily integrated into compact planar circuits. To overcome this problem, we propose to use another type of discharge, the Micro Hollow Cathode Discharge, MHCD [2]. With dimensions in the millimeter range, this discharge can be directly integrated into planar microwave devices. In fact, this MHCD acts as an electron source for a second discharge occurring outside the MHCD hole when the incident microwave power is higher than a threshold. This second discharge then limits the transmission of the microwave threat by absorbing and/or reflecting it. In this communication, we propose to analyze the temporal response of this plasma-based microwave power limiter in order to evaluate its effectiveness and to understand the non linear coupling between the microwave and the plasma. The response time has been first evaluated for a typical MCSD [3] (Micro Sustained Cathode Discharge) configuration supplied by pulsed DC voltage for different pressure and electric field conditions. Experimental results have been then compared to theoretical results and numerical simulations with a good agreement. Optical measurements have been also conducted in order to analyze the formation of the discharge. In a second time, several equivalent microwave circuits have been designed in order to compare previous pulsed DC results to microwave discharge ones. The response time and optical measurements have been performed for these microwave designs with different electric field conditions. [1] L. D. Smullin and C. G. Montgomery, Microwave Duplexers. McGraw-Hill, 1948, vol. 14 of MIT Radiation Laboratory Series.[2] K. H. Schoenbach et al. "High-pressure hollow cathode discharges". In : Plasma Sour. Sci. Technol. 6.4 (1997), p. 468–477.[3] R. H. Stark and K. H. Schoenbach, "Direct current glow discharges in atmospheric air", Appl. Phys. Let, Vol. 74, n∘ 25 (1999), p. 3770.*

*Intervenant

# Theoretical study of molecular spectra in nitrogen

Abdel Majid Kassir*[1], Yann Cressault[1], Mathieu Masquère[1], and Philippe Teulet[1]

[1]Laboratoire plasma et conversion d'énergie – Université Paul Sabatier - Toulouse III – France

**Résumé**

In most plasma applications, physical contact can exist between the plasma and the studied medium. Spacecrafts, for example, undergo an important heat ow due to their interaction with plasma generated by the shockwave during their planetary entries, sometimes damaging their bodies. To correctly estimate the energy exchanges, the plasma temperature is one of the parameters that one should carefully evaluate in order to control and avoid overheating the studied medium. Depending on time and the region of the plasma, electrons and ions can be in thermodynamic equilibrium, and a single temperature is enough to characterize the plasma.In other cases, such as during the current phase zero in HVCB or in colder regions, non-equilibrium plasma can exist, characterized by an electron temperature much higher than the gas temperature.
Several years of scientific research in our team have contributed to the establishment of a spectroscopic database for CHON mixtures in local thermodynamic equilibrium (LTE). A line-by-line radiation code that considers atomic and molecular transitions has been developed. Studies have been conducted to test the aforementioned code in concrete cases of radiative transfer in air, CO2, and CO-H2 plasmas in terms of total integrated emission, covering the spectral range of 300–30000 cm1 and temperatures of up to 15000 K.

This study is focused on the validation of the spectral emission of molecular bands obtained with this code in the case of LTE and non-LTE plasmas. We considered a pure nitrogen plasma as a good starting point because nitrogen plasma provides us with a wealth of vibrational and rotational bands as long as the temperature is sufficiently low to prevent not only the dissociation of the N2 molecule but also the presence of atomic nitrogen lines. We were particularly interested in the first negative system of the N2+ ion (N2+ B 2 Σu+ – X 2 B 2 Σg+) because it presents a convenient way to measure the rotational and vibrational temperatures, it can be validated by comparisons with already published works, and it is an important complementary part of our experimental work.

The first part of the investigation has been led at atmospheric pressure and in thermodynamic equilibrium conditions, and no in-depth attention was paid to the molecular bands' belongings in terms of vibrational or rotational sequences. Some enhancements were added to the code by taking into account the different line-broadening mechanisms, mainly Doppler, pressure, and instrumental, even though after thorough examination the apparatus function proved to be dominant in the temperature range of interest.
Afterward, spectra simulations were conducted for different LTE temperatures, and comparisons were made with works found in literature. The results show agreement with the latter works, proving the validity of our physical model in LTE assumptions. The second part of the examination presents our efforts to extend the code's field of study to the case of non-equilibrium plasmas. Spectra calculations as functions of different rotational and vibrational

*Intervenant

temperatures will be shown. Some preliminary results and perspectives will be discussed, the use of our simulated spectra to fit our experimental spectra and measure the different characteristic temperatures (rotational, vibrational, electronic etc...), as well as quantify the degree of chemical and thermodynamic non-equilibrium in our experimentally-investigated microwave plasma.

# Study of emitted radiations in High Intensity Discharge ( HID) Lamps

Antoine Sahab*[1], Mohamad Hamady , Georges Zissis[2], and Yann Cressault[3]

[1]Laboratoire Plasma et Conversion dÉnergie [Toulouse] – Institut National Polytechnique [Toulouse], Université Paul Sabatier - Toulouse 3, Centre National de la Recherche Scientifique : UMR5213 – France

[2]Laboratoire Plasma et Conversion d'Energie [Toulouse] (LAPLACE) – Université Paul Sabatier (UPS) - Toulouse III, CNRS : UMR5213, Institut National Polytechnique de Toulouse – 118 Route de Narbonne 31062 TOULOUSE CEDEX 9, France

[3]Université de Toulouse, UPS, INPT, Laboratoire Plasma et Conversion d'Energie (Université de Toulouse, UPS, INPT, LAPLACE) – Université de Toulouse, UPS, INPT – 118 route de Narbonne, F-31062 Toulouse Cedex 9, France

**Résumé**

Plasma discharge lamps are of great interest due their different applications. These lamps produce visible radiations used in domestic and outdoor lighting as well as in Ultra Visible radiations used in water sterilisation. These radiations come from different mechanisms that take place inside the lamp. The knowledge of atomic and molecular data responsible for these radiations is essential to describe the radiations that take place in plasma discharge Lamps. Obtaining such data was been the goal of many different laboratories and authors. We will study the importance of these data in radiation transport calculations of HID (High Intensity Discharge) lamps. These lamps generate light by applying an electrical current across an ionized gas. Different methods were been used to calculate the radiative properties of these lamps [1]. A model for radiation transport calculation based on ray tracing method is going to be adopted [2,3]. The model is based on the resolution of the radiative transfer equation that describes the change of spectral intensity Il (Wm–3sr–1) along a path. The discharge will be divided into elementary cells responsible for launching rays in all directions. We will determine for each ray the crossed mesh and the distance travelled in each mesh. The radiative transfer equation (RTE) will then be solved along each ray. These calculations will consider that the discharge has a cylindrical symmetry and assume that the plasma is at local thermodynamic equilibrium (LTE). Hence, the only knowledge of the temperature profile and pressure from experiments is sufficient to calculate the chemical composition of plasma and to account the mechanisms of broadening of spectral lines in the treatment of radiative transfer. We deduce from energy calculations the photometric characteristics: Luminous flux, luminous efficacy, photometric curves, color temperature and chromaticity coordinates. In this work, the atomic data is the only resource to calculate both coefficients. We will show the results for a pure mercury HID lamp. For each spectral line, the local absorption and emission coefficients are strongly dependant on the broadening constants that are calculated from the atomic data of each spectral line. Calculations reported in the literature use different values for these constants, leading to marked differences in output of the models.

*Intervenant

# Dust particle formation and bulk material alteration through the interactions between non equilibrium hydrogen/argon plasmas and carbon and metal samples

Khaled Hassouni[1], Karim Ouaras , Catalina Quiros-Lara , Armelle Michau* , Guillaume Lombardi , Michael Redolfi , Jonathan Mougenot , Swaminathan Prasanna , Thierry Chauveau , and Ovidiu Brinza

[1]Laboratoire des Sciences des Procédés et des Matériaux, LSPM. – CNRS, Université Paris 13, Sorbonne Paris Cité – France

**Résumé**

The interactions between plasmas and surrounding solid materials may result in significant changes both in the pristine plasma phase and at the surface or in the bulk of the materials. The investigation of such transformations may be of great interest in many application fields such as nanocarbon allotropes based functional materials synthesis [1-3] and plasma facing component development for fusion reactors [4-6]. These last two applications are directly linked to a two case studies we are discussing in this contribution that aims at illustrating how plasma-surface interaction affects the plasma composition and/or the material characteristics. In the first example, we discuss how the interaction between argon plasmas and a graphite cathode in a DC discharge may result in the formation of carbon nanoparticles in the plasma phase. We especially analyze the sputtering and subsequent molecular growth processes that lead to particle nucleation. We also discuss the aerosol dynamics experienced by the produced solid particles and that result in the observed particle size distribution. The dusty plasma effect and the consequence of dust formation on the plasma characteristics in terms of discharge equilibrium and ionization/attachment kinetics, will be also discussed. The second case study presented in this contribution deals with the interaction of hydrogen and hydrogen/argon plasmas with metallic, i.e. tungsten or aluminum, samples. We first focus on the change experienced by the morphology of the aluminum sample surface when submitted to high fluence low pressure non equilibrium hydrogen plasmas. We place a special emphasis on blister formation and show how it can be correlated to the plastic deformation of the metallic sample along the slip planes, which determines the blister morphology. We eventually show how deep hydrogen diffusion may result in bubble formation in the bulk of the material. The consequence of the surface and bulk material alteration in terms of tungsten nanoparticles formation in hydrogen/argon plasma will be analyzed on the basis of three different mechanisms: (i) blister burst, (ii) sputtering and subsequent molecular growth and (iii) micro-arcing followed by local melting of the surface and droplet ejection and solidification. We show that although all these three mechanisms are active under low pressure non equilibrium discharge conditions, micro-arcing is by far the most dominant one. It leads to the formation of a fairly large amount of nanoparticles with a typical size around

*Intervenant

50 nm that always come with the classically observed micrometer size particles resulting from the solidification of metal microdroplet produced through the local interaction of a micro-arc or spark with a metal substrate.

References

V. Georgakilas, J. A. Perman, J. Tucek, R. Zboril, ‘Broad family of carbon nanoallotropes : classification, chemistry and applications of fullerenes, carbon dots, nanotubes, grapheme, nanodiamonds, and combined superstructures’, Chemical Reviews, 115(11), 4744-4822(2015).

R. Dubrovsky, V. Bezmelnitsyn, Bulk production of nanocarbon allotropes by a gas outflow discharge approach, CARBON 42 (8-9) 1861-1864 (2004)

R. Hatakeyama, ; T. Kato ; Y.F. Li ; T. Kaneko, Plasma Processing Based Synthesis of Functional Nanocarbons, Plasma Chemistry and Plasma Processing, 34(3), 377-402 (2014).

Y. Ueda; K. Tobit; Y. Katoh, PSI issues at plasma facing surfaces of blankets in fusion reactors. Journal of Nuclear Materials, 313, 32-41(2002)

V. Rhode, M. Balden, T. Lunt. ‘Dust investigation at ASEDEX Upgrade’. Physica Scripta, T138, 014024, DOI: 10.1088/0031-8949/2009/T138/014024

B. D. Wirth, K.D. Hammond, S.I. Krasheninnikov, D. Maroudas, ”Challenges and opportunities of modeling plasma–surface interactions in tungsten using high-performance computing”, J. Nucl. Mater. 463, 30-38 (2015)

# Contribution to the study of the electric arc displacement

Mohamed Boukhlifa*[1], Romaric Landfried[1,2], Thierry Leblanc[1], and Philippe Testé[1]

[1]Laboratoire Génie électrique et électronique de Paris – Centre National de la Recherche Scientifique : UMR8507, CentraleSupélec, Université Pierre et Marie Curie - Paris 6, Université Paris-Sud - Paris 11 – France

[2]Laboratoire GeePs UMR8507 – CNRS-CentaleSupelec-Université Paris Sud-UPMC – 3-11 rue Joliot Curie 91190 Gif sur Yvette, France

**Résumé**

i) Introduction

Many devices use moving electric arcs: circuit breakers in which the arc is guided in the splitting chamber, plasma torches in which the motion is used to reduce and make uniform the electrode surface temperature, chemical reactors... The arc structure, its behavior and displacement mode are essential parameters to understand the arc displacement. The work presented here is an experimental contribution to the study of the electric arc motion in air at atmospheric pressure. In our case, the arc is put into motion between two parallel bars under the action of its self-induced magnetic field.

ii) Experimental setup

The arc is initiated between two parallel copper electrodes (40 cm length rails) thanks to a copper fuse wire located at half the length of the electrode. The power supply used allows then to create a DC electric arc ($Iarc$ = 30 A under a maximal voltage equal to 540 VDC). The arc is put into motion thanks to the Lorentz force and then moves along two rails. Arc current intensity and arc voltage are recorded and the arc is observed with a high speed camera (Photron SA1.1).

iii) Experimental observations

In the chosen configuration of pressure, arc current intensity and electrode gap (15 mm), it has been observed that the cathode arc root has a continuous motion on the electrode surface and that the anode root motion is a succession of stagnation times and jumps.

The arc displacement goes through three stages:

- The anodic root which is fixed and the cathodic root moves in a continuous way up to a distance of 16 mm between roots (the arc column has a much greater length at this distance). The arc voltage increases regularly due to the increase of the arc column length.

*Intervenant

- When the distance between roots reaches a specific value (depending on experimental conditions as pressure, current value, voltage applied...), two anodic roots (and two columns) will coexist. The new one is closer to the cathodic root so that the arc column is shorter. The arc voltage evolution shows a progressive decrease of the arc voltage during the anode arc root "jump".
- The initial anodic root disappears and the new one remains as the only anodic root.