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Thermal modelling of an atmospheric pressure cylindrical DBD reactor for NOx removal

Nicolas Bente¹, Hubert Piquet¹, Nofel Merbahi¹, Eric Bru¹

¹ LAPLACE, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France

(*) nicolas.bente@laplace.univ-tlse.fr

Nitrogen oxides (NOx) emissions pose significant environmental and health issues, motivating the exploration of innovative technologies for their abatement. Cold plasma systems, particularly dielectric barrier discharge (DBD), have emerged as promising solutions for NOx reduction. Our investigations focus on understanding the impact of all physical parameters – electrical, thermal, fluidic, and geometric – on deNOx efficiency. To conduct these studies, we developed a complete deNOx test bench comprising an open-flow cylindrical DBD reactor [Fig. 1] operating at atmospheric pressure with a synthetic N2/NO gas mixture. The power supply, an AC square-wave current source designed at LAPLACE [1], allows adjustable frequency, amplitude, and duration of the current pulses.

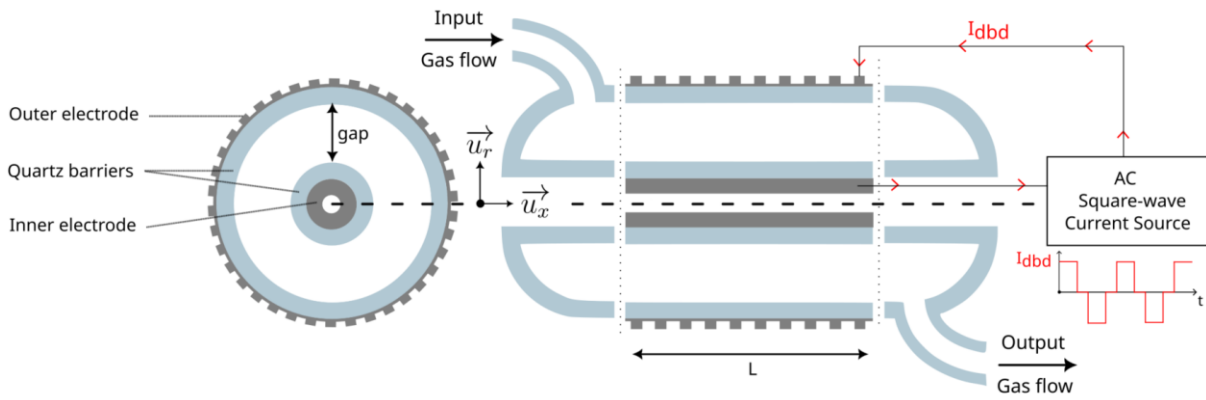


Figure 1: Reactor schematic

Initial simulations of the process using ZDPlasKin [2] and BOLSIG+ [3], two plasma chemistry simulation programs developed at LAPLACE lab., point out the crucial influence of gas temperature on treatment efficiency. However, to our knowledge, thermal studies of this reactor type are lacking. To address this gap, and to understand better the relation between the experimental setup and the performances, we propose a comprehensive analytical thermal model of our reactor. Under assumptions of steady-state thermal and laminar flow regime, the reactor can be discretized in infinitesimal dx length slices along the x -axis direction and modelled by three different temperature layers [Fig. 2]: one for the gas and two others for outer and inner quartz & electrodes. A thermal balance on each layer leads to the following coupled analytical differential equations:

$$\begin{cases} \lambda_1 S_1 r \frac{d^2 T_1}{dx^2} - T_g - T_1 \left(1 + \frac{r}{R}\right) = \frac{r}{R} \cdot T_0 & (1) \\ q_m c_g r \frac{dT_g}{dx} + 2T_g - T_1 - T_2 = r \cdot p_j(x) & (2) \\ \lambda_2 S_2 r \frac{d^2 T_2}{dx^2} - T_g + T_2 = 0 & (3) \end{cases}$$

Ambient T_0

Equation (2) describes the axial gas temperature distribution $T_g(x)$. Two modes of heat transfer are considered for the gas: convection at interfaces with outer and inner layers, and transport.

Figure 2: Heat transfer modes on a dx length slice

The heat transport is modelled by the first order x-derivative term, with q_m the gas mass flow rate and c_g the gas isobaric specific heat capacity. The plasma contribution is modelled via the source term $p_j(x)$ which represents the Joule losses density: we consider that all electrical power injected into the reactor is converted into heat. $p_j(x)$ has no variation along the radial direction, meaning that plasma sheath phenomenon is neglected. Equations (1) and (3) describe outer $T_1(x)$ and inner $T_3(x)$ wall temperatures. Two modes of heat transfer are considered: conduction along the x-axis and convection at interfaces with both gas and ambient air. The x-axis heat conduction is modelled by the second order x-derivative term with λ the thermal conductivity of the layer and S its axial cross-section surface. The two convective thermal resistances r and R model heat exchange at gas/walls interfaces and outer layer/ambient air interface. All these values can be easily determined for our test bench, except R , mainly influenced by parameters such as ambient air velocity, flow regime and hydraulic diameter that we don't know precisely. We chose R within a coherent range that matches similar flow found in literature [4]. We present [Fig. 3] two numerical solutions of the gas temperature distribution with uniform p_j . We also simulated a more complex equivalent 3D finite elements model on COMSOL for comparison. The experimental gas temperature distribution, which is measured in steady state via spectroscopic techniques [5] on a uniform plasma, shows good agreement with models.

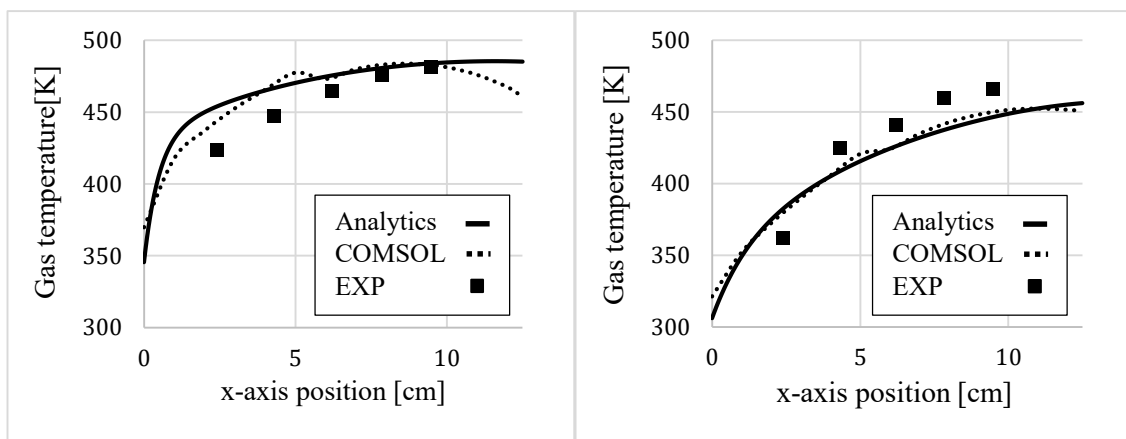


Figure 3: Gas temperature distribution comparison for $p_j = 360 \text{ W/m}$ at two gas flow rates :
 [Left : 2 LPM – Right : 6 LPM]

Conclusion: a concise and analytically thermal model is presented that characterizes the axial gas temperature distribution within a cylindrical open-flow DBD. Coupled with plasma chemistry simulator program, this approach helps identifying the key physical parameters affecting deNOx treatment, thereby facilitating its enhancement. The same approach is also applicable for sealed systems, such as lamps.

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