350 participants
7 pays
173 présentations

4 participants hors Asie : Zhuoxiang Ren (Geeps), J. Yan and M.Fang (UK), Y. Cressault (Laplace)

2 ½ journées
20 plenary talks
4 sessions parallèles/jour (12’ par talk)
95% des présentations en chinois

9 topics : academic and industrial presentations

Arcs-Sparks discharges
Corona discharges
Pressure discharges
Multiphysics computation
Insulation materials
SF_6 replacement
Streamers and breakdown
Discharges interactions with insulated materials
Discharge surface and diagnostics
+ 2 workshops COMSOL+SIMDROID

IDCOMPU 2019

Historical and future development of switching arc modelling and computer simulation : a personal perspective (M. Fang, UK)

Point de vue personnel sur l’évolution de la recherche sur les appareillages de coupure et leur simulation

De 1985 à 1995 : modèle hybride, méthodes intégrales et différentielles

1er constat : les données

Incertitudes sur les propriétés des gaz : transport et NEC (larges différences parfois au niveau des calculs théoriques, encore plus lorsque l’on compare le NEC aux mesures expérimentales)

2ème constat : les modèles

Modèle d’arc basé sur hypothèse non-LTE avec « laminar flow » ne permet pas d’estimer correctement la RRRV

Plusieurs exemples sont donnés sur les lois de mélanges, NECs et transport avec les différences, avec différents codes de simulation utilisés pour simuler les appareils : k-epsilon, chem-kim, RNG, realisable k-epsilon model, mixing length turbulence model (son préféré)

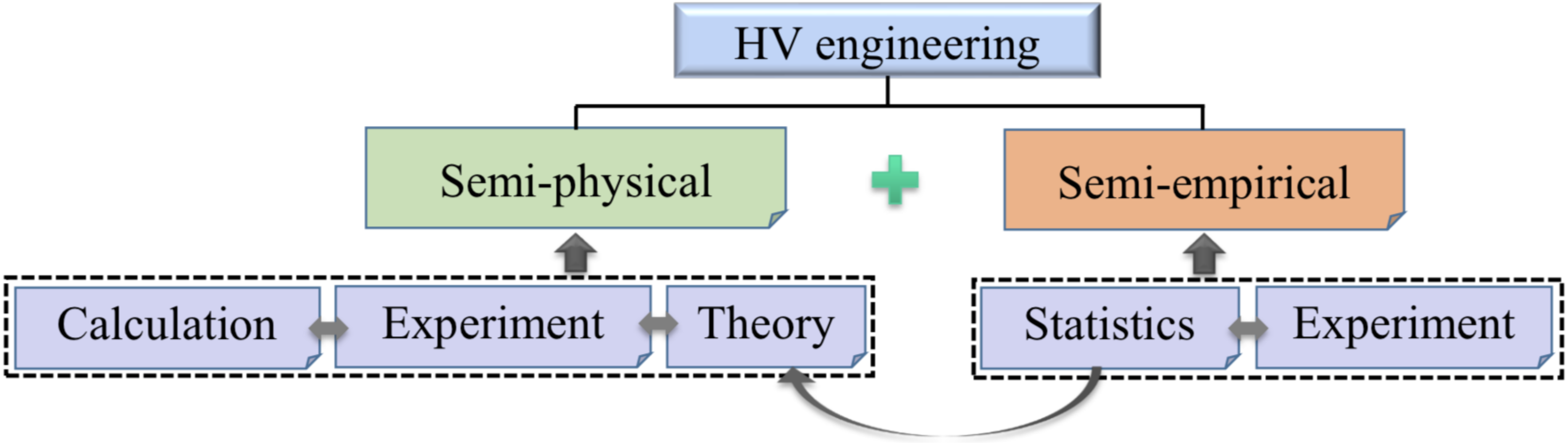
Futur :

Vérifier expérimentalement les propriétés radiatives et les propriétés de transport
Estimer l’ablation de PTFE sous l’effet du rayonnement
Confirmer ou infirmer que $\rho * C_p$ est suffisant pour déterminer de l’efficacité de coupure d’un gaz
Les méthodes conventionnelles ne sont pas valables à haute T° (>20kK) et hautes pressions (surtout la conductivité électrique)
Modèles 2T non adaptés actuellement si non prise ne compte du champ électrique dans la détermination de la EEDF

Progress of Computational High Voltage Engineering (CHVE) (Xuzhu Dong, China Southern Power Grid – Chine)

Depuis quelques années, augmentation de la puissance et vitesse de calcul des ordinateurs
Coût d'une simulation en Chine : 0.1RMB par CPU heure (0.7€/h)
Utilisation prononcée de la CHVE dans le domaine de la biologie et de la mécanique, pourquoi pas dans le HV

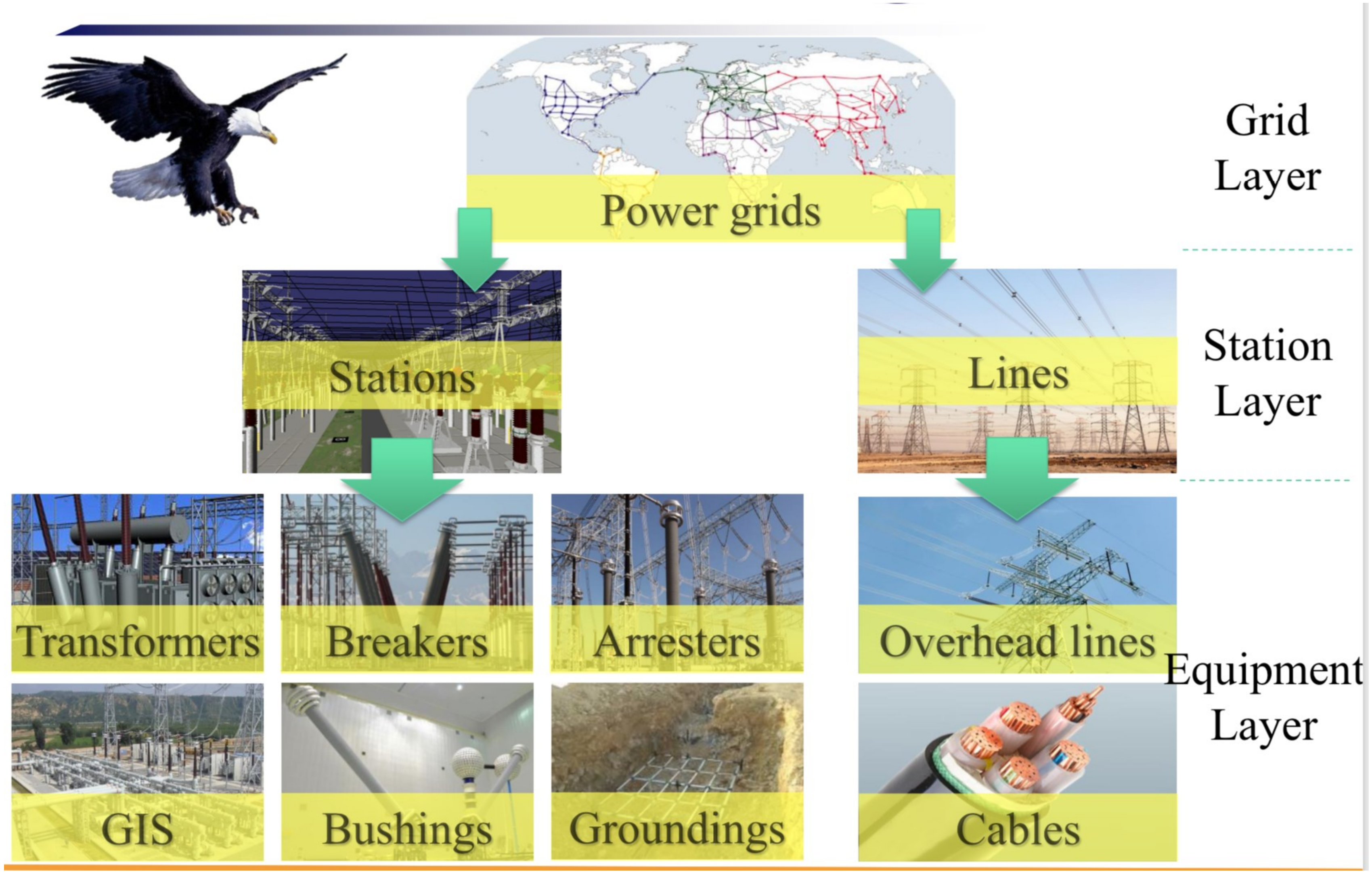
CHVE = HV + Computer science + Applied physics
Adaptable aux interfaces gaz/liquides/solides/décharges
Adaptable à la fabrication et caractérisation des matériaux d'isolation
Adaptable au couplage de phénomènes multiphysiques



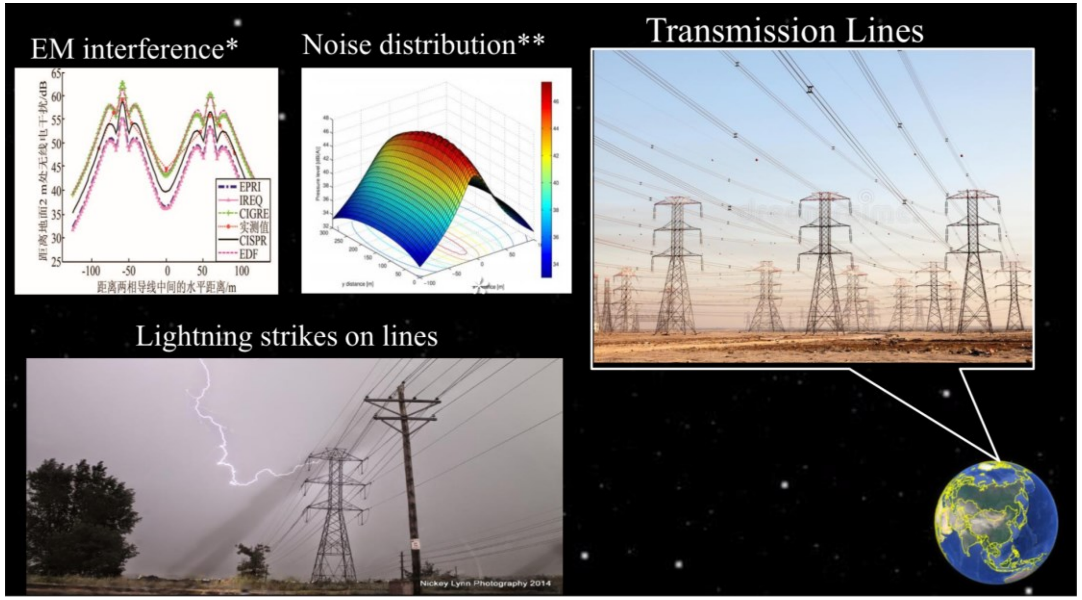
Progress of Computational High Voltage Engineering (CHVE) (Xuzhu Dong, China Southern Power Grid – Chine)

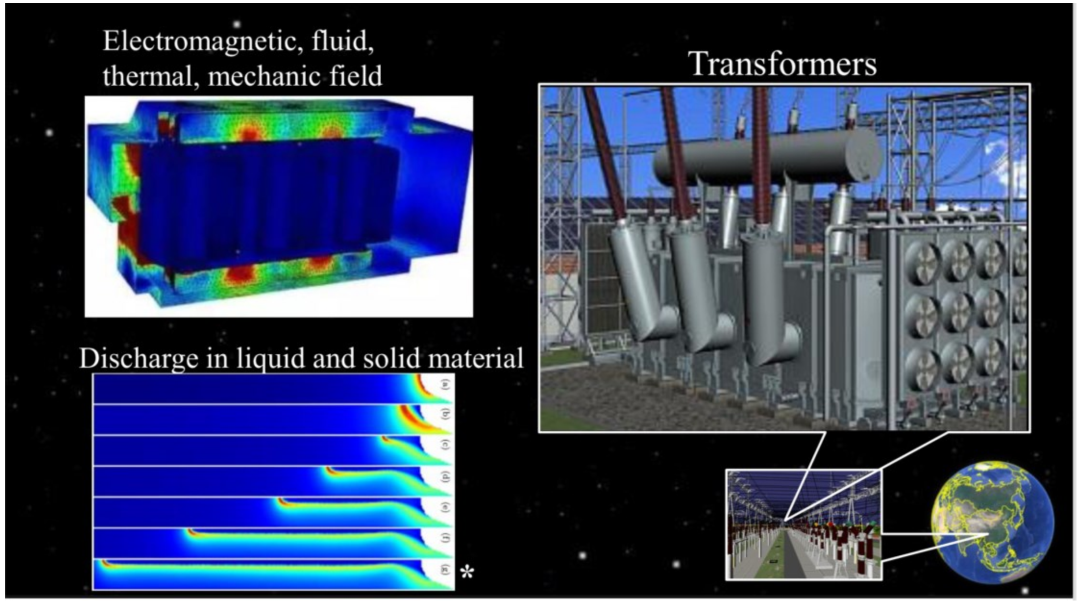
Objectif de l'entreprise :

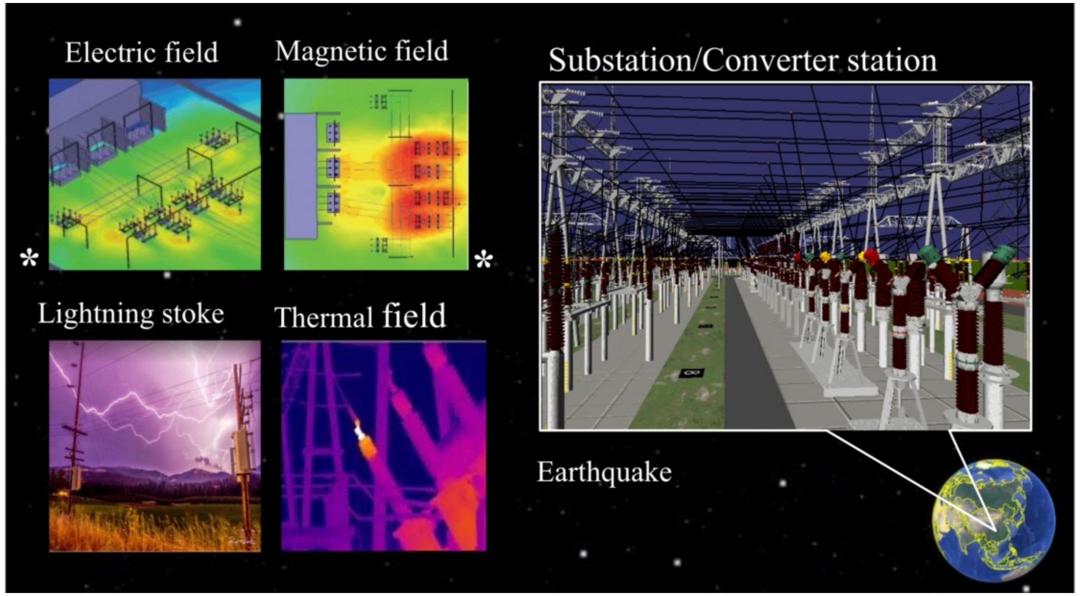
Créer un grid layer (solar, storm, ice, external phenomena) + station layer (electromagnetic field) + equipment layer ()



Progress of Computational High Voltage Engineering (CHVE) (Xuzhu Dong, China Southern Power Grid – Chine)

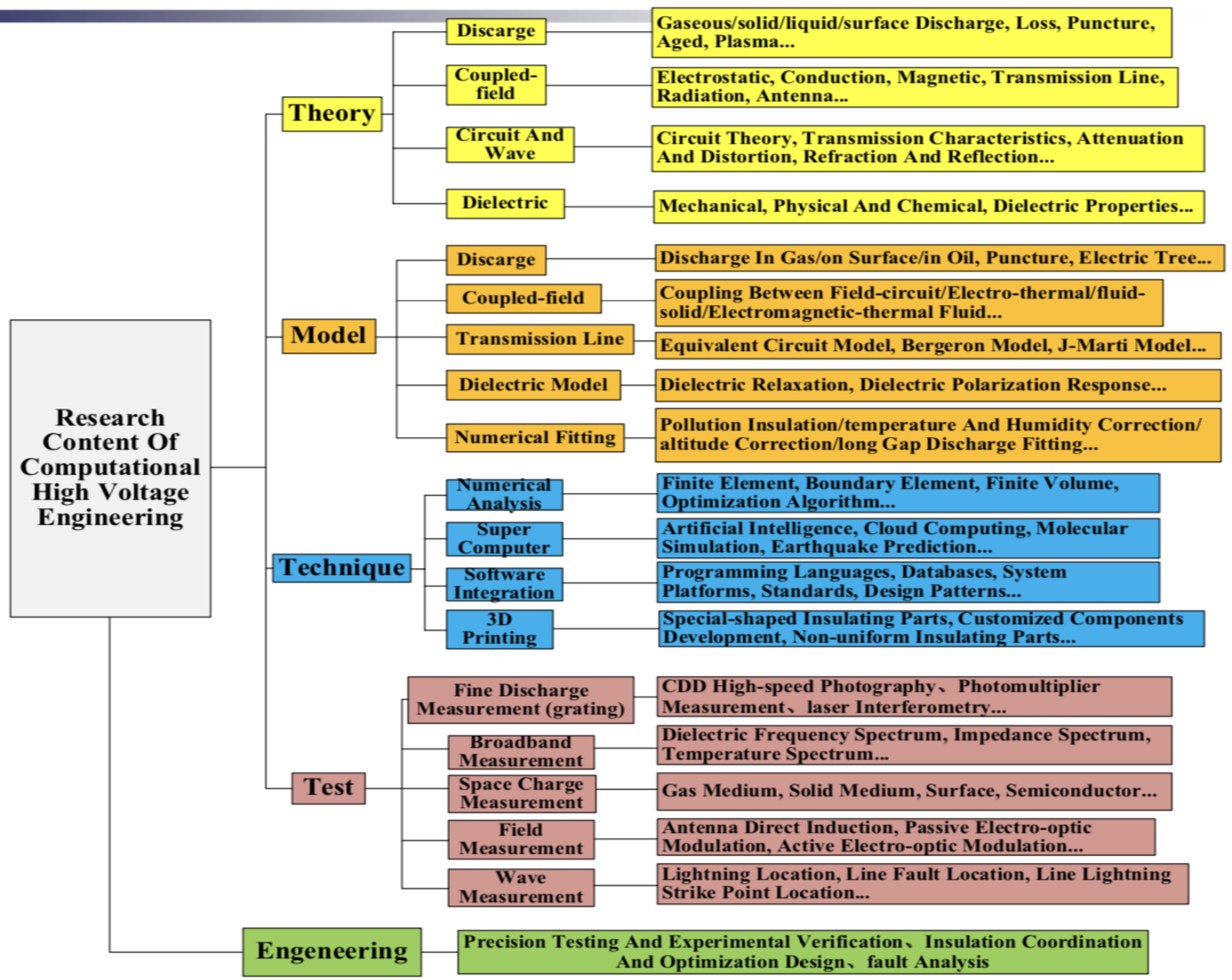






3. CHVE Architecture

中国南方电网
CHINA SOUTHERN POWER GRID



3. Architecture of CHVE – Testing

- To measure **electrical**, **thermal**, **mechanical** and **micro parameters** of dielectric materials for the models.

Electrical	Thermal	Mechanical	Micro
Rated parameters, Electrical conductivity, Magnetic permeability, Dielectric constant, Charge density, B-H curve, Electric field, Magnetic field	Specific heat capacity, Thermal conductivity, Emissivity, Dynamic viscosity, Kinematic viscosity, Boiling point, Melting point, Coefficient of thermal expansion, Temperature	Modulus of elasticity, Poisson's ratio, Shear modulus, Yield strength, Tensile strength, Ductility, Toughness, Hardness, Fatigue strength	Electron mobility, Free path, Electron lifetime, Fermi level, Recombination rate, Bond energy parameter, Bond angle parameter

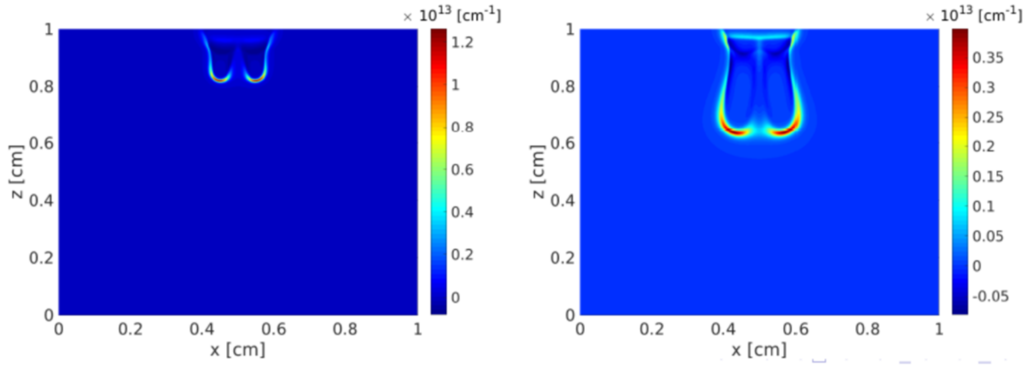
Progress of Computational High Voltage Engineering (CHVE) (Xuzhu Dong, China Southern Power Grid – Chine)

Test sur streamer double-headed – 1s de temps de calcul avec 1000CPU

4.1 3D simulation of streamer discharge *

(Chijie Zhuang, Tsinghua University)

- A double-headed streamer was simulated within a cubicle of 1 cm^3, with mesh size 2048×2048×2560, which generated 1 billion degrees of freedom in simulation.
- Tianhe 2-JK in Beijing was used for 3D simulation. The computing time is about 1s when using 1000 GPUs.



<u>Challenges pour demain :</u>

Etude précise de la génération et du mouvement de particules chargées

Convergence améliorée pour le couplage de différents champs

Amélioration de la qualité de production

IDCOMPU 2019

Decomposition C_4F_7N gas (Wangxinxin, Chine)
D'autres papiers avec d'autres auteurs sur CF_3I/N_2, C_4F_7N/CO_2, C_5-PFK, $C_6F_{12}O/CO_2$

C_4F_7N représente un bon candidat pour remplacer le SF_6 (à cause du N – donc ajout de O ou O_2)

<u>Objectif :</u> Modéliser la production de produits décomposés/formés

<u>Technique :</u> Décomposition par la méthode DFT (Density Functional Theory)
Couplage hybride de 2 méthodes : B3LYP Becke, 3-parameter, Lee–Yang–Parr (non-local-density approximation) + TZP (triple-zeta exponential)

<u>Exemples de chemins possibles</u>

C_4F_7NO -> $C_3F_4NO + CF_3$ (moyenne énergie nécessaire)
-> $C_3F_5N + CF_2O$ (faible énergie)
-> $C_3F_7O + CN$ (moyenne énergie)
-> $C_3F_3NO + CF_4$ (faible énergie)
-> $C_4F_7O + N$ (haute énergie, difficile)

Faible énergie : 2kcal/mol
Moyenne énergie : 110kcal/mol
Haute énergie : 320kcal/mol

Analyse de deux réactions de décomposition, notées A et D
Taux de réactions pour A et B calculés de 300K à 3500K par la méthode TST (transition state theory)

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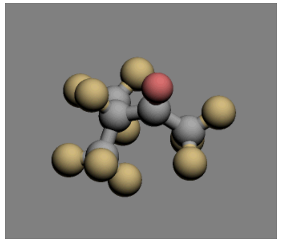
A machine learning based model for predicting moleclar ionization cross sections (Linlin Zhong, Chine)

Part du constat que :

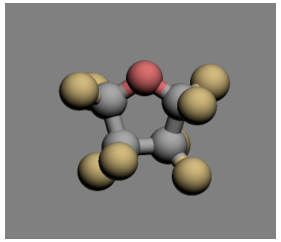
1/ Les collision électrons-molécules (elastic-inelastic excitation, ionisation, attachment) -> processus fondamental pour l'ionisation du milieu

2/ Les sections s'obtiennent par des études expérimentales (chères), ou des calculs théoriques (gourmands en temps de calcul par les méthodes de Binary Encounter Bethe BEB model ou Deutsch-Mark DM model)

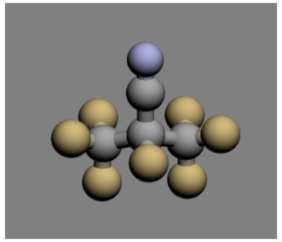
3/ Le temps de calcul augmentent exponentiellement avec le nombre d'atomes de carbones dans la chaine



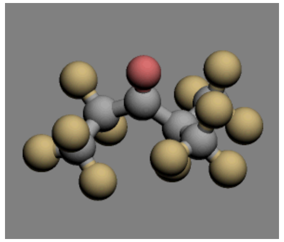
$C_5F_{10}O$



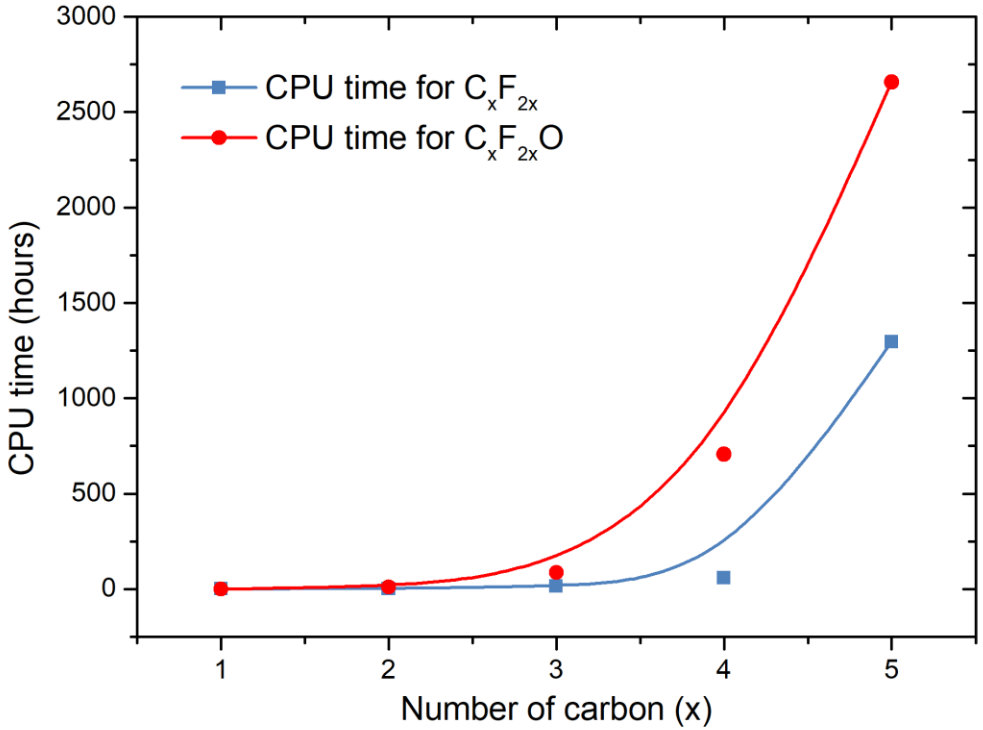
C_4F_8O



C_4F_7N

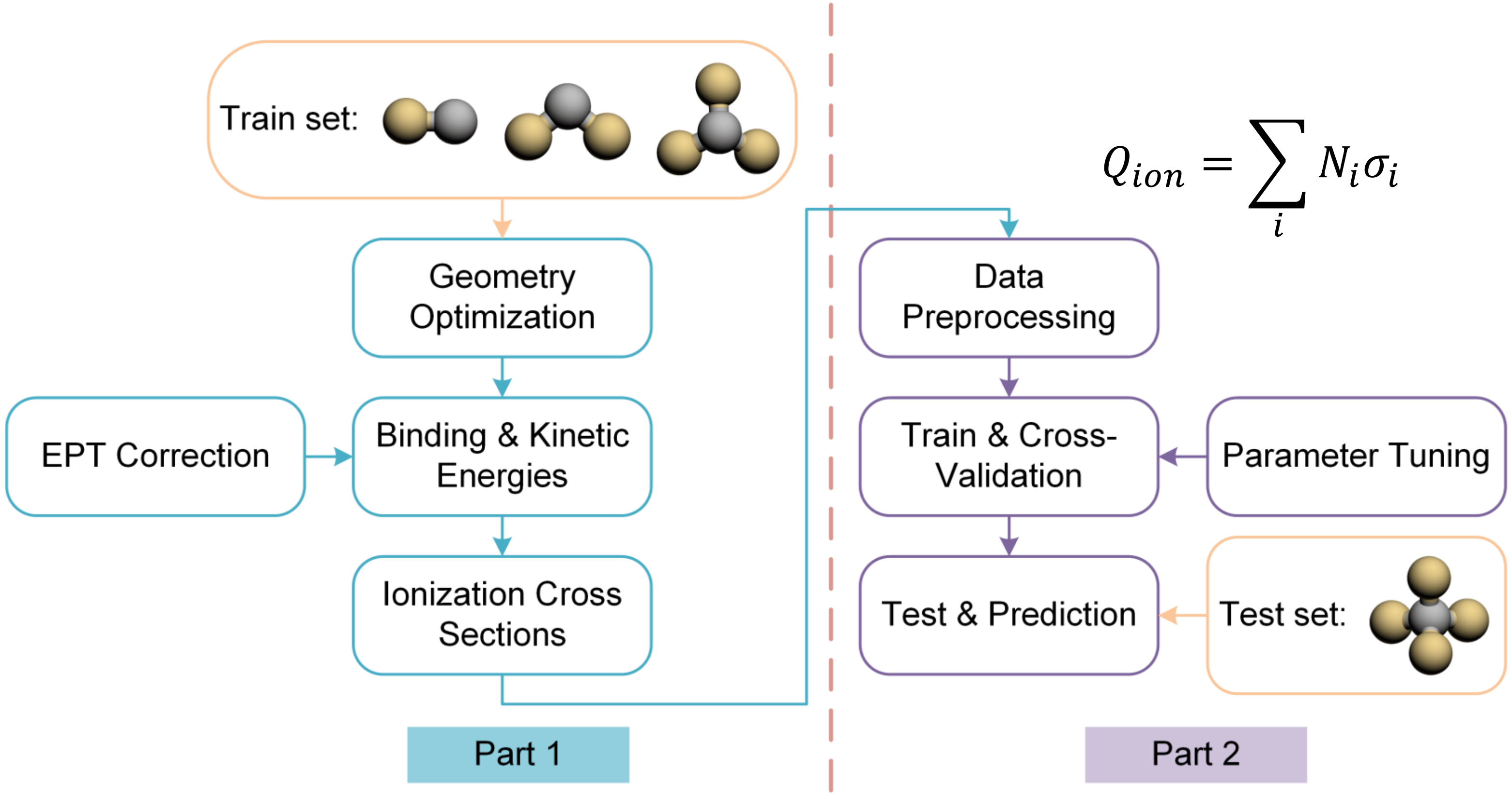


$C_6F_{12}O$



A machine learning based model for predicting moleclar ionization cross sections (Linlin Zhong, Chine)

4/ Il semble possible de déterminer la section efficace de collision d’ionisation Q_{ion} de grosses molécules connaissant celle des plus petites qui la composent



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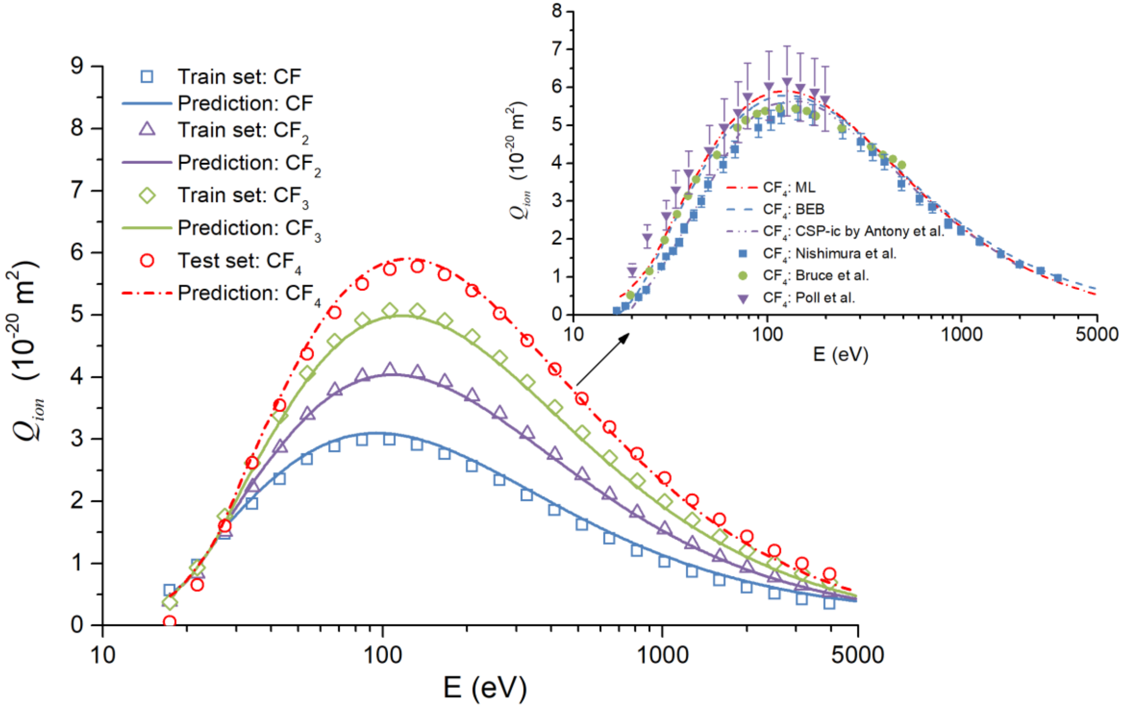
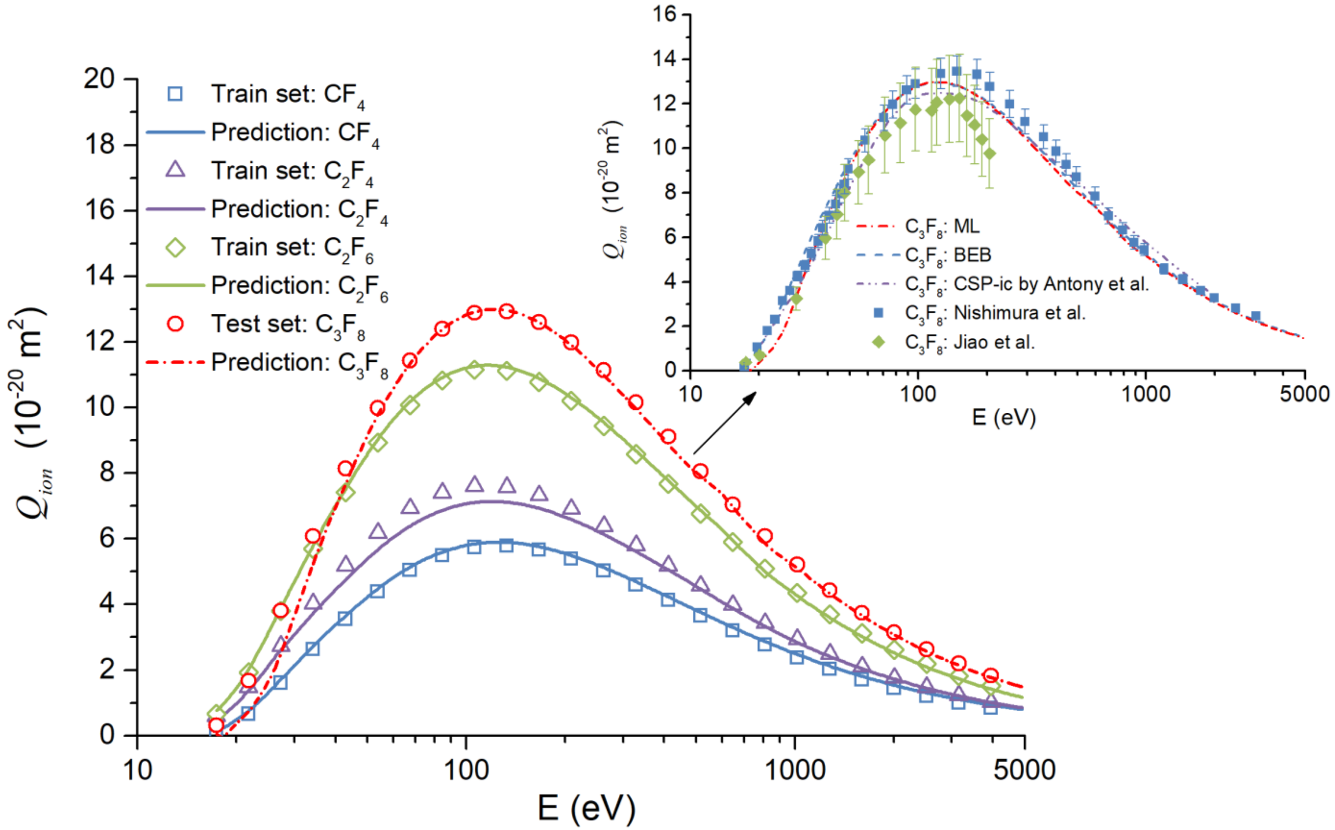
A machine learning based model for predicting moleclar ionization cross sections (Linlin Zhong, Chine)

Cette méthode ne donne pas d'expression algébrique pour calculer Qion mais apprend du comportement similaires des sections efficaces Q_{ion} d'autres molécules, en étudiant le comportement de la fonction

f(incident energy electron)=$y_{\text{ionisation cross section}}$

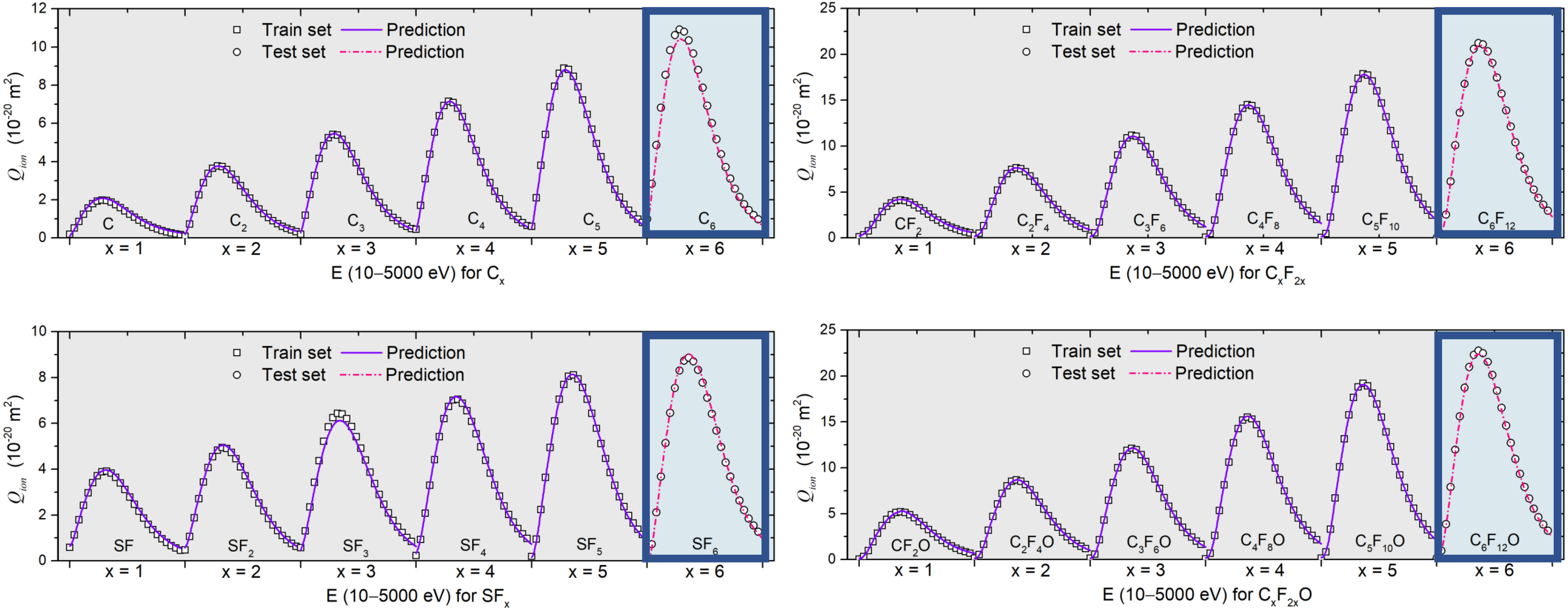




A machine learning based model for predicting moleclar ionization cross sections (Linlin Zhong, Chine)

Part du constat que :

Ca marche, exemples donnés pour 4 molécules complexes : $C_{6,}$ $SF_{6,}$ C_6F_{12}, $C_6F_{12}O$



Metal vapor in arc plasmas : thermophysical properties, measurements and modelling (A.B Murphy, Australia)

Dans les applications TIG : les vapeurs métalliques viennent du weld pool - Electrodes en tungsten

Modèle: TIG dans Helium + vapeurs Fe / Cr

- Les expériences montrent présence de vapeurs proche workpiece mais aussi cathode (déposition de Cr par ex)
- Equations du modèle, utilisation des coefficients de diffusion combinés étendus à des mélanges ternaires (Cr-Fe-He)
- But du modèle : montrer que la diffusion joue un rôle important, coefficient combiné D_E

Résultats : Bon accord entre calculs et mesures radialement (basé sur l'émission des raies Cr à 520.8nm)
Sans vapeurs T_{max}=21000K, avec vapeurs T_{max}=13000K, la diffusion sous effet du champ électrique est un processus dominant (for upward transport of metal vapor). On observe des vapeurs Cr proche de la cathode, déposées dans des régions où $T>T_{boil}$

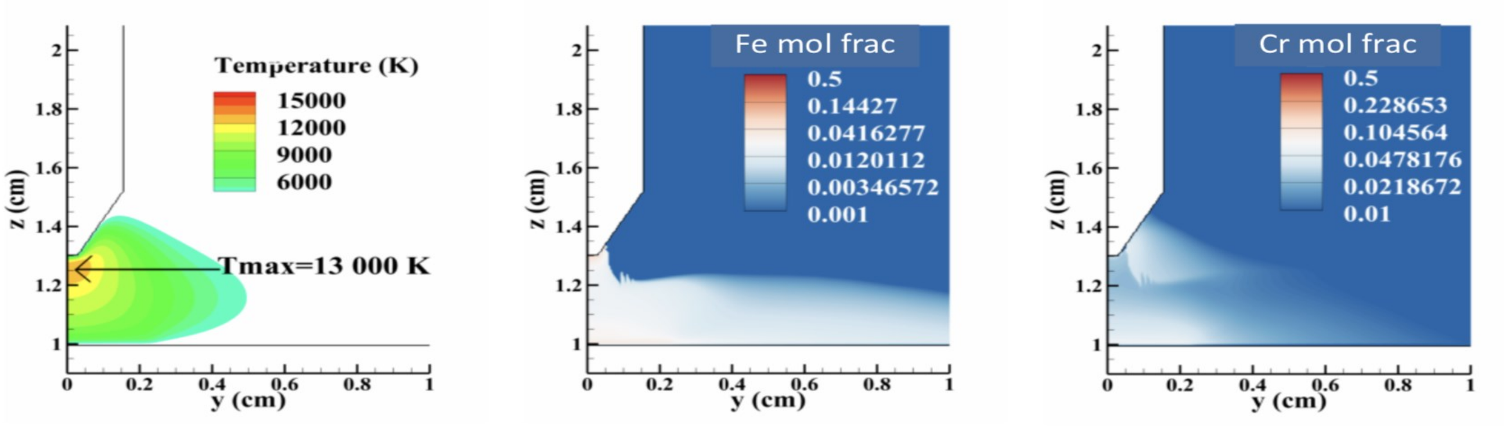


Fig. 4. Distributions of (a) temperature, (b) iron vapour mole fraction and (c) chromium vapour mole fraction in helium TIG welding of stainless steel.

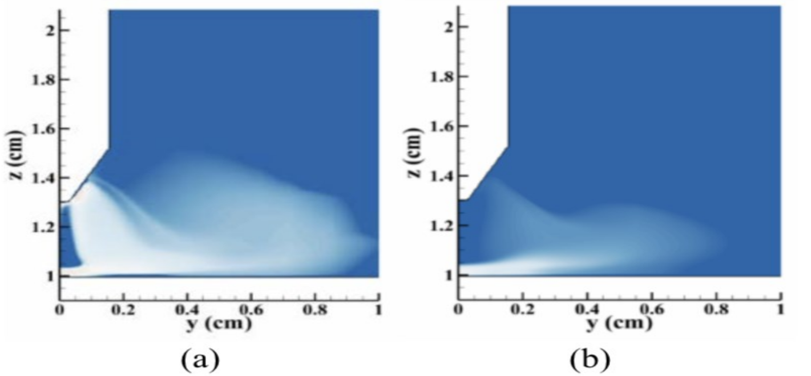


Fig. 2. Distributions of chromium vapour mole fraction neglecting (a) diffusion driven by electric fields and (b) diffusion driven by temperature gradients. The mole fraction scale is the same as in Fig. 1(c).

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Metal vapor in arc plasmas : thermophysical properties, measurements and modelling (A.B Murphy, Australia)

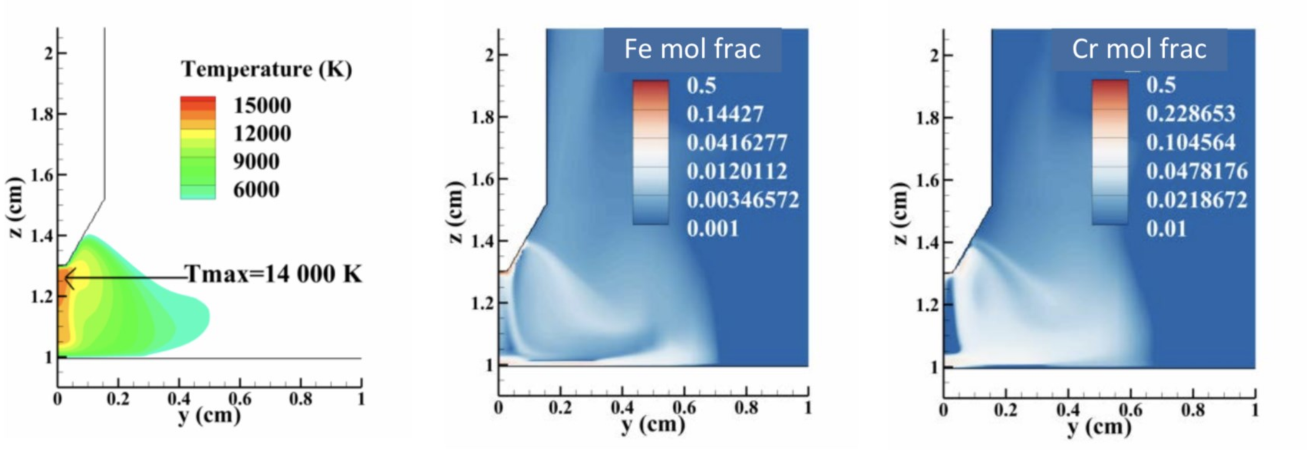
Modèle: **TIG dans Argon + vapeurs Fe / Cr**

- Comparaison faite avec et sans diffusion sous Champ Electrique, avec et sans diffusion sous gradient T

Résultats:

- La diffusion à cause des gradients de températures est dominant (pas par E), plus forte à basses T pour Ar-Fe-Cr que He-Fe-Cr, les coefficients de diffusion combinés D_E sont plus faibles pour Ar-Fe-Cr que He-Fe-Cr
- Les vapeurs métalliques sont produites à l'anode, puis diffusion upwards to recirculating flow, et trapped near cathode tip by upward diffusion -> importance de la convection

Validation par mesures expérimentales : OES montre la présence de Cr proche cathode



(a) (b) (c)

Fig. 1. Distributions of (a) temperature, (b) iron vapour mole fraction, (c) chromium vapour mole fraction in argon TIG welding of stainless steel.

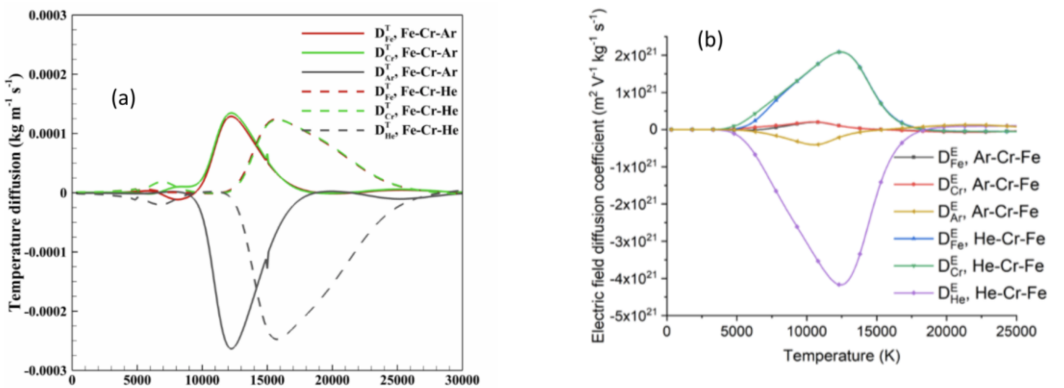


Fig. 3. Combined (a) temperature and (b) electric field diffusion coefficients for mixtures of 10% wt% iron and 10 wt% chromium with argon or helium.

Objectifs pour la prochaine conférence

Hors de Chine

Elargir le ISC

Garder les mêmes topics

Mélanges de présentations académiques et industrielles

Calculation of radiative properties for thermal plasmas : the state of art and outlooks

Y. Cressault, Ph. Teulet, X. Baumann, N. Kabbaj, L. Hermette, F. Reichert, A. Petchanka

cressault@laplace.univ-tlse.fr

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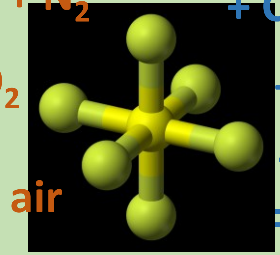
1953 : High Voltage Circuit Breakers SF_6

1 Environnemental

SF_6
CO_2
CF_3I
C_4F_7N
$C_xF_yO_z$
g^3

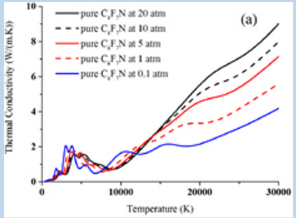


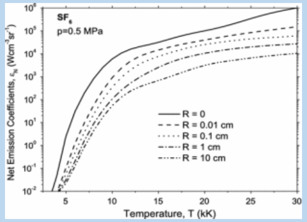
+ CO_2
+ N_2
+ O_2
+ air
+ Cu
+ Al
+ Ag
+ Fe

SF_6, N_2, Air, CO_2, SF_6/N_2, SF_6/Air, SF_6/CO_2, SF_6/H_2, SF_6/CF_4, SF_6/C_2F_4, CF_4, C_2F_6, C_3F_8, c-C_4F_8 (+Ar/O_2/N_2/CO_2/CF_4), CF_3I (+O_2/Air/CO_2), C_4F_7N (+N_2/CO_2/OH/Cl/O_2), $C_5F_{10}O$, $C_6F_{12}O$ (+N_2/Air), CF_3NSF_2, CF_3Cl, CHF_2, CF_nCl_{3-n}, CHF_nCl_{3-n}, C_nH_{2n+2} , CCl_2F_2 (R12) ...

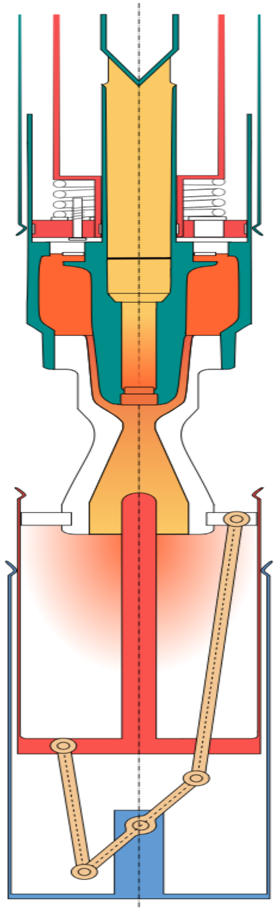
2 Thermal properties

Composition of the plasmas
Thermodynamic / transport
Radiative properties





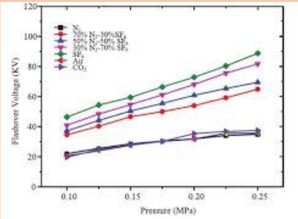
= f(T, P, R, %, LTE or non LTE/LCE)

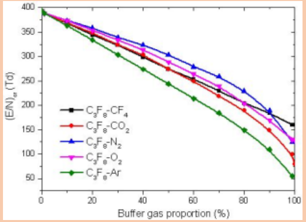


5 Experiments

3 Dielectric properties

Attachment coefficient
Ionization coefficient

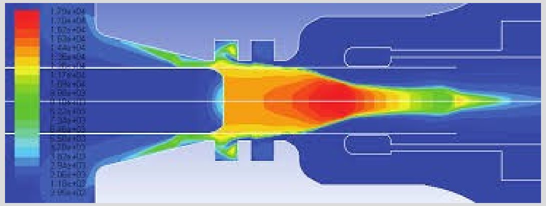




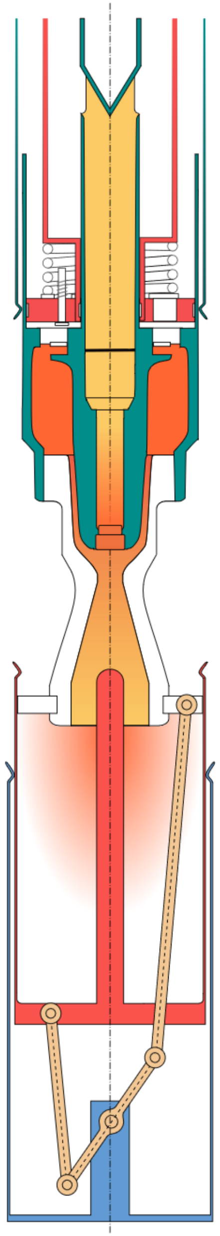
E/N critical electric field
Breakdown voltage

4 Numerical model 2D/3D

Comsol / Fluent Ansys
Home code



Ignition, extinction
Erosion, ablation



Magneto-Hydro-Dynamic modelling (MHD)

Equations of conservation (mass + transport + energy) + Maxwell equations

Thermal conductivity

$$\frac{\partial(\rho h)}{\partial t} + \vec{\nabla}.(\rho\vec{u}h) = \frac{\partial P}{\partial t} + \vec{\nabla}.(\kappa_t \vec{\nabla} T) + \frac{\vec{j}.\vec{j}}{\sigma} + \frac{5}{2}\frac{k_B}{e}\left(\frac{\vec{j}.\vec{\nabla}h}{C_p}\right) - S_{rad}$$

Mass density

Mass enthalpy

Electrical conductivity

Radiative properties

1. How to treat the radiative losses in hottest regions (strong emission) -> NECs
2. How to treat the radiative losses in intermediate / cold regions (absorption) -> P1 model (MACs) / DOM
3. How to develop the degenerative methods (optimization and comparison with the exact calculation)
4. How to calculate the 2T properties (for the current zero phase for example)

Radiative losses :

Exact solution of RTE

The Radiative Transfer Equation (RTE)

Divergence of the Radiative Flux (DRF)

$$S_{rad} = \vec{\nabla} \cdot \vec{F_r}$$

$$\vec{F}_r = \int\int L_\lambda(\vec{r}, d\vec{\Omega}) \cdot \vec{s} \cdot \vec{n} \cdot d\Omega \cdot d\lambda$$

$$\frac{dL_\lambda}{dr}$$

Radiative Transfer Equation (RTE)

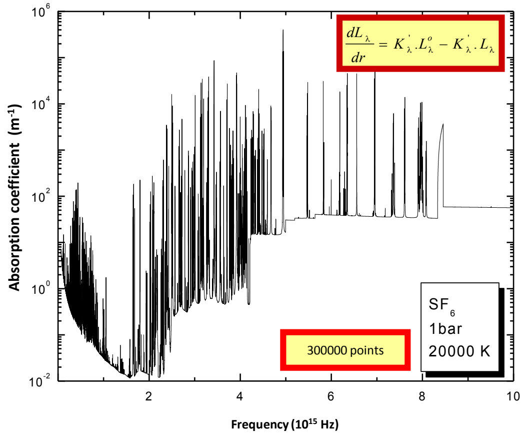
$$\vec{s} \cdot \vec{\nabla} L_\lambda = K_\lambda' \cdot L^0{}_\lambda - K_\lambda' \cdot L_\lambda$$

Directions

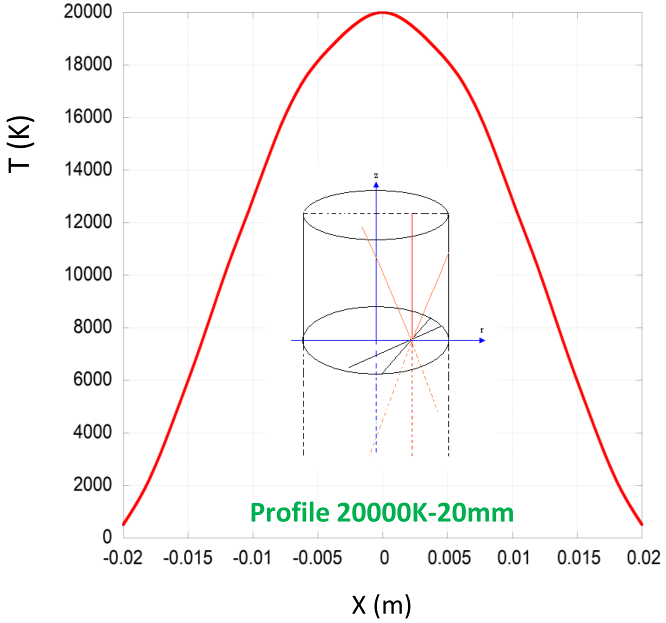
T, P, λ

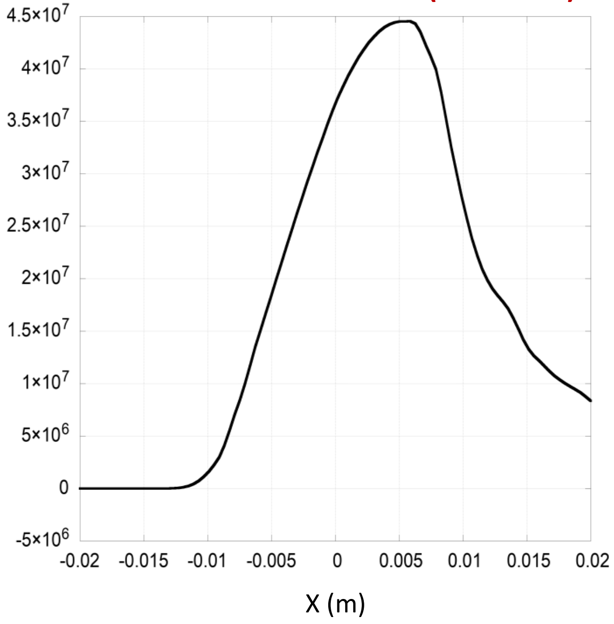
Wavelengths

Radiative properties

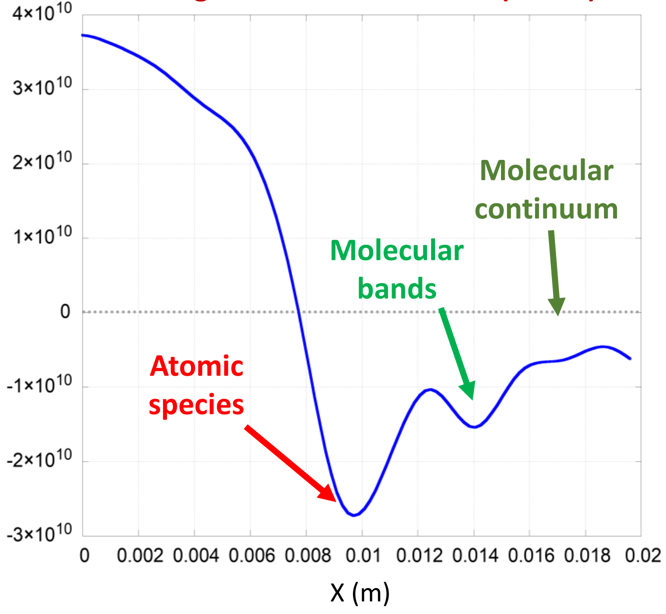


Resolution of the Radiative Transfer Equation (RTE) – Exact solution

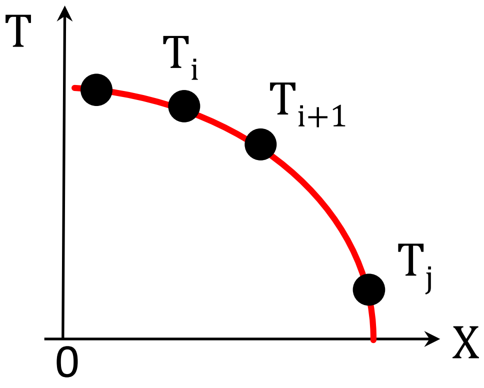




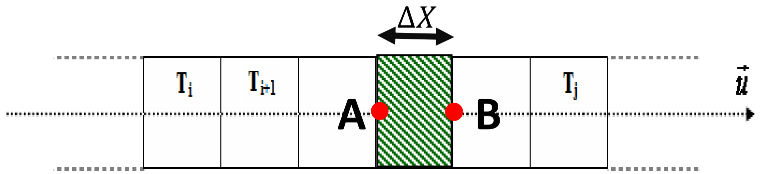
Integration



Solution in 1D of the Radiative Transfer Equation (RTE) – Exact solution



Temperature Profile

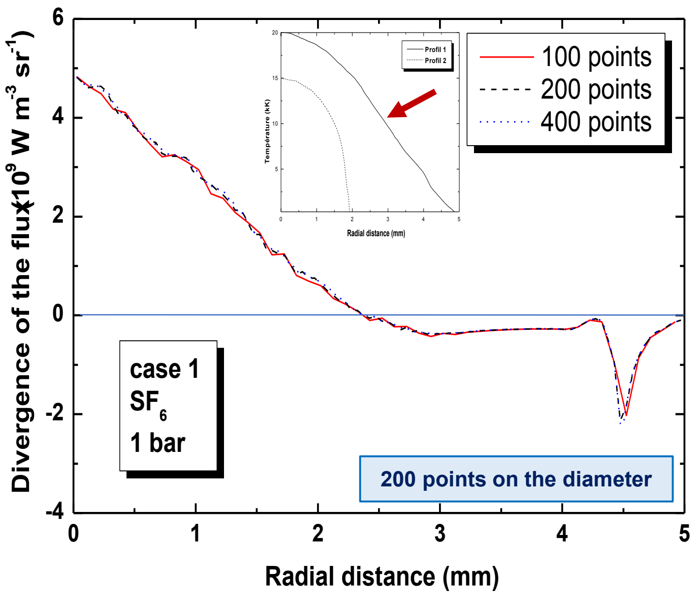


Discretization of the profile in 1D

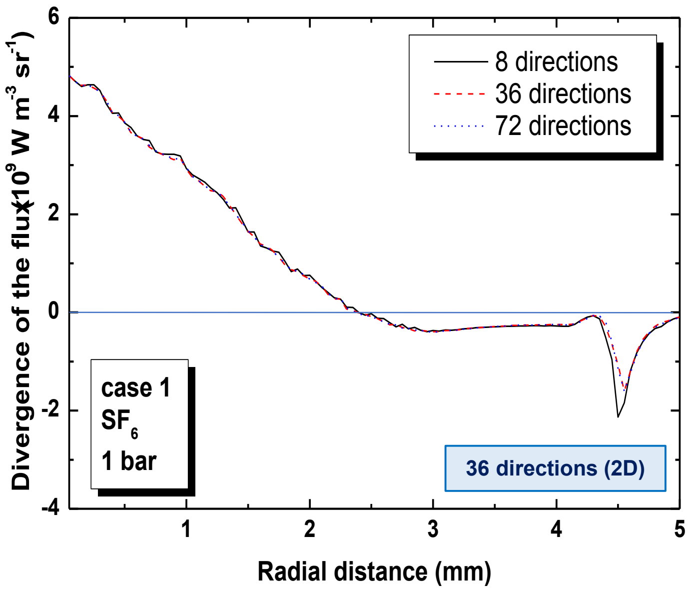
$$L_\lambda(i) = L_\lambda(i-1) \cdot \exp(-K' \cdot \Delta X) + L^0{}_\lambda(T_i) \cdot (1 - \exp(-K' \cdot \Delta X))$$

- $L_\lambda(i)$: Directional flux in the point B
- $L_\lambda(i-1)$: Incident at point A
- $\exp(-K' \cdot \Delta X)$: Absorbed by the cell
- $L^0{}_\lambda(T_i) \cdot (1 - \exp(-K' \cdot \Delta X))$: Emitted by the cell

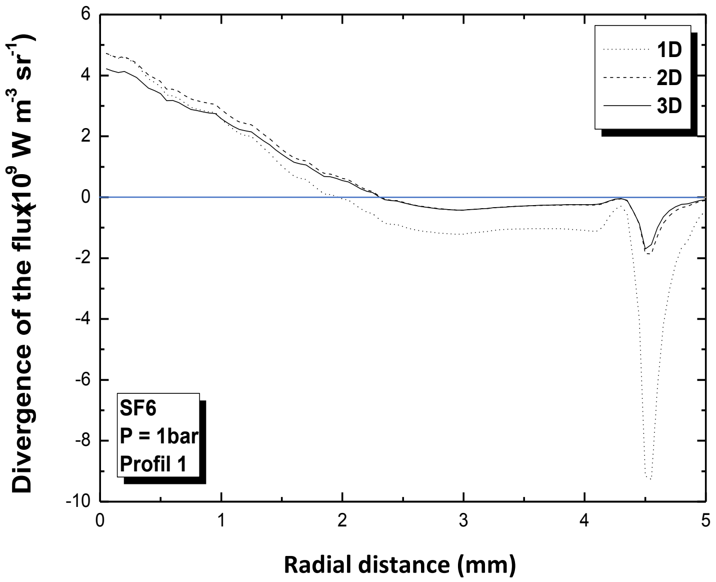
Influence of the discretization



Influence of the number of directions



Influence - 1D/2D/3D



Radiative losses :

Use of geometrical simplifications

to solve the RTE

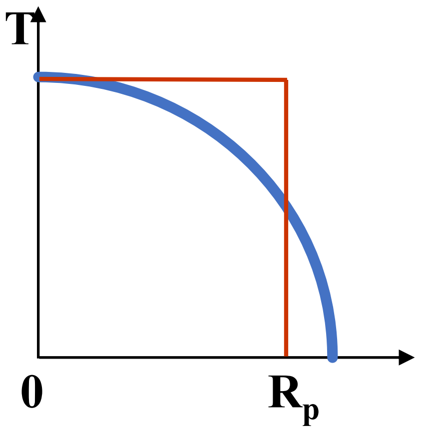
Radiative Transfer Equation (RTE)

$$\vec{s} \cdot \vec{\nabla} L_\lambda = K_\lambda' \cdot L^0{}_\lambda - K_\lambda' \cdot L_\lambda$$

Directions → Too many space variables → **Geometrical simplifications**

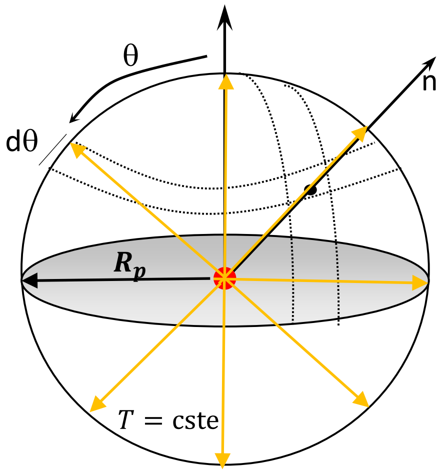
The Net Emission Coefficient (NEC) – Lowke and Capriotti (1969)

Isothermal plasma



+

Homogeneous plasma



80%-90% of accuracy

+

Spherical plasma of radius R_p

$$\varepsilon_n = \int K'(\lambda, T) \cdot L^0{}_\lambda \exp(-K'(\lambda, T) \cdot R_P)\, d\lambda$$

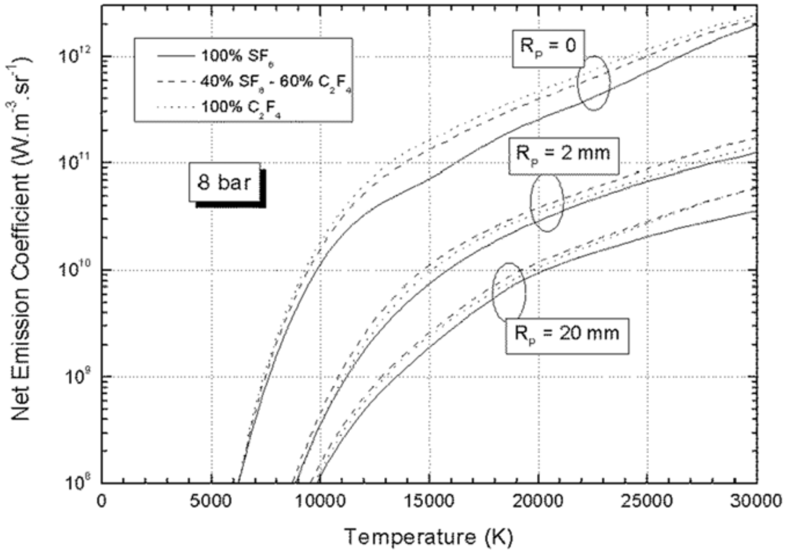
$$\vec{\nabla} \cdot \vec{F} = S_{rad} = 4\pi\varepsilon_n$$

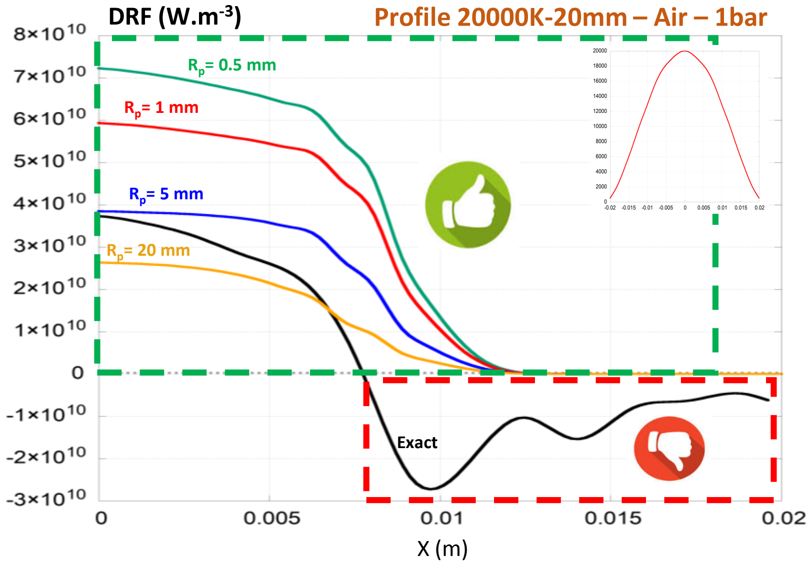
This technique has demonstrated its efficiency to model **radiations emitted by central hot regions of the arc**.

The Radiative Transfer Equation (RTE) - The Net Emission Coefficient (NEC)

If temperature ↗	NEC ↗
If pressure* ↗	NEC ↗
If plasma's size R_p ↗	NEC ↘
If metallic vapors ↗	NEC ↗
If organic vapors ↗	NEC ↗↘
If escape factor	NEC ↗

* Limited by Black body radiation





How to choose the value of R_p ?

Proposition of M. Fang & A. Gleizes

*R_p roughly corresponds to the radius of the hot region of the plasma, which is an expression not very precise, but a rather good estimation is the **distance from the axis** where the temperature has a value of **about 80% of the axis temperature**.*

$$R_p = r\ (T=80\%T_{max})$$

Y Cressault, A Gleizes and G Riquel, « Properties of air–aluminum thermal plasmas », J. Phys. D: Appl. Phys. 45 (2012) 265202 (12pp)

Proposition of L. Fulcheri

*The plasma thickness R_p which helps better handling peaks in the absorption spectrum, can be fairly **approximated with $2*r_o$** (r_o radius of the cylindrical arc). However, the arc radius r_o is a function of the pressure, current and the tube radius R.*

$$\frac{2}{r_0^2}\int_0^{r_0} r dr \nabla\cdot\vec{q}_{rad} = \frac{2\pi B_\nu}{r_0} S_{exact}(k'_\nu r_0) \Rightarrow r_o \Rightarrow R_p = 2*r_o$$

P. Gueye, Y. Cressault, V. Rohani, and L. Fulcheri, « A simplified model for the determination of current-voltage characteristics of a high pressure hydrogen plasma arc », Journal of Applied Physics 121, 073302 (2017)

Proposition of N.Kabbaj

*To have a good estimation of the radiative losses in the hottest regions, the value of R_p depends on the maximal temperature, the width of the temperature profile, and the pressure. Nevertheless, different tests on air seems to confirm that **R_p=r at 90% of T_{max}** is a good approximation.*

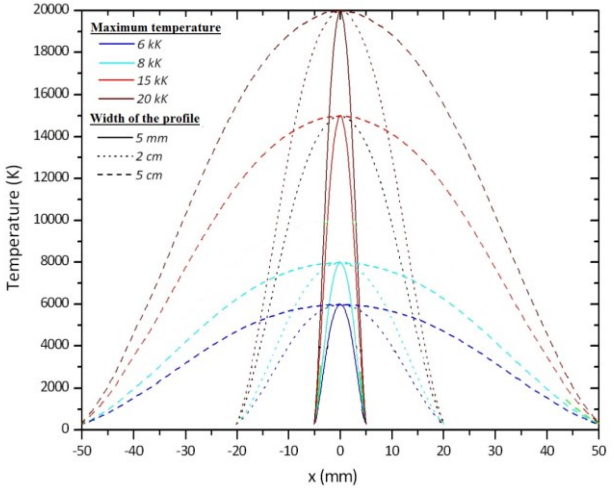
$$R_p = r\ (T=90\%T_{max})$$

N. Kabbaj, « étude du transfert radiatif d'un plasma thermique d'air : Influence des propriétés radiatives dans la modélisation d'un arc libre », PhD Thesis, University of Toulouse (2019)

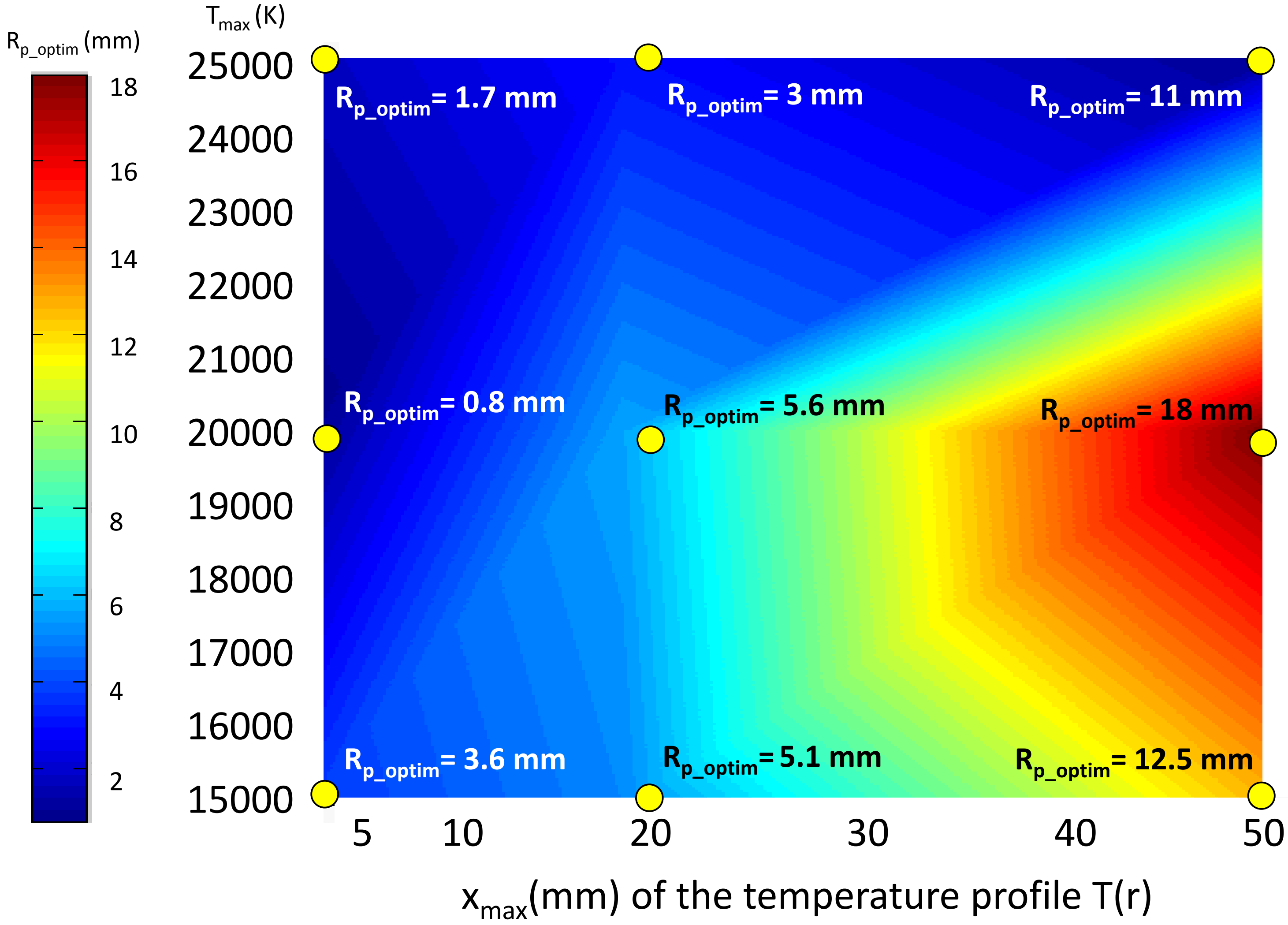
Optimization of R_p → Minimization of $F'_{NEC(R_p)} = \frac{|DRF_{exact}(X=0) - DRF_{NEC-Rp}(X=0)|}{DRF_{exact}(X=0)}$ → Simplex Nelder Mead algorithm

To find the best R_p to use in modelling

T(r) profiles tested in the case of Air -1bar



	r_{max}=5mm		r_{max}=20mm		r_{max}=50mm	
T_{max} (K)	$R_{p\text{-}optim}$ (mm)	% of T_{max}	$R_{p\text{-}optim}$ (mm)	% of T_{max}	$R_{p\text{-}optim}$ (mm)	% of T_{max}
15000	3.6	92	5,1	90	12.5	95
20000	0.8	93	5,6	88	18	81
25000	1.7	91	3	91	11	85



Conclusions for R_p

R_p = x ~ 90% of T_{max} is a good choice

Radiative losses :

Use of spectral simplifications

to solve the RTE

Radiative Transfer Equation (RTE)

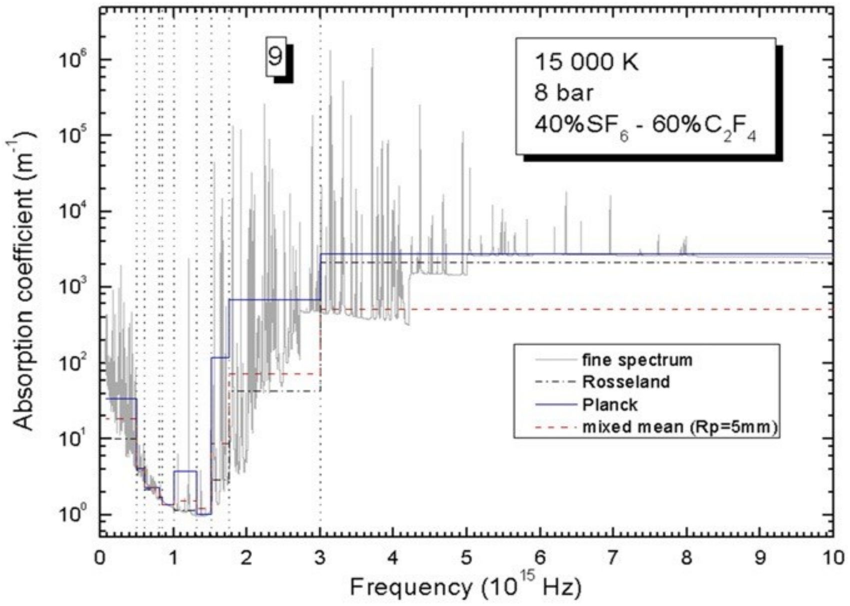
$$\vec{s} \cdot \vec{\nabla} L_\lambda = K' \cdot {L^0}_\lambda - K' \cdot L_\lambda$$

Wavelengths → Too many spectral variations

Spectral simplifications

The Mean Absorption Coefficients (MACs)

The mean absorption coefficients (MACs) allow an acceptable description of the radiation absorption in the cold regions of the plasma
The latter is a very simplified spectral description based on the splitting of the spectrum into a restricted number of intervals



Choice of the spectral intervals (SF_6)

n°	f_1 (10^{15}Hz)	f_2 (10^{15}Hz)
1	0.066	0.200
2	0.200	0.822
3	0.822	1.700
4	1.700	2.074
5	2.074	2.505
6	2.505	4.212
7	4.212	10

H.Z Randrianandraina, Y Cressault and A Gleizes, « Improvements of radiative transfer calculation for SF_6thermal plasmas » J. Phys. D: Appl. Phys. 44, 19 (2011)

H Nordborg and A A Iordanidis, « Self-consistent radiation based modelling of electric arcs: I. Efficient radiation approximations », J. Phys. D: Appl. Phys. 41 (2008) 135205 (10pp)

ν_{10} ={0.0, 1.0, 1.4, 1.77, 2.0, 2.2, 2.5, 3.0, 10.0}

Choice of the spectral intervals (SF_6-C_2F_4)

n°	f_1 (10^{15}Hz)	f_2 (10^{15}Hz)
1	0.066	0.5
2	0.5	0.6
3	0.6	0.8
4	0.8	0.85
5	0.85	1.0
6	1.0	1.31
7	1.31	1.52
8	1.52	1.76
9	1.76	3
10	3	10

C Jan, Y Cressault, A Gleizes and K Bousoltane, « Calculation of radiative properties of SF_6–C_2F_4 thermal plasmas—application to radiative transfer in high-voltage circuit breakers modelling », J. Phys. D: Appl. Phys. 47 (2014) 015204 (14pp)

Choice of the spectral intervals (CO_2)

n°	f_1 (10^{15}Hz)	f_2 (10^{15}Hz)
1	0.10	0.50
2	0.50	1.50
3	1.50	2.20
4	2.20	2.72
5	2.72	3.29
6	3.29	8.49
7	8.49	10

S. KOZU, T. FUJINO, T. YOSHINO, T. MORI, RADIATIVE TRANSFER CALCULATION OF CO2 THERMAL PLASMA USING A HYBRID PLANCK-ROSSELAND MEAN ABSORPTION COEFFICIENT, GD2018 conference, Serbia, 2018

Classic mean function

$$\overline{\kappa'}([\lambda_i,\lambda_j],T)=\frac{\int_{\lambda_i}^{\lambda_j}\kappa'(\lambda,T)d\lambda}{\int_{\lambda_i}^{\lambda_j}d\lambda}$$

Valid at very low T

Planck mean function

$$\overline{\kappa'}([\lambda_i,\lambda_j],T)=\frac{\int_{\lambda_i}^{\lambda_j}\kappa'(\lambda,T)\cdot L_\lambda^0(T)d\lambda}{\int_{\lambda_i}^{\lambda_j}L_\lambda^0(T)\cdot d\lambda}$$

Optically thin Overestimation

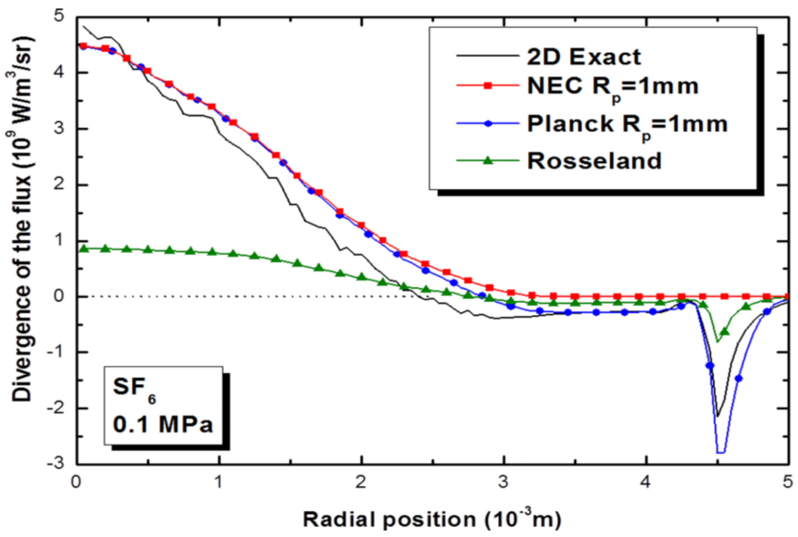
Planck Modified Mean Function (PMMF)

$$\overline{\kappa'}([\lambda_i,\lambda_j],T,\mathbf{R})=\frac{\int_{\lambda_i}^{\lambda_j}\kappa'(\lambda,T)\cdot L_\lambda^0(T)\cdot\exp(-\kappa'(\lambda,T)\cdot\mathbf{R})\,d\lambda}{\int_{\lambda_i}^{\lambda_j}L_\lambda^0(T)\cdot d\lambda}$$

Rosseland mean function

$$\overline{\kappa'}([\lambda_i,\lambda_j],T)=\frac{\int_{\lambda_i}^{\lambda_j}\frac{dL_\lambda^0(T)}{dT}\cdot d\lambda}{\int_{\lambda_i}^{\lambda_j}\frac{dL_\lambda^0(T)}{dT}\cdot\frac{1}{\kappa'(\lambda,T)}\cdot d\lambda}$$

Optically thick Underestimation



How many spectral intervals?
Which mean function do I use?

- **Recent works – different approaches - HVCB**

1/ Use of PMMF : H. Norborg (SF_6, 2008), H.Z. Randrianandraina (SF_6, 2011), by improvement of spectral intervals.

2/ Mix of Mean functions : C. Jan (SF_6-C_2F_4, 2013)

3/ Optimization algorithm : P. Kloc (Air, 2017), N.Kabbaj (Air, 2018)

4/ Hybrid Mean function : H. Norborg (SF_6, 2018), T. Fujino (CO_2, 2018), P. Kloc (Air, 2019)

Optimization algorithm : To find the best unique R (for all spectral interval) or best R_i for each interval

Define on each spectral interval a characteristic absorption length

$R = [R_{1\text{-}optim}, R_{2\text{-}optim}, R_{3\text{-}optim}, R_{4\text{-}optim}, R_{5\text{-}optim}, R_{n\text{-}optim}]$

Objectives

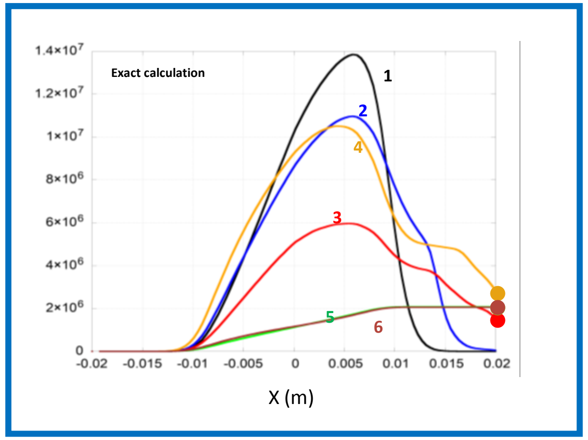
Simplex Nelder Mead

X points along the diameter (1D)

Minimization of the errors on radiative quantities

Minimize

$$F'_{MAC-Function}(R) = \frac{\frac{1}{X}\sum_{i=1}^{X}|F_{exact,i} - F_{CMA,i}(R)|}{\frac{1}{X}\sum_{i=1}^{X}|F_{exact,i}|}$$

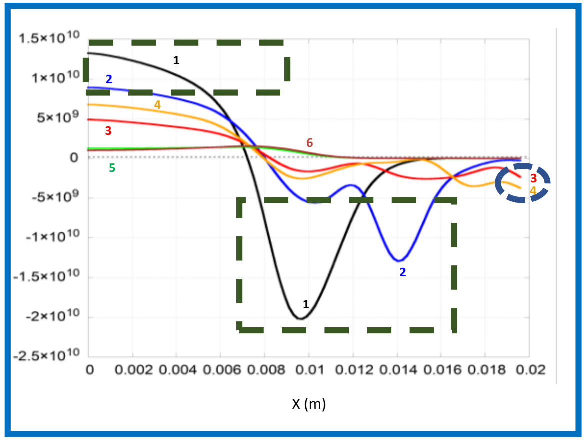


1- Outgoing Radiative Flux (ORF)

R_1-optim to R_n-optim

2- DRF

R_1-optim to R_n-optim

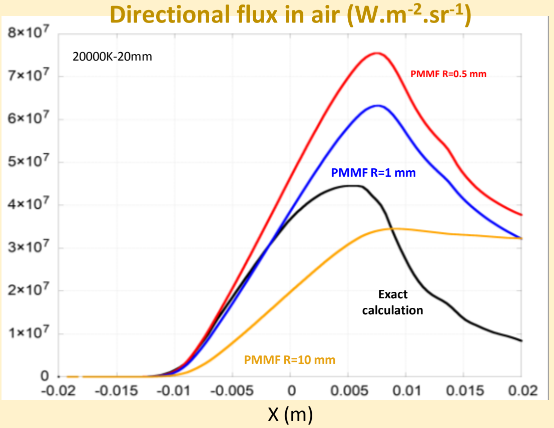


3- Simultaneously the DRF and the ORF

$R_{1\text{-}optim\text{-}DRF}$ & $R_{i\text{-}optim\text{-}DRF}$ + $R_{j\text{-}optim\text{-}ORF}$ to $R_{6\text{-}optim\text{-}ORF}$

Optimization algorithm : To find the best unique R (for all spectral interval) or best R_i for each interval

1- Outgoing Radiative Flux (ORF)



R_1-optim to R_6-optim

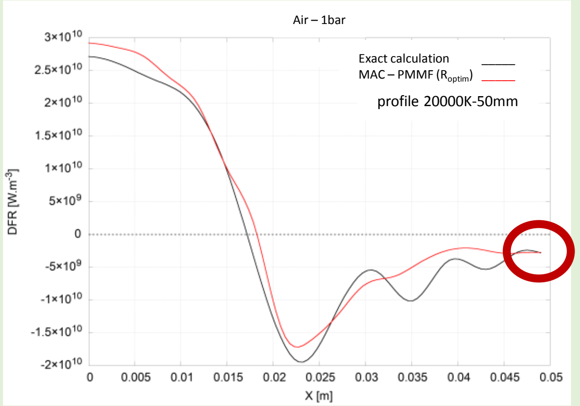
Profile	$F'_{MAC-ORF}$ (%)
15000K-5mm	1.2
15000K-20mm	0.08
15000K-50mm	0.09
20000K-5mm	0.62
20000K-20mm	0.61
20000K-50mm	0.04
25000K-5mm	0.6
25000K-20mm	0.0012
25000K-50mm	0.0009

Growth of the error

With unique R: 9%

Error less than 1.5%

2- DRF



R_1-optim to R_6-optim

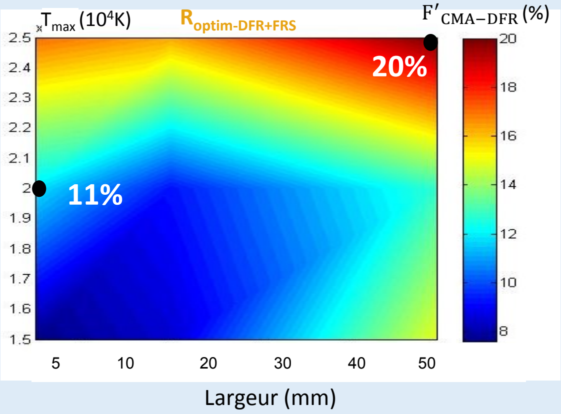
Profile	$F'_{MAC-DRF}$ (%)
15000K-5mm	6
15000K-20mm	7.1
15000K-50mm	8.8
20000K-5mm	9
20000K-20mm	9.5
20000K-50mm	11.4
25000K-5mm	14
25000K-20mm	14.2
25000K-50mm	18

Growth of the error

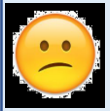
With unique R: 47%

Error between 6-14%

3- Simultaneously the DRF and the ORF



Profile	$F'_{MAC-DRF}$ (%)	$F'_{MAC-ORF}$ (%)
15000K-5mm	7.6	3
15000K-20mm	8.5	0.007
15000K-50mm	15	3
20000K-5mm	11.83	0.9
20000K-20mm	9.24	3.6
20000K-50mm	12.8	4
25000K-5mm	17	6.2
25000K-20mm	16.3	0.002
25000K-50mm	20	8



Error between 0.1-20%

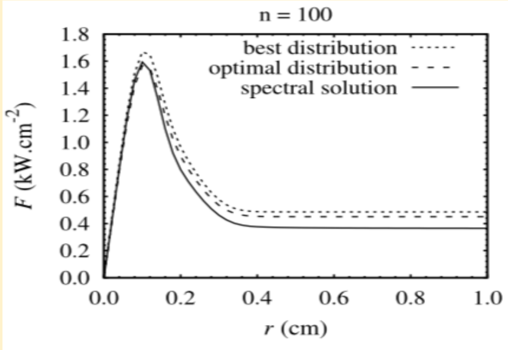
Use of Hybrid Planck-Rosseland (P-R) → $\kappa_{i,Hybrid} = (1-\gamma)\kappa_{i,Planck} + \gamma\kappa_{i,Rosseland}$

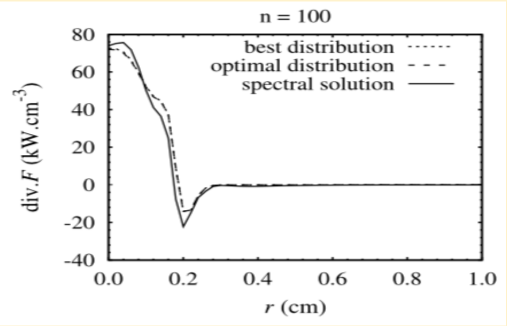
Special treatment for atomic lines → $\kappa_{\nu,line} = \frac{1}{h}(1-\exp(-\kappa_{\nu,line}h))$

Model 1D, 79.714 frequencies,
7 spectral intervals, profile T_{max}=20000K
2.20 – 2.7210^{15}Hz

P. Kloc (Air, 0.5-5 bar, 2018)

2 profiles, 3 bands
optimization function





H = 2R_p (0.5bar) - 3R_p (5 bar)
L_1=2.93759x10^{15}hz, L_2=3.51299x10^{15}Hz

P Kloc, V Aubrecht and M Bartlova, Numerically optimized band boundaries of Planck mean absorption coefficients in air plasma, Journal of Physics D: Applied Physics, 50, 30, 305201 (2017)

R. Fuchs (SF_6, 10 bar, 2018)

LTE stabilized arc, cylindrical, SF_6
I=100A, 400 pts, T_{wall}=300K, r_{wall}=5mm,
7 : 0.066, 0.35, 1.54, 2.65, 2.94, 3.52 × 10^{15}Hz

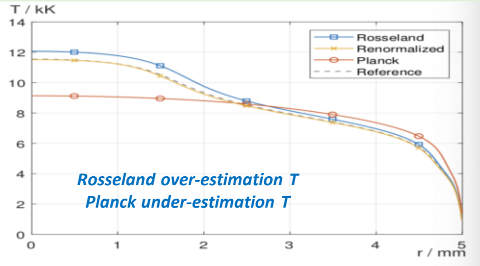
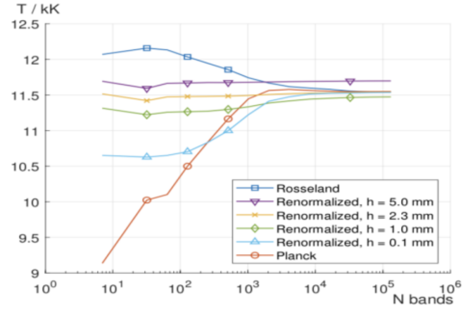


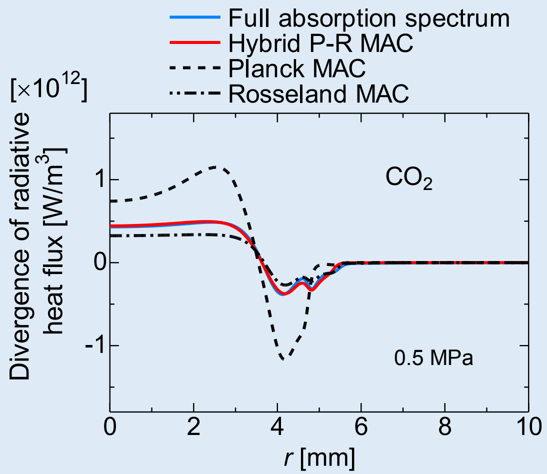
Fig. 1: Temperature profiles for low number of spectral bands.

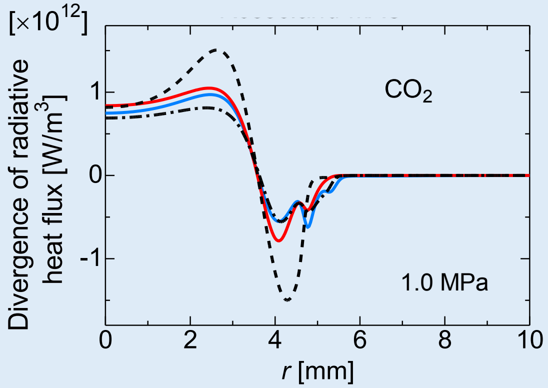


Planck mean = Rosseland mean if bands > 10^3
Re-normalized function is acceptable with
h=2.3mm

R. FUCHS, H. NORDBORG, SYSTEMATIC INVESTIGATION ON RADIATION MODELING ERRORS OF A WALL-STABILIZED ARC SIMULATIONS, GD2018 conference, Serbia (2018)

T. Fujino (CO_2, 0.5-1 bar, 2018)





S. Kozu, T. Fujino, T. Yoshino, T. Mori, Proceedings of 22nd International Conference on Gas Discharges and Their Applications, No. A21, pp.127-130 (2018)

Radiative properties in non LTE

❶ Some works on applications such as atmospheric entry, combustion : *Lamet et al, Riviere et al, Perrin et al*

❷ Recent works 2T numerical modelling (*J.P. Trelles, M.Baeva, M.Benilov, J.Yan, P.Freton :* 2 equations : with T_e and T_g)

❸ Any work on radiative properties for HVCB and RTE equation in 2T (some works on transport properties, compositions)

❹ First studies in Laplace laboratory with SF_6, SF_6-C_2F_4 with first steps : use of the Net Emission Coefficient (NEC) in 2T

Compositions defined from different assumptions (Mass action law, Kinetic model, Radiative collisional model….)

→ Different assumptions on the temperatures (T_{ex}, T_e, T_g, T_{vib}, T_{rot}) and **parameter θ**

For the radiation of the continuum (atomic + molecular)

- Recombination (T_e) + Bremsstrahlung electron-atom (T_e)
- Bremsstrahlung electron-ion (T_e) + Attachment (T_e)

$$\varepsilon_N^{cont}(\theta, T_e) = \int_0^\infty \epsilon_\lambda^{cont}\, e^{-\kappa'^{tot} R_p}\, d\lambda = \int_0^\infty B_\lambda(\lambda, T_e)\, \kappa'^{cont}\, e^{-\kappa'^{tot} R_p}\, d\lambda$$

$$\kappa'^{tot}(\theta, T_e) = \kappa'^{cont}(T_e) + \kappa'^{lines}(T_{ex})$$

For the radiation of the atomic lines

- Broadenings : Doppler (T_g) + Resonance (T_{ex}) + Van der Waals (T_g) + quadratic Stark (T_e) + Griem corrections (T_e for electrons, T_g for ions) + quadripolar Stark (T_e)

$$\varepsilon_{\lambda,ul}^{A} = \frac{he^2}{2\varepsilon_0 m_e (\lambda_{ul} + \Delta_{ul})^3} \frac{n_A}{Q_{int}^A} g_l\, e^{-\beta_{ex} E_u^A} f_{lu}\, V(\lambda - \lambda_{ul} - \Delta_{ul})$$

$$\kappa_{ul}'^{A} = \frac{e^2 (\lambda_{ul} + \Delta_{ul})^2}{4\varepsilon_0 m_e c^2} f_{lu} \frac{n_A}{Q_{int}^A} g_l\, e^{-\beta_{ex} E_u^A} \left[e^{\beta_{ex} \frac{hc}{(\lambda_{ul} + \Delta_{ul})}} - 1 \right] V(\lambda - \lambda_{ul} - \Delta_{ul})$$

The Net Emission Coefficient (NEC) - LTE

NEC gives a good estimation of radiation in the hottest regions (if high temperatures and low temperature gradients <20% in the first mm)
NEC gives information on the influence of T, P, metallic and/or organic vapors, on self-absorption (R_p)
NEC considers all radiative processes / the spectral dependence, NEC is very simple to implement in MHD models
NEC does not describe the radiative flux, NEC does not consider the absorption in intermediate/cold regions
NEC is limited by the Blackbody radiation, R_p must be well chosen in MHD model

The Mean Absorption Coefficients (MACs) - LTE

MACs can give a good estimation of radiation in the intermediate regions by considering the absorption
MACs allow the calculation of the radiative & divergence of the radiative flux, MACs considers all radiative processes
MACs efficiency depends on the mean functions used, MACs using Modified Planck Function need to find the good R_p
Its is very difficult to estimate correctly the radiative flux and the divergence of the radiative flux with the same MACs

Future works – The radiative properties for Thermal Plasmas

NEC : No new developments - Elaboration of new databanks (new gases or mixtures), Validity at very high pressure (non ideal gas) ? Optimization to find the best R_p. Validation is necessary by experimental measurements (Laplace group did it on Air and ArH2 mixtures on spectral intervals and atomic lines).

MACs : calculations to perform - must be carefully performed to describe the increase of pressure in HVCB (absorption of radiation / ablation of materials), MACs with hybrid Planck + Rosseland seems to be a good solution (at 1atm or close to 1atm). And for very high P (>5bar) ? MACs for complex mixtures (SF_6/C_2F_4…) ? RTE with a non-symmetrical temperature profile ? Validation is necessary by experiment measurements (Laplace group and Siemens did it by comparing the increase of pressure in SF_6/C_2F_4 HVCB experiments-modelling)

2T properties : not necessary to have good accuracy because we have a low radiation in these regions.
No relation between absorption and emission!!! To use Kirchhoff law is questionable! Kirchhoff's law (T_e *or* Tex): $\epsilon \rightarrow \kappa'$
NEC is a first approximation at low temperature. Not so good or not so bad??? What about MACs at 2T ?
Necessary to develop a **CR model by levels** : more accurate but it is a very BIG work

???

Some authors to read : J.J. Lowke, M.F. Modest, R. Siegel & J.R. Howell, V. Sevast'yanenko / V. Aubrecht et al, Y. Cressault et al, A. Essoltani, A. Gleizes et al, J. Menart et al, H. Norborg et al.
* M. Seeger, « perspectives on research on high voltage gas circuit breakers », Plasma Chem. Plasma Process, 35, pp527-541 (2015)
* A. Gleizes, « Radiative plasma heat transfer », In: Kulacki F. (eds) Handbook of Thermal Science and Engineering. Springer, Cham, pp2599-2656 (2018)