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Maxime Gautier, Yann Cressault, Sabri Takali, Vandad-Julien Rohani, Laurent Fulcheri. Heat and mass transfer modelling in a three-phase AC hydrogen plasma torch: Influence of radiation and very high pressure. ISPC 22 - 22nd International Symposium on Plasma Chemistry, Jul 2015, Antwerp, Belgium. hal-01159694

HAL Id: hal-01159694

https://hal-mines-paristech.archives-ouvertes.fr/hal-01159694

Submitted on 3 Jun 2015

Heat and mass transfer modelling in a three-phase AC hydrogen plasma torch: Influence of radiation and very high pressure

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Abstract: A 3 dimensional CFD simulation of a hydrogen plasma process is performed for two different operating pressures. Special attention is given to radiative heat transfer by computing a highly detailed spectral data base for hydrogen. Results show the importance of radiative heat transfer in the concerned plasma technology. A key role of the ceramic protection in this process has also been confirmed.

Keywords: Radiation, plasma, hydrogen, three-phase torch

1. Introduction

Thermal conversion of hydrocarbon compounds by plasma process has been investigated for many years in PERSEE group of Mines-ParisTech [1-3]. These researches lead to the development of an innovative three-phase AC plasma technology [4]. To date, most of modelling studies in this plasma configuration neglect or even set aside radiative heat transfer [5]. However, experimental researches by Pateyron [6], on hydrogen plasma, showed that around 30 % of the total electric power is transport by radiative heat transfers. This result is confirmed by a recent transient CFD-MHD simulation of the electric arc which is produced by a three phase plasma torch [7]. According to these observations, an important need in accurately modelling radiative heat transfers has to be filled. In partnership with LAPLACE laboratory from Paul Sabatier University, specialized in high thermal plasma radiations [8-10], this present study aims to evaluate the influence of the radiation on mass and heat transfers within the three-phase AC plasma torch, currently in development in the PERSEE group. The electrical power of this torch under hydrogen is assessed to be of 250 kW. The operating pressure is between 1 bar and 20 bar. In this study lowest and highest pressure conditions of this process are simulated.

2. Numerical model

The three-phase AC plasma torch can be described by a steel vessel with water refrigerated wall, three graphite electrodes with their own support in boron nitride, and an intern ceramic protective cylinder. The ceramic protection is used to reduce the thermal stress undergone by the steel vessel. The reactor geometry has three symmetric planes which enable to reduce the domain to model to one third of the reactor. Fig.1 shows this geometric reduction and the 3D modeling of one third of the reactor. Fig.2 shows a scheme of a vertical section and a detailed description of every part of the plasma torch.

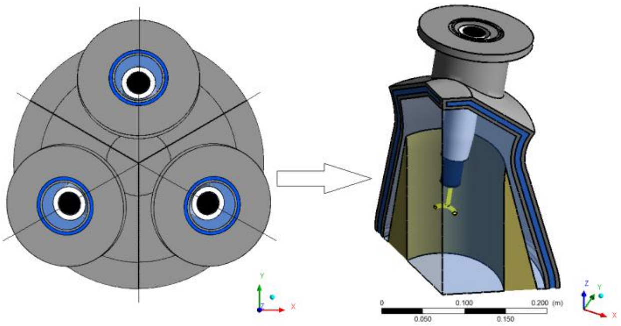

Fig. 1. Above view and 3D visual of one third of the modelled plasma torch

For one third of the geometry, since only one electrode is modeled, there are only two H_2 gas inlets. The first inlet, denoted as principal inlet, is situated around the electrode support whereas the secondary inlet, with a smaller section, is directly around the electrode. The feed gas rates at standard conditions (300 K and 101325 Pa) are; 92.3 Nm^3h^{-1} for the principal inlet and 230 Nm^3h^{-1} for the secondary one. The feed water flow rate is 4.32 Nm^3h^{-1} and has been calculated in order to have a water temperature variation between the inlet and the outlet smaller than 20 K.

Fluent software is used to solve the coupled equation system coming from the mass, momentum and energy conservation, the RNG k-ε turbulence model and the radiative transfer equation. The turbulence model used improves near wall flow modeling by combining a two-layer model with enhanced wall function. The Discret Ordinates (DO) model is used to solve the radiative transfer equation. Gas density, heat capacity, thermal conductivity and dynamic viscosity are calculated with the code T&Twinner [11] for a temperature from 300 K to 20 000 K. Thermal property of water and solid part are set constant to their ambient temperature value.

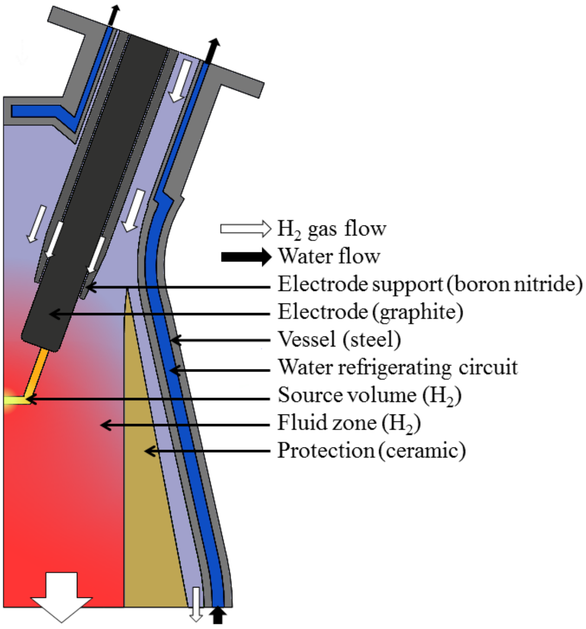

Fig. 2. Sectional view of the plasma torch

The source volume adds heat power and momentum source term in the Navier-Stokes equation system. The heat source term corresponds to the joule heating released by electrical arc. The momentum source term describes the Lorentz forces toward the fluid. The source volume, the Joule power and the Lorentz momentum forces have been estimated integrating the past transient MHD simulation made on the three phase geometry [12]. The final volume can be described as a tore linked with every electrode surface by arc roots [13]. The total volume is about 4 cm^3.

The mesh sensibility study results in a final mesh of 375 000 nodes. The number of ray for the DO model is set to 9 (3 along polar angle and 3 along azimuth angle), since using more ray does not change results. The computational time to obtain a converged solution is about 1 hour without using the DO radiative model and 4 hours with using it. Simulations have been run on a Windows work station using 7 parallel processors at 2.4 GHz.

3. Spectral data for hydrogen

The radiative transfer equation is described in equation (1). The scattering is neglected and the refractive index is keep to 1.

$$\nabla \cdot \left(I_\lambda \mathbf{s}\right) = \kappa_{a,\lambda}\left(n^2\frac{\sigma T^4}{\pi} - I_\lambda\right) \qquad (1)$$

Hydrogen plasma radiation and the establishment of a data base for absorption coefficient, denoted here $\kappa_{a,\lambda}$, have already been studied formerly [14-16]. In the present study, a recent data base has been used derived from the recent work of T. Billoux [10] where both background continuum and line spectrum were considered. This database gives spectral absorption coefficient with a temperature range from 300 to 30.000 K with wave lengths from 0.209 µm to infrared. It considers the radiation from back continuum, molecular (H2), atomic (H2), and 74 lines spectrum for hydrogen. Using this data base, Mean Absorption Coefficients (MACs) has been calculated by integrating over the three following spectral bands: [3.33E-2 – 1.67E-1], [1.67E-1– 3,33] et [3,33 – 1.00E+2] µm. A coherent comparison of resulting MACs has been done with literature values for different integration ways [13]. A Planck mean is used for the data at atmospheric pressure. A Rosseland mean has been preferred for data at 20 bars, since most of spectral absorption coefficient values, for this pressure, are above the Planck validity domain. In this study, no particular line spectrum treatment has been done during the MAC calculation. Fig.3. shows the resulting MACs over the temperature for each spectral band and for the two different pressure values. Absorption coefficients at 20 bars are two orders of magnitude higher than those at atmospheric pressure. As a result, radiative transfers are expected to be more important at 20 bars than at atmospheric pressure.

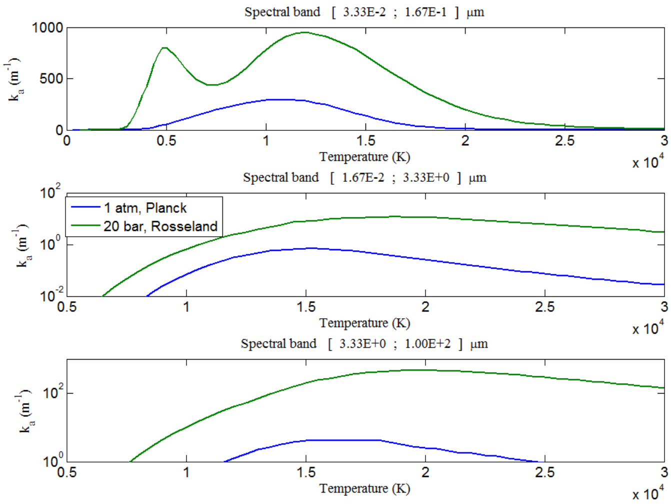

Fig.3 Mean Absorption Coefficients at atmospheric pressure and at 20 bars over gas temperature for 3 spectral bands

4. Radiative model influence

A preliminary comparative study on results using or not the radiative model has been done. Thermal field values and wall power loss are represented Table 1 for a simulation at atmospheric pressure without modelling radiation and with modelling radiation. Results show a global increase of the mean temperature of the vessel steel, of the ceramic protection and of the water; and a decrease of the arc temperature when using the radiative model. Radial power loss is only 0.86% of the total injected power without modelling the radiation which demonstrates the large efficiency of the ceramic isolation against convective heat flux toward steel wall. In contrast, radial power loss is about 30% when modelling radiative heat transfers. This value is coherent with Pateyron observations [6]. Results with radiative transfer also show a hot part zone for ceramic, water, and steel parts which corresponding to an horizontal plan going through the middle of the source volume.

Table. 1. Thermal and power loss results with or without taking into account radiative heat transfers

	Mean T° (K)		Tmax - Tmin	
	No rad	Rad	No rad	Rad
Electrode	8,90E+02	1,21E+03	2,89E+03	2,61E+03
Fluid	1,61E+03	1,66E+03	1,56E+04	1,15E+04
Arc	1,33E+04	1,16E+04	1,25E+04	9,12E+03
Water	3,00E+02	3,10E+02	3,21E+00	8,04E+01
Steel	3,02E+02	3,84E+02	3,95E+01	6,43E+02
Ceramic	1,22E+03	1,66E+03	2,86E+03	7,58E+02

	No rad	Rad
P_out wall	0,86%	30,0%

*rad : modeling radiation heat transfer

5. Pressure influence

The operating pressure is fixed to 20 bars. Thermal properties have been recalculated with T&Twinner considering this pressure condition. Inlet velocities for both gas inlets are reduced by a 20 factor in order to conserve the mass feed gas rate compare to the case at atmospheric pressure. The analysis of the Froude number applied to Lorrentz forces showed that the Lorrentz force influence on the flow is dependent of the gas velocity. In order to keep the same flow deviation between the case at atmospheric pressure and the case at 20 bar, and since the gas velocity has been divided by 20, Lorrentz force magnitude is also divided by 20. Table 2 shows results on temperature fields and radial power loss at atmospheric pressure and at 20 bar. In first observation, results are not as different as the atmospheric pressure case whereas absorption coefficient had been largely increased. All mean temperatures are very similar between the two cases. Nevertheless, a larger hot fluid zone can be seen (>5 000 K) for the 20 bars case by plotting the temperature field over a sectional view of the reactor. In both cases, the radial power loss is about 30% of the total injected power.

Table. 2. Thermal and power loss results at atmospheric pressure and 20 bar

	T° moy (K)		Tmax - Tmin	
	1 atm	20 bar	1 atm	20 bar
Electrode	1,21E+03	1,17E+03	2,61E+03	2,96E+03
Fluid	1,66E+03	1,79E+03	1,15E+04	1,17E+04
Arc	1,16E+04	1,22E+04	9,12E+03	8,72E+03
Water	3,10E+02	3,10E+02	8,04E+01	7,12E+01
Steel	3,84E+02	3,83E+02	6,43E+02	5,91E+02
Céramic	1,66E+03	1,67E+03	7,58E+02	7,22E+02

	1 atm	20 bar
P_out wall	29,9%	29,5%

6. Conclusion

This study successfully showed the significant contribution of radiative heat transfer in a particular plasma process under hydrogen. A detailed radiative data base has been used. Results showed good agreement with literature [6]. Simulations performed already confirm the key role of the ceramic protection in the plasma process developed in the PERSEE group of Mines-ParisTech at atmospheric and at 20 bars.

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