Plasma-assisted combustion for gas turbine application

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Abstract

Development of modern combustion system designs pushed the requirements on operability, durability, fuel efficiency and also on pollutant emissions. Often these requirements are contradictory. In particular low NO_x emissions can be achieved by making the fuel-air mixture very lean but as the equivalence ratio approaches the lean flammability limit, undesirable combustion dynamics ("lean blow out") begin to occur. In gas turbine combustion systems, flame stabilization is often achieved through the use of recirculation zones created by flame-holders (see [1] and references therein). However, these devices are static in nature and may be difficult to optimize. A still more promising solution is the use of electrical discharges. The plasma is expected to provide a local source of heat and radicals advancing the chemical kinetics, enhancing combustor performance, and possibly acting as a virtual flame-holder to stabilize the flame during transients. In this work, the developed kinetic plasma-chemical mechanism of natural gas combustion at high pressures is applied for mutual analysis of the two aspects: flame stability and NOx production. The mechanisms of the initiation of combustion under pulse plasma effect and influence of the plasma upon pathway of NOx generation are discussed in term of optimal conditions (methane concentration, pressure, electric field strength, temperature) to provide both low concentration of NOx and stable operation of the turbine in "lean blow out" limit. The results of the modeling are compared with results of the experiment of the pulse periodic discharge used for extension of flammability limits of gas turbine combustion system.

Keywords: combustion, plasma initiation of combustion, flammability limits, gas turbine combustion system, NO_x emissions, chemical and plasma mechanism, plasma energy input, Chemical Work Bench code.

Model of the plasma nozzle.

The analysis of the combustion in the plasma nozzle was analyzed in frame work of the Chemical Work Bench [2] code. This code permits to simulate chemistry and plasma based phenomena using rather simple description of hydrodynamic effects (OD and 1D models). Taking into account that principal aim is analysis of plasma effect upon NOx chemistry, such approach permitted us to apply detailed chemical and plasma mechanism using well-known simple plug-flow, well stirred and calorimetric bomb models based on our knowledge about character of hydrodynamic flow in every part of nozzle and combustor. The sketch of the nozzle and used model is shown on the fig.1.

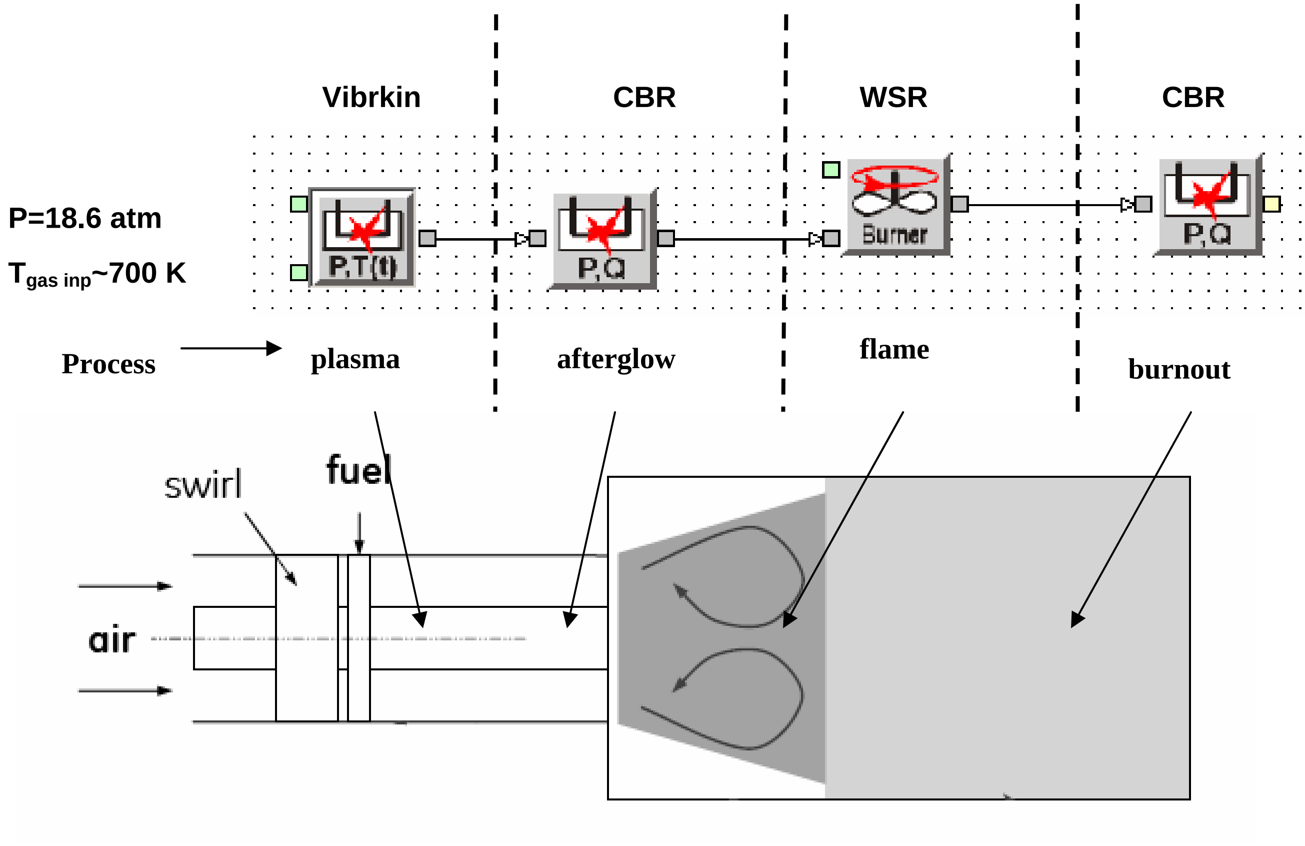

Fig.1 Model of the plasma nozzle and combustion zone

The plasma ignition, combustion and flame phenomena were interpreted as a sequence of the following models: plasma model with given profile of electric field strength simulate interaction of air-fuel mixture with plasma; after glow zone was simulated by plug flow model with taking into account secondary plasma processes; flame zone was simulated by perfect stirred reactor model with given mixing time and ignition temperature; to simulate burnout zone the plug flow model was chosen. Characteristic residence times in every zone was varied in dependence of gas flow rateand were about ms in plasma and after glow zone, 0.5 ms and dozens of ms in the flame and burnout zones respectively. Applied electric field was in the range 80-300 Td, plasma energy input was variated in the range 30-300 nJ/l.

Flame stability limits and NOx generation

The results of the analysis of the plasma effect are presented in the two forms: extension of the combustion limits and acceleration of the chemical processes including NOx generation.. Actually, plasma effects on the combustion by stabilization of the flame. It extends limits of the combustion to lean and rich operation regime. Figure 2 demonstrates plasma effect upon extension of the combustion. This effect upon combustion limits presents as dependence of stoichiometry of the air-methane mixture vs residence time in combustion zone for two cases: plasma initiation of combustion by pulsed plasma with E/N=200 Td, total plasma energy input 0.045 eV and without plasma but with the same heat equivalent of total energy input. One can see that plasma provides extension of the zone of stable combustion in the term of stoichiometry of the mixture and residence time in combustion zone.

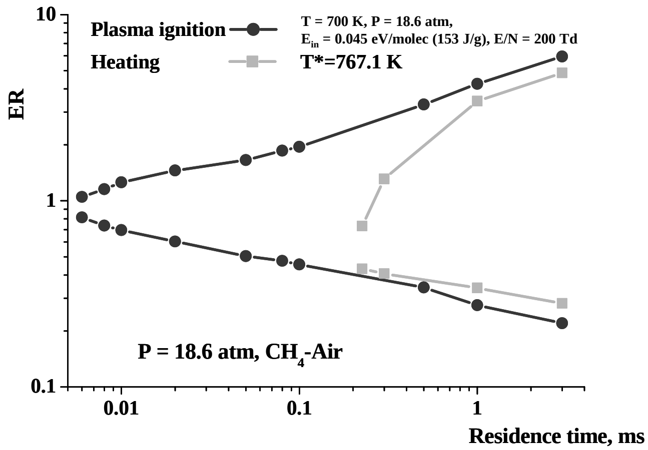

Fig.2 Extension of combustion limits as a function of stoichiometric ratio vs residence time in combustion zone. Two cases: initiation by mixture preheating and by pulsed plasma.

At the same time presence of the plasma in the ignition zone may lead to additional production of NOx due to reaction of primary and secondary plasma particles (ions and radicals) with nitrogen. Figure 3 permits to compare both positive (reduction of the temperature of the stable flame) and negative (additional NOx production) effects together.

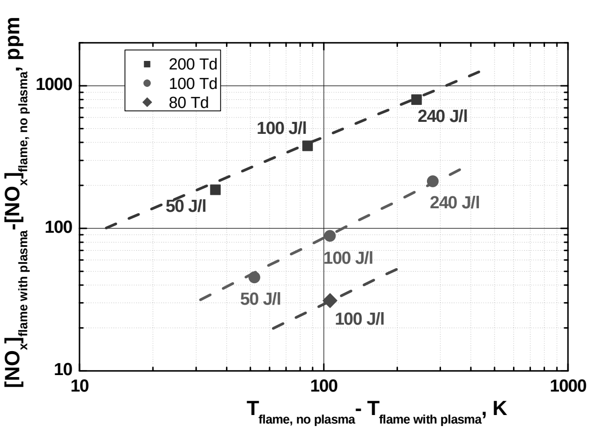

Fig.3 Effect of the plasma on stable flame Temperature and NOx generation (calculation results). Three cases of different electric field strength 80, 100 and 200 Td at different plasma energy input 50-240 nJ/l.

One can see that positive effect of reducing of flame temperature (up to ~100 K) is accompanied by additional NOx production. The second important feature is strong dependence of NOx concentration vs electric field strength. Application of the electric field on the level corresponding limit of existence of self-sustain discharge may fulfill two demands together: stabilization of the flame at the relatively low NOx concentration. However, the stabilization effect is too small (60 K) for allowable level of NOx (<20 ppm).

Analysis of the reaction mechanism indicates that main channels responsible for NOx generation in post discharge zone at the temperature range corresponded to turbine application (T>500 K) are:

$O+O_2+M <=> O_3 +M$	$O+N_2 => NO +N$
O_2- +O => O_3 +e	$N+O_2=> NO+O$
$O_3+NO=>NO_2+O$	$NO+O+M=>NO_2+M$
$O+CH_4 => OH+CH_3$	$NO_2+O=>NO+O_2$
$HO_2+NO => NO_2 + OH$	
$CH_3O_2+NO=>CH_3O+NO_2$	

and the rate of reactions (see Fig. 4) of plasma active species participation in the NOx formation is large than other sinks of these particles (recombination, oxidation). Indeed, the frequency of the NOx generation due to reaction of atomic oxygen and nitrogen with the air is compatible or larger than, for example, participation of these radicals in the imitation of the chain oxidation in the temperature range 400-1300K that leads to effective generation of NOx.

Finally, similar numerical analysis was carried out for other types of non-equilibrium plasma- plasma of the gliding arc and electron beam. The summary of the results concerning of efficiency of NOx production is presented on the Figure 5 together with some experimental points. The results are compared with effective energy cost of NOx production in the pure thermal flame (black line). In accordance with results of analysis of the NOx generation mechanism, the efficiency is strong function the temperature (see data for 300 and 700 K calculations) what is the sequence of ozone input the NO reduction reactions and threshold character of the thermal mechanism of NOx production. It is also reason of advantage of the non-equilibrium system application (EB, pulsed, DBD discharge [3]) in comparison with equilibrium one.

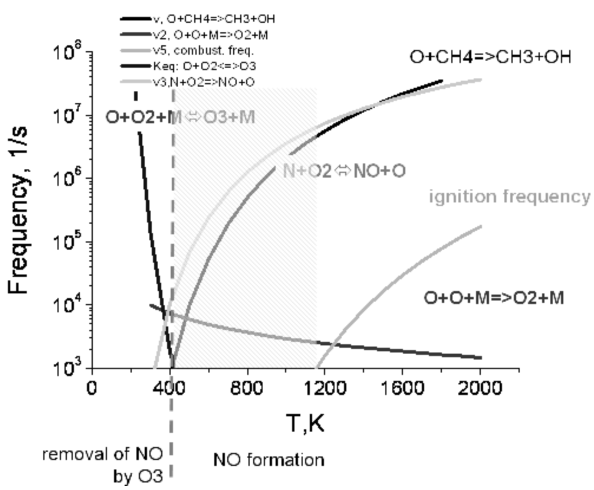

Fig. 4 Principal channels of NOx formation/reduction.

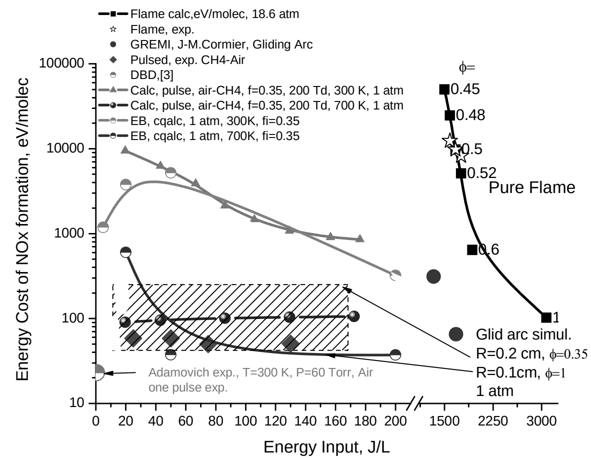

Fig.5 Energy cost of NOx production as a function of effective energy input for different type of the plasma and for thermal flame.

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