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NO_X FORMATION IN THE RICH QUENCH LEAN COMBUSTION MODE: CHEMICAL KINETIC MODELLING

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NO_x formation in the Rich Quench Lean combustion mode: chemical kinetic modelling

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INTRODUCTION

The Rich Quench Lean (RQL) technique is defined as a combustion mode whereby combustion is staged in two sequential phases:

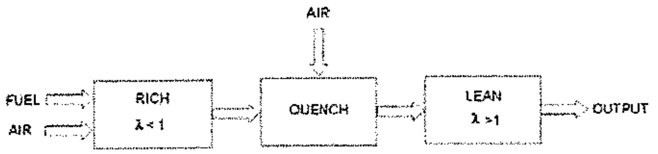

Fig. 1. RQL concept (λ=1/Φ)

- ignition and combustion in rich conditions (Φ>1) which assures low NO_x production due to oxygen shortage
- combustion in lean conditions (Φ<1) where burnout is achieved with low NO_x formation due to the lean stoichiometry. Φ is the equivalence ratio, defined as the fuel/air ratio normalised with respect to the stoichiometric one; in the following its reciprocal-λ is used.

The switch-over from the rich phase into the lean burnout mode is accomplished via quick quench by air (fast quench is necessary to avoid the formation and persistence of stoichiometric gas zones).

The RQL combustion concept has been proposed since the 1970s; experiments by Fenimore [1] and other researchers [2-4] showed that is possible to control NO_x emissions from Fuel-Bound-Nitrogen (FBN) combustion under rich conditions.

In experimental studies by Novick *et al.* [5], NO_x emissions appeared to be controlled only by rich zone equivalence ratio, whereas CO and UHC (smoke) were influenced markedly by both rich-zone and lean-zone equivalence ratios. A minimum lean-zone equivalence ratio of 0.6 was needed to achieve acceptable smoke levels.

Jackson *et al.* [6] used the RQL at 10 atmospheres; the gas used had a nominal heating value of 4370 kJ/kg and included 4600 ppm (by vol) of ammonia (the FBN). They fixed an equivalence ratio of 1.25 in the rich phase and regulated the quenching on the outlet temperatures of exhaust gases finding a minimum value of NO_x emissions.

The RQL concept is currently studied for aircraft application by Pratt and Whitney Company and others laboratories in the USA. Most of the work carried out so far on RQL concept has confirmed its potential for low conversion of FBN into NO_x. RQL combustion systems are also being considered for suppression of thermal NO_x in high-speed civil transport [6].

In this work a chemical reactor simulation package (Chemkin) has been used with the GRI 3.0 kinetic mechanism. Two possible applications of the RQL have been considered:

a) Rich Quench Lean run in a single combustion chamber (at constant pressure)
b) Sequential RQL combustion: rich and lean combustion are carried out in two different combustors at different pressures (rich phase run at high pressure and lean phase at lower pressure). Between the two combustion chambers an expansion stage provides for energy extraction.

The two configurations are studied under several operating conditions in a systematic approach. The analysis of the RQL behaviour under real GT operating conditions will be the subject of future work.

Clean fuel and Fuel-Bound-Nitrogen (FBN) have been used; in particular FBN has been simulated adding different quantities of ammonia in the fuel.

Main objectives of the present investigation are:

- to identify the presence of an optimum operation point in the rich phase
- to investigate the influence of the residence time in the rich phase on NO_x emissions
- to study the response of the RQL combustion with different amount of NH_3 in the fuel.

Finally the NO_x emissions in the RQL technique have been compared with those obtained in a Lean-Premixed (LP) combustion under the same operating conditions.

MODEL SET-UP

Figures 2 and 3 show the Chemkin models used to simulate the single and sequentially staged RQL combustion, respectively.

As concerns the single combustion chamber model, the primary zone of the combustion (rich phase) has been simulated connecting a perfect stirred reactor (PSR, for ignition) and a plug flow reactor (PFR, for the secondary combustion zone).

Three different values of the residence time in the PFR_{RICH} have been used (5-10-15 ms). Simulations have been performed considering a rich stoichiometry range (equivalence ratio) of 0.5÷0.75. A mixer module connects the rich and the lean burnout phases simulating quenching by air intermediate feeding.

The lean phase has been carried out at $\Phi=0.5$ and with the residence time necessary to reach the condition: $CO=1.5*CO_{eq}$.

Rich and lean phase run at constant pressure. Two different pressures have been considered in the simulations: 1 and 20 bar. Clean (CH_4) and nitrogen fuel (CH_4+NH_3) combustion has been investigated. For Fuel-Bound-Nitrogen the ammonia concentration in the fuel has been varied within the range 0.3%÷0.5%.

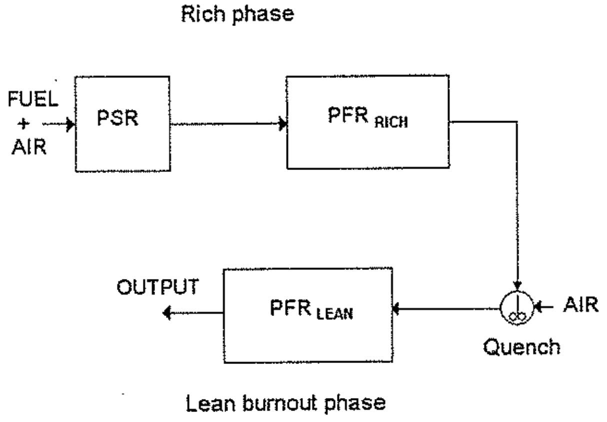

Fig. 2. Single combustion chamber

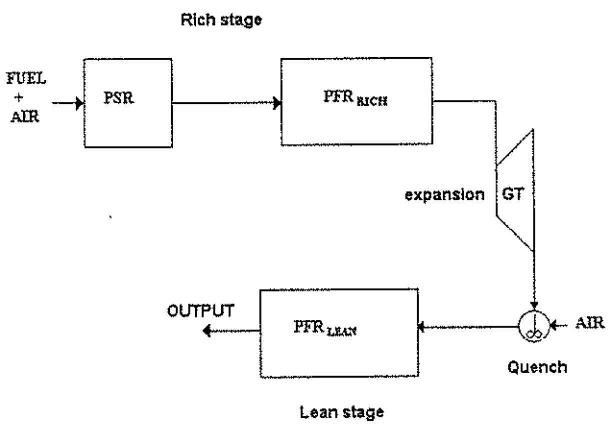

Fig. 3. Sequential RQL combustion

Figure 3 shows the sequential RQL combustion model. The rich (PSR+PFR) and lean (PFR) stages are separated by an expansion stage (GT). The rich stage runs at 20 bar while the lean stage is operated at 10 bar. An isentropic expansion has been considered for the gas turbine stage. Also in this case the quench is regulated to obtain $\Phi=0.5$ in the lean phase.

In a last effort the single-chamber RQL model has been directly compared with a classic Lean Premix model set-up. The Lean Premix model consists of a connection of a PSR and a PFR reactor. The PSR simulates the well-mixed flame stabilisation zone, created by a vortex breakdown phenomenon, while the PFR reactor is used to model the eventual burnout. Overall residence time refers to the minimum value which allows a CO concentration 50%

higher than the equilibrium value. Same inlet and operating conditions have been used to have a common basis of comparison.

RESULTS

Figure 4 and 5 show the NO_x emissions predicted for the single combustion chamber for τ_{RICH}=10 ms and NH_3=0.4%, a s a function of the stoichiometry in the rich phase.

In the clean fuel case, the NO_x emissions increase approaching the stoichiometric conditions (Φ=1) in the rich phase and decrease for high pressure (Fig.4a).

In the FBN case the presence of an optimum λ_{rich} value has been detected (this optimum being more evident at high pressure) (Fig.4b).

The influence of the residence time in the rich stage on NO_x emissions can be summarised as follows:

- for the clean fuel, at 1 bar, NO_x emissions increase with residence time, while at 20 bar, the influence of the residence time in the rich phase is negligible;
- for the FBN case, long residence times in the rich phase depress NO_x emissions (due to the onset of reburning mechanism); the effect is stronger in proximity of the optimum rich stoichiometry.

The influence of ammonia concentration is shown in Figures 5 and 6: high ammonia concentration in the fuel produces higher NO_x emissions; the effect is weaker for high pressure at the optimum λ_{rich}.

NO_x trends in the sequential RQL combustion are similar to those of the single combustion chamber: in the clean fuel case higher emissions for higher λ_{rich} are obtained, whereas with FBN the presence of an optimum point is confirmed.

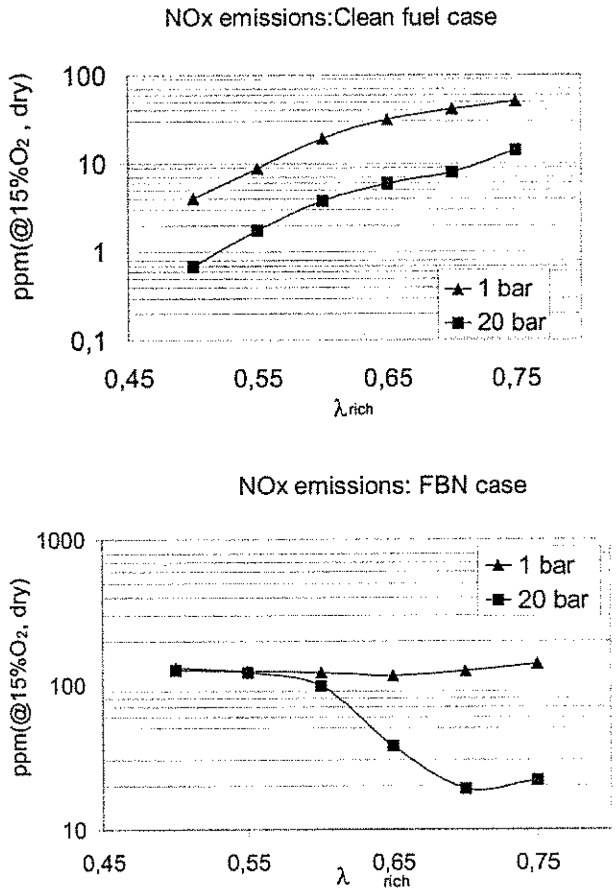

Fig. 4. NOx predictions for the single combustion chamber, with methane (a) and FBN (b).

Figures 5 and 6 report also the comparison between the RQL mode in a single combustion chamber and the Lean Premixed combustion. The results show that the Lean Premix mode is preferable in the clean fuel case (especially at atmospheric pressure), while in the FBN case the use of a RQL mode would help considerably reducing the NO_x emissions.

CONCLUSIONS

The RQL combustion allows to reduce NO_x emissions, especially at high pressure and when nitrogen-containing fuel is employed; in these cases it is advantageous with respect to Lean Premix combustion. The stoichiometry in the rich phase is very important, and an optimal value is observed for FBN, that is dependent on pressure. In conditions close to the optimal one, the systen is only slightly affected by the nitrogen content of the fuel, and this

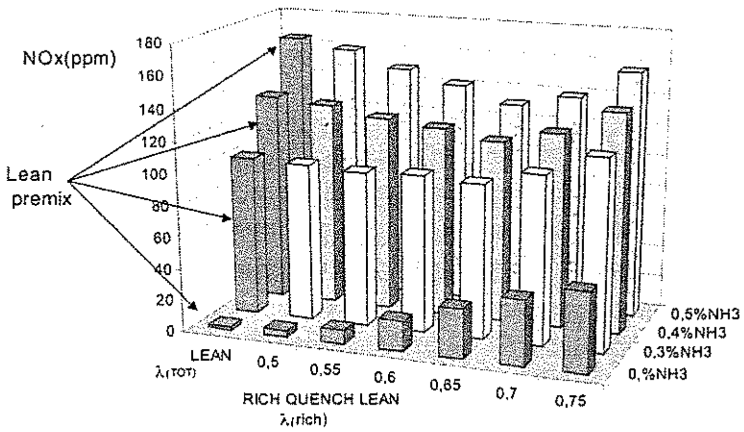

Fig. 5. Comparison RQL-Lean Premix: pressure 1 bar

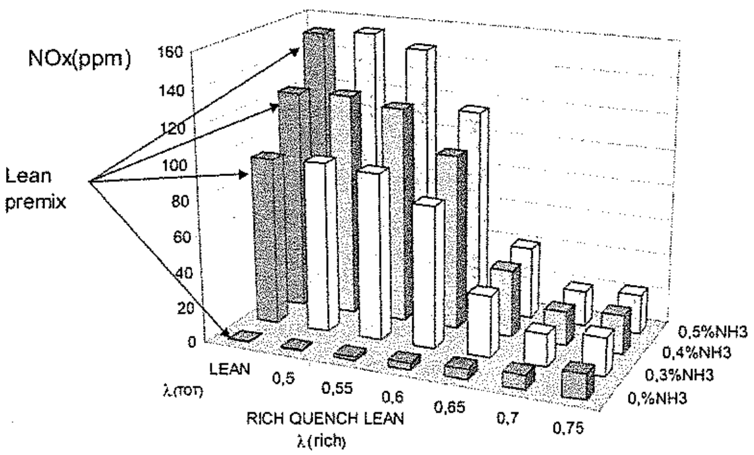

Fig. 6. Comparison RQL-Lean Premix: pressure 20 bar

could allow the design of flexible systems. The influence of the residence time is dependent on pressure and fuel composition.

The preliminary results suggest that RQL combustion can be very advantageous for NO_x control; future work will investigate the performance in real operating conditions.

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