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OVERVIEW ON STUDIES OF MARTIAN LIKE CO₂-N₂ MIXTURE BY INDUCTIVELY COUPLED PLASMA TORCH

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ABSTRACT

The purpose of the work is to make an overview on the results obtained through the studies on martian plasmas created by inductively coupled plasma torches (ICP). As the main advantage of the ICP torch is the absence of electrode compared to the others various test facilities, the radiative properties of this kind of plasmas are of interest to propose test cases in order to validate radiation models. ICP torches can work under various operating conditions in terms of pressure, enthalpy or flow. As a consequence, the studied plasma can be either at thermodynamical equilibrium or out of equilibrium, without problems of stability in time. The presentation concerns only the plasmas formed with a martian like CO₂-N₂ mixture and all the parameters of test facilities will be precised.

The following paper corresponds to the first step of a global paper which will be proposed later and it reports only the oral presentation which has been done during the third International Workshop of RHTG.

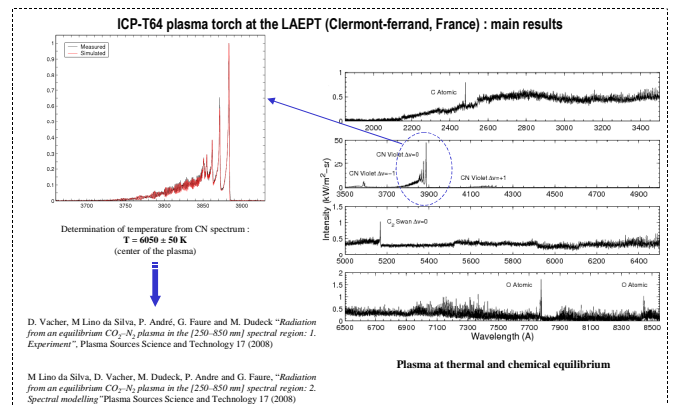
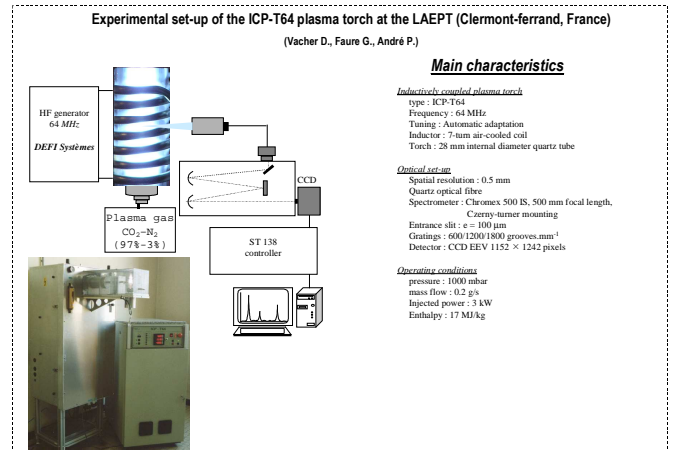
1. INTRODUCTION

Five laboratories have been found concerning the study of CO₂ or CO₂-N₂ plasmas by inductively coupled plasma torch. The laboratories which are about to start this kind of study do not appear in this presentation.

The laboratories which have obtained results are the following :

- L.A.E.P.T. (Laboratory of Electrical Arc and Thermal Plasmas) located in Clermont-Ferrand, France;
- C.O.R.I.A. (Complexe de Recherche Interprofessionnel en Aérothermochimie) located at Rouen, France;
- I.R.S. (Institut für RaumfahrtSysteme) located at Stuttgart, Germany;
- V.K.I. (Von Karman Institute) located at Rhode Saint Genese, Belgium;
- I.P.M. (Institute for Problems of Mechanics) located at Moscow, Russia.

2. L.A.E.P.T. (Clermont-Ferrand, France)



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1. D.Vacher, M. Lino da Silva, P. André, G. Faure and M. Dudeck (2008) *Radiation from an equilibrium CO₂-N₂ plasma in the [250-850 nm] spectral region: 1. Experiment* Plasma Sources Science and Technology 17 (2008) 035012 (8pp)
2. M. Lino da Silva, D. Vacher, M. Dudeck, P. André and G. Faure (2008) *Radiation from an equilibrium CO₂-N₂ plasma in the [250-850 nm] spectral region: 2. Spectral modelling* Plasma Sources Science and Technology 17 (2008) 035013 (9pp)
3. M. Lino de Silva, *An adaptative Line-by-Line-Statistical Model for Fast and Accurate Spectral Simulations in Low-Pressure Plasmas* JQSRT, Vol. 108, n°1, pp. 106-125

3. C.O.R.I.A. (Rouen, France)

ICP torch at the CORIA (Rouen, France) : (1)
(Rond C, Bultel A, Boubert P., Chéron B.G.)

Main characteristics

Inductively coupled plasma torch
 Frequency: 13.56 MHz
 Inductor: 7 turns water-cooled coil
 Torch: 60 mm (coil location)
 90 mm (downstream)

Optical set-up
 spectroscopy system
 Spectrometer: SpectraPro-300L
 Entrance slit: $e = 50 \mu\text{m}$
 Gratings: 1200 grooves/mm² (blazed at 300 nm)
 Detector: ICCD camera PI-Max (Princeton)

Operating conditions
 pressure: 1-2 mbar
 flow rate: 0.1 - 0.3 dm³/min
 Max. injected power: 2 kW
 Power delivered to the plasma: 80-160 W
 Specific enthalpy: 13.4 - 40.8 MJ/kg

This experimental set-up has been presented by A. Bultel :
 - Spatial evolution of the radiation from a non equilibrium CO₂ RF plasma.

ICP torch at the CORIA (Rouen, France) (1) : main results
(Rond C, Bultel A, Boubert P., Chéron B.G.)

Aim of the study :

- to analyse the CO₂ dissociation at low pressure
- to calculate CO-O chemiluminescent emission
- to investigate the evolution of the plasma chemistry from the creation zone to downstream
- to estimate the CO and O densities in their ground state and their excited ones

Plasma under thermal and chemical nonequilibrium

	T _g (K)	T _e (K)	T _{ex} (K)	density of the upper state (m ⁻³)
Triplet (d _{3,2} → a ¹ T ₁)	500	1000	5000	10 ¹⁷
Assault (a ¹ T ₂ → a ¹ T ₁)	500	7000	5000	10 ¹⁴

Estimation of temperatures from CO system in the post discharge

ICP torch at the CORIA (Rouen, France) : (2)
(Boubert P.)

Main characteristics

Inductively coupled plasma torch
 Frequency: 176 MHz
 Inductor: 5 coils
 Torch: 100 mm diameter quartz tube

Optical set-up
 Spectrometer: Sopra1500
 Entrance slit: $e = 7 \mu\text{m}$
 Gratings: 2400 grooves/mm² (blazed at 400 nm)
 Detector: Photodiode array (Thorn D17821)

Operating conditions
 pressure: 20 mbar
 flow rate: 18 L/min
 injected power: 25 kW
 specific enthalpy: 7 MJ/kg
 plasma gas: CO₂-N₂-Ar (95%-3%-2%)

Conclusion of the study :

- CN : good accuracy experiment theory
- C₂ : notable differences between experiment and theory
- simulation of static
- anomalies of states population

Violet system of CN	T _g (K)	ΔT _{ex} (K)	T _{ex} (K)	ΔT _{ex} (K)
FWHM = 0.06 nm	8000	500	10000	200
FWHM = 0.08 nm	8000	500	10000	200

C ₂ system	T _g (K)	ΔT _{ex} (K)	T _{ex} (K)	ΔT _{ex} (K)
FWHM = 0.075 nm	9000	1000	10000	1000

Estimation of temperatures

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3. P. Boubert (1999) *Méthodes spectroscopiques appliqués aux plasmas et aux milieux à hautes enthalpies*, PhD Thesis, University of Rouen

4. I.R.S. (Stuttgart, Germany)

ICP torch at the IRS (Stuttgart, Germany)
(Herdrich G., Endlich P. and al.)

Main characteristics

Inductively heated generator IPG4
 Frequency: 0.6 MHz
 Inductor: 5 turns water-cooled coil
 Torch: 84mm internal diameter quartz tube
 Nozzle throat diameter: 50 mm

Optical set-up
 mini-Spectrometer:
 Entrance slit: $e = 7 \mu\text{m}$
 Gratings: 1
 Detector: 2000 pixel detector (pixel resolution: 0.3 nm)

Operating conditions
 pressure: 1.9-8 mbar
 CO₂ mass flow: 3.7 g.s⁻¹
 N₂ mass flow: 70 m.g.s⁻¹
 Thermal plasma power: 20 kW

Measurements in the plasma :

- Heat flux
- Pitot pressure
- Thermal plasma power (calorimeter)
- Study of the influence of dust particles (injection of iron oxides and silicon dioxides with $\phi < 10 \mu\text{m}$)

ICP torch at the IRS (Stuttgart, Germany) : Example of spectra
(Herdrich G., Endlich P. and al.)

No values of the estimated temperatures of plasma

ICP torch at the IRS (Stuttgart, Germany) : First estimation of temperatures
(Lein S., Herdrich G. and al.)

The results are issued from a poster presented in the 6th International Planetary Probe workshop (2008)
 - Characterization of CO₂ plasma free stream conditions for atmospheric entry simulation *

Final Conclusion : disagreement theory-experimental data (quantitatively not qualitatively)

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3. P. Endlich, M. Auweter-Kurtz, G. Herdrich, *Mars Entry Simulation with Dust Using an Inductively Heated Generator*, Paper AIAA-2002-3237, 22nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, St. Louis, MI, USA, 24-26 June 2002

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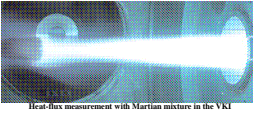
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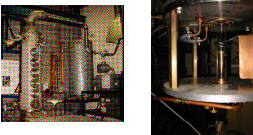
5. V.K.I. (Rhode Saint Genese, Belgium)

ICP torch at the VKI (Rhode Saint Genese, Belgium)
(Chazol O., Carbonaro M. and al.)

	Plasmatrix	Minitech
Frequency (MHz)	1.16	1.16
Power (kW)	1200	15
Operating pressure	1-12 mbar	Martian atmosphere
Inductor	3	2
coiled (d=4mm)	water	water
external diameter tube (mm)	80-140	250
Internal diameter (mm)	150	175
Flow rate	0.50	1.00
Embassy	0.050 m/s	1.00



Heat-flux measurement with Martian mixture in the VKI Plasmatron



Overview of the minitech

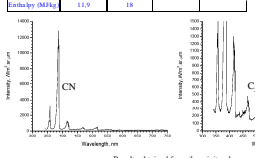
Available instrumentation:

- cooled pressure and heat fluxes probes
- Langmuir probes
- Laser Doppler velocimeter
- One meter emission spectrometer with CCD camera
- two color pyrometer
- Laser spectroscopy techniques (TALIF)
- (Two photon Absorption Laser Induced Fluorescence)

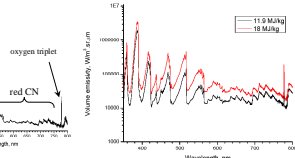
ICP torch at the VKI (Rhode Saint Genese, Belgium)
(Playez M. and al.) [TRP-ESA]

	test1	test2	test3	test4
Power (kW)	15	30	3.2	3.2
Pressure (mbar)	8	8	10	7.5
Flow rate	CO ₂ (97%) - N ₂ (3%) (flow 0.50m/s)			
Mass flow (g/s)	8	8	0.51	0.51
Embassy (M/s)	11.6	18		

Optical setup:
Spectrometer: Ocean Optics HR4000CG-LV-NIR;
Wavelength interval: 200-1400 nm
Entrance slit: $\tau = 5$ nm
Gratings: 300 grooves/mm²
Detector: 3048-elements linear silicon CCD array

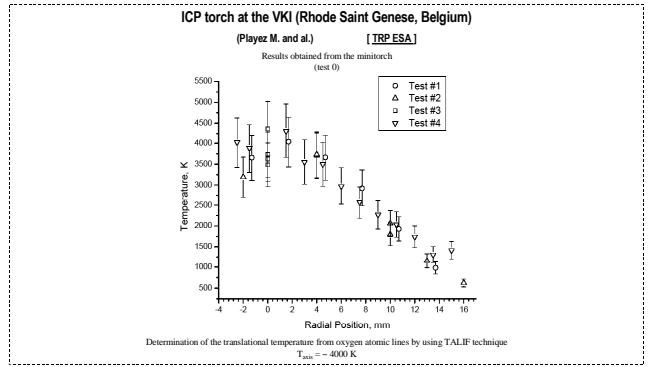


Results obtained from the minitech (test 1)



Results obtained from the plasmatron (test 1-2)

Difficulty of interpretation - fluctuations of the jet



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The informations are given by M. Playez.

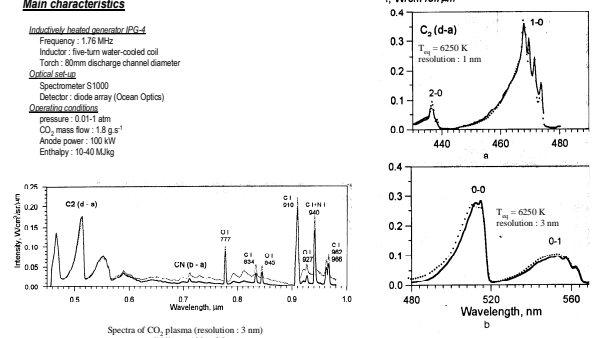
6. I.P.M. (Moscow, Russia)

ICP torch at the IPM (Moscow, Russia)
(Baronets P.N., Bykova N.G. and al.)

Main characteristics
Inductively heated generator IIG-4
Frequency: 1.16 MHz
Inductor: five-turn water-cooled coil
Torch: 80mm discharge channel diameter

Optical setup
Spectrometer: S1000
Detector: diode array (Ocean Optics)

Operating conditions
pressure: 0.05-1 atm
CO₂ mass flow: 1.8 g.s⁻¹
Anode power: 100 kW
Embassy: 10-40 M/s

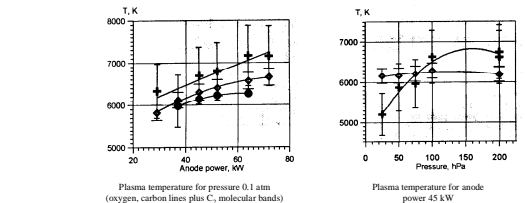


Spectra of CO₂ plasma (resolution: 3 nm)
- solid lines: 100% CO₂
- dotted line: CO₂ + 3% N₂ + (0-10%) Ar

Correlation of C₂ Swan system band head.
dotted line: experimental spectrum
solid line: calculated spectrum

ICP torch at the IPM (Moscow, Russia)
(Baronets P.N., Bykova N.G. and al., 1998)

Plasma temperature measurements by optical methods



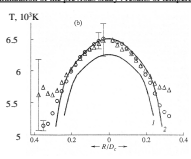
Plasma temperature for pressure 0.1 atm (oxygen, carbon lines plus C₂ molecular bands)

Plasma temperature for anode power 45 kW

- RI values, averaged of 2 OI lines pairs
- AI values, averaged over three oxygen and four carbon lines
- Values from C₂ molecular bands

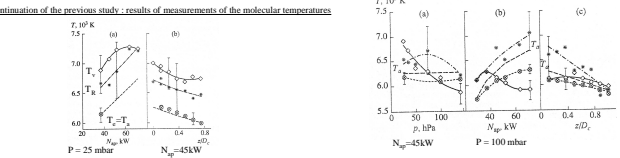
ICP torch at the IPM (Moscow, Russia)
(Bykova N.G., Kuznetsova L.A., 2004)

Continuation of the previous study - results of temperature measurements from atomic lines

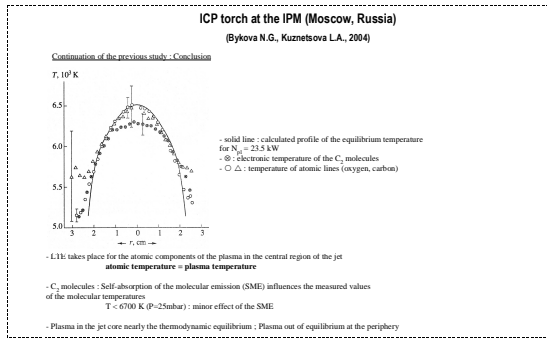


Radial profiles of the atomic temperature of a CO₂ plasma:
- N₀ = 45 kW
- P = 100 mbar
solid line (1): calculated equilibrium temperature for N₀ = 19 kW
solid line (2): calculated equilibrium temperature for N₀ = 23.5 kW

Continuation of the previous study - results of measurements of the molecular temperature



Influence of the self-absorption of molecular emission (C₂, I)



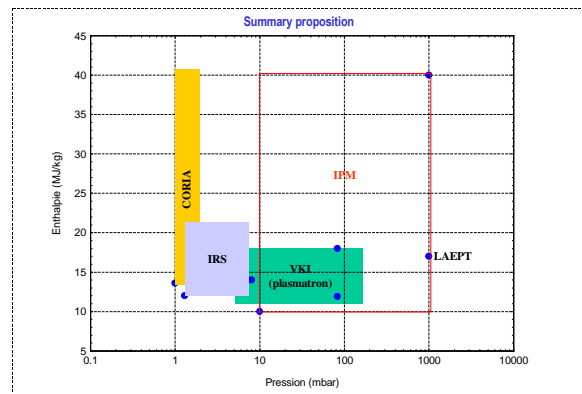
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7. CONCLUSION

A conclusion can not be done due to the fact that each laboratory works under different conditions in terms of flow, injected power, operating frequency and operating pressure. However, it is very interesting to gather all the data in order the domain of applications of each laboratory and also in order to create a connection between all these laboratories.

The following figure propose a regrouping of the data of each laboratory in terms of specific enthalpy and pressure. Of course, The field of investigation of each laboratories is likely to evolve.



ACKNOWLEDGMENTS

I would like to thank all the colleagues who permitted to this presentation to exist. I express all my recognition to them and thanks once again them for all the informations that they sent to me. These colleagues are : P. Boubert, A. Bultel, G. Herdrich, A.F. Kolesnikov, M. Playez and C. Rond.

I wish that the discussion will continue in order to still work together on the atmospheric entries with inductively coupled plasma torches.