Evaluation of Fuel Pre-Processing For Lean Premix Combustion

UTSR Fellowship Report

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GOALS

The goal of the project is to evaluate fuel pre-preprocessing for gas lean premix combustion gas turbine systems.

CONCEPT OVERVIEW

Preprocessing can be used to modify the fuel reactivity by manipulating the fuel composition and temperature before primary lean combustion. This makes it possible to increase the lean premix-operating range (box) by extending weak extinction and combustion dynamic limits. Potential benefits include reduced emissions, increased turn down and improved fuel flexibility. Fuel can be pre-processed prior to combustion in many ways. For this project three types of fuel preprocessing were considered auto-thermal reformation, catalytic partial oxidation, and aero-ignited partial oxidation.

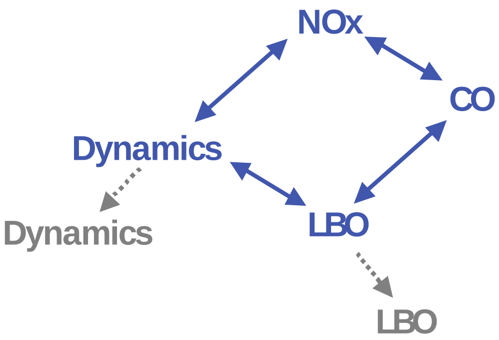

Figure 1 Fuel preprocessing lean premix operating box improvement.

APPROACH

Effects of preprocessing on lean premix combustion systems were investigated in terms of equilibrium calculations and chemical kinetics studies. The approach was to first evaluate various forms of fuel preprocessing, including auto-thermal reformation, catalytic partial oxidation, and aero-ignited partial oxidation. The effects of fuel preprocessing on lean blow out limits, induction time, and pollutant emissions were then evaluated.

MODELS

Chemical equilibrium and thermodynamic models of each of the fuel preprocessor was developed for analysis. A schematic of the model developed for auto-thermal reformation is shown in Figure 2. Each of the fuel preprocessor was evaluated for integration with lean premix combustion.

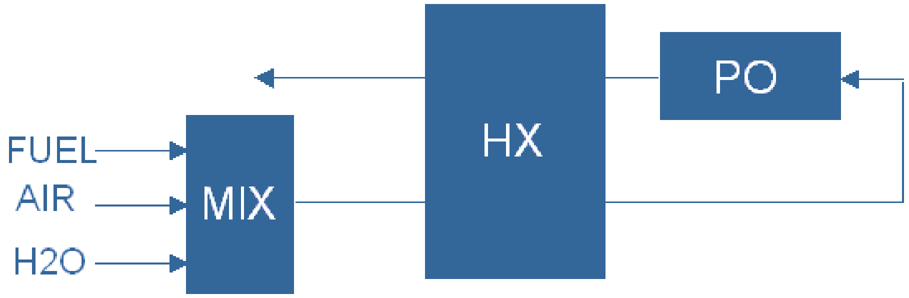

Figure 2 Schematic of auto-thermal reformation system modeled.

Once the fuel preprocessor was evaluated individually, the effects of fuel preprocessing on lean blow out limits, induction time and pollutant emissions were evaluated. This was accomplished by developing models for parametric analysis. A lean blow out model, schematically described in Figure 3, was developed to determine the lean blow out equivalence ratio and flame temperature for an inlet fuel and air mixture that can be partially pre-oxidized.

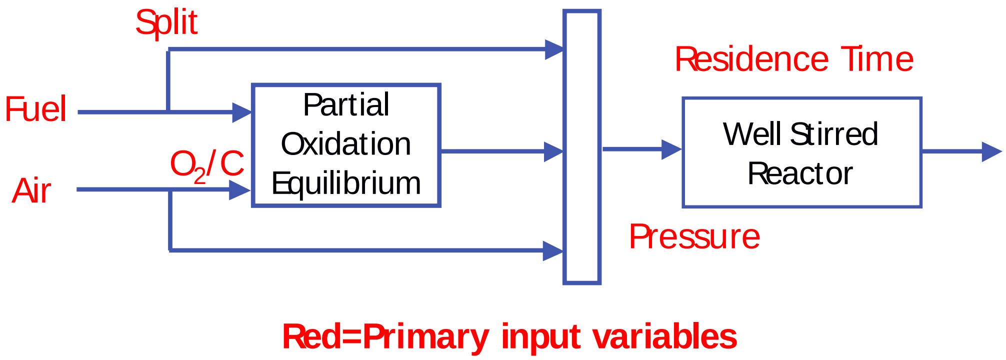

Figure 3 Schematic of the lean blow out models.

An induction time model, schematically described in Figure 4, was developed to evaluate the ignition time of various combustion fuel inlet composition and temperature. The model simulates the aero-ignition characteristic of premix combustion where hot combustion products, potentially containing radicals are re-circulated to provide an ignition source. The ignition time or induction time is a good first approximation of flame holding in aero-ignited combustors.

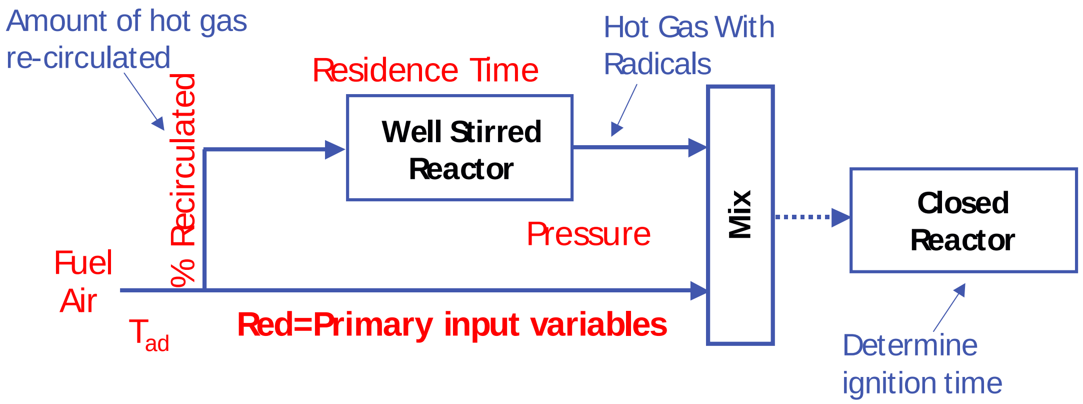

Figure 4 Schematic of the induction time model developed.

A simplified pollutant emissions model, schematically described in Figure 5, was developed to evaluate potential carbon monoxide and nitrous oxide pollutant emissions reduction. The model does not model well the absolute pollutant emissions, but indicates trends for various operating conditions and gives insight to potential emissions reduction.

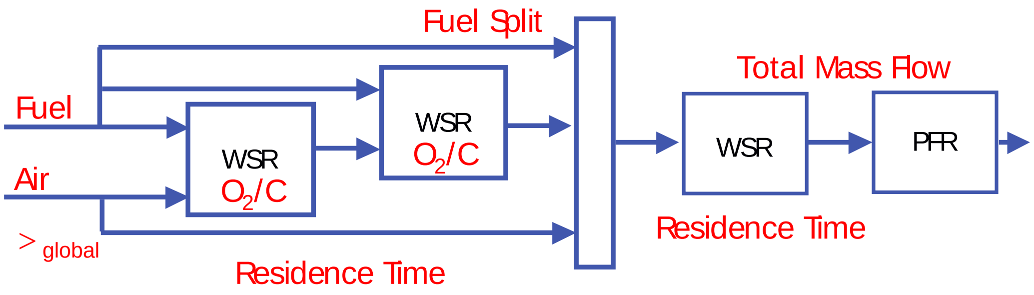

Figure 5 Schematic of the simplified emissions model developed.

RESULT SUMMARY

Evaluation of various fuel preprocessors:

The outlet compositions and temperature of auto-thermal reformation, and partial oxidation was investigated. Auto-thermal reformation and partial oxidation can be used to provide a reformate 50% and 35% hydrogen rich respectively. By varying the oxygen to carbon ratio in auto-thermal reformation it is possible to control the reformer exit temperature. The effect of reformer operating temperature and steam to carbon ratio was investigated on the reformer exit composition.

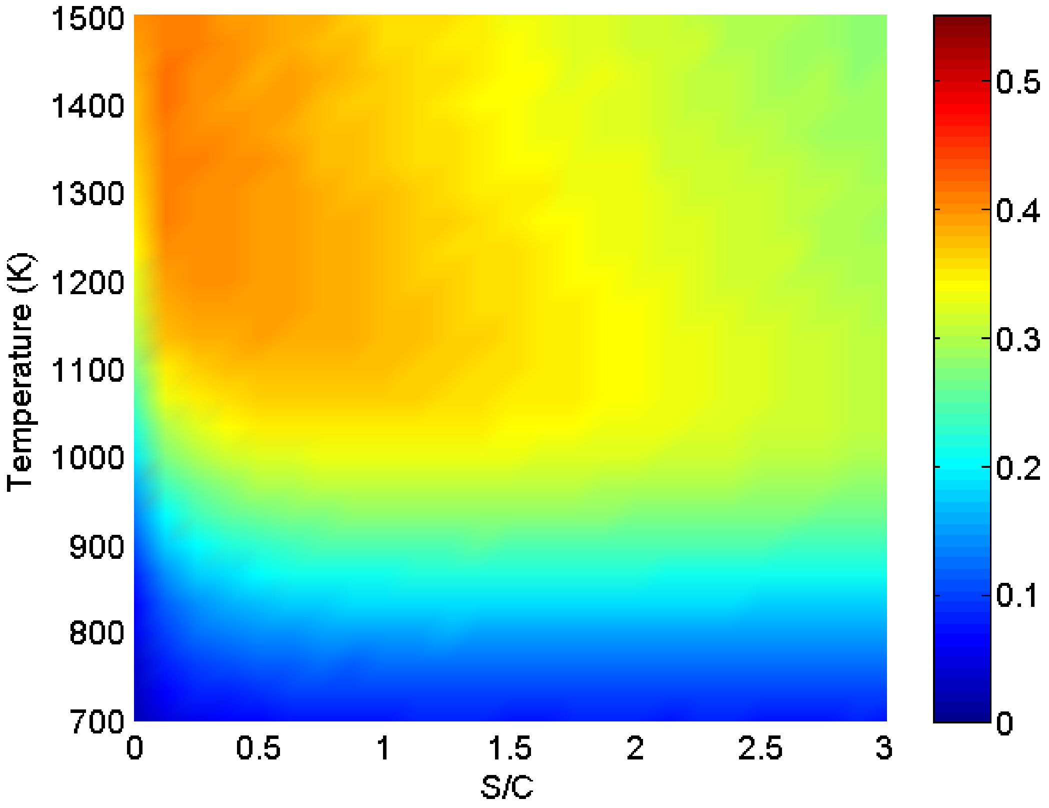

Figure 6 Equilibrium auto-thermal reformation hydrogen mole fraction for various reformer steam to carbon ratio and reformer exit temperature.

It was concluded that the use of steam can be very expensive on the large scale and may not be desired. Instead it maybe desired to use partial oxidation where no steam will be required. The tradeoff is that less hydrogen can be generated by partial oxidation and some control of the exit temperature is lost. By using a catalyst in partial oxidation it is possible to reform richer and generate slightly more hydrogen. However, a catalytic partial oxidation will require both a catalyst as well as a heat exchanger, which will add cost. Clearly a tradeoff exists between performance and cost.

Evaluation of fuel preprocessing on combustion:

The effects of fuel preprocessing on lean premix combustion ignition, and weak extinction (lean blowout) limits was investigated by means of equilibrium and well-stirred reactor analysis in Cantera. Auto-ignition was identified as a potential problem. Figure 7 demonstrates fuel preprocessing can have an order of magnitude effect on the lean pre-mixture auto-ignition time. To avoid auto-ignition it may not be possible to preprocess all the fuel. Instead a portion of the fuel may have to be mixed back with the preprocessed fuel to quench and lower auto-ignition.

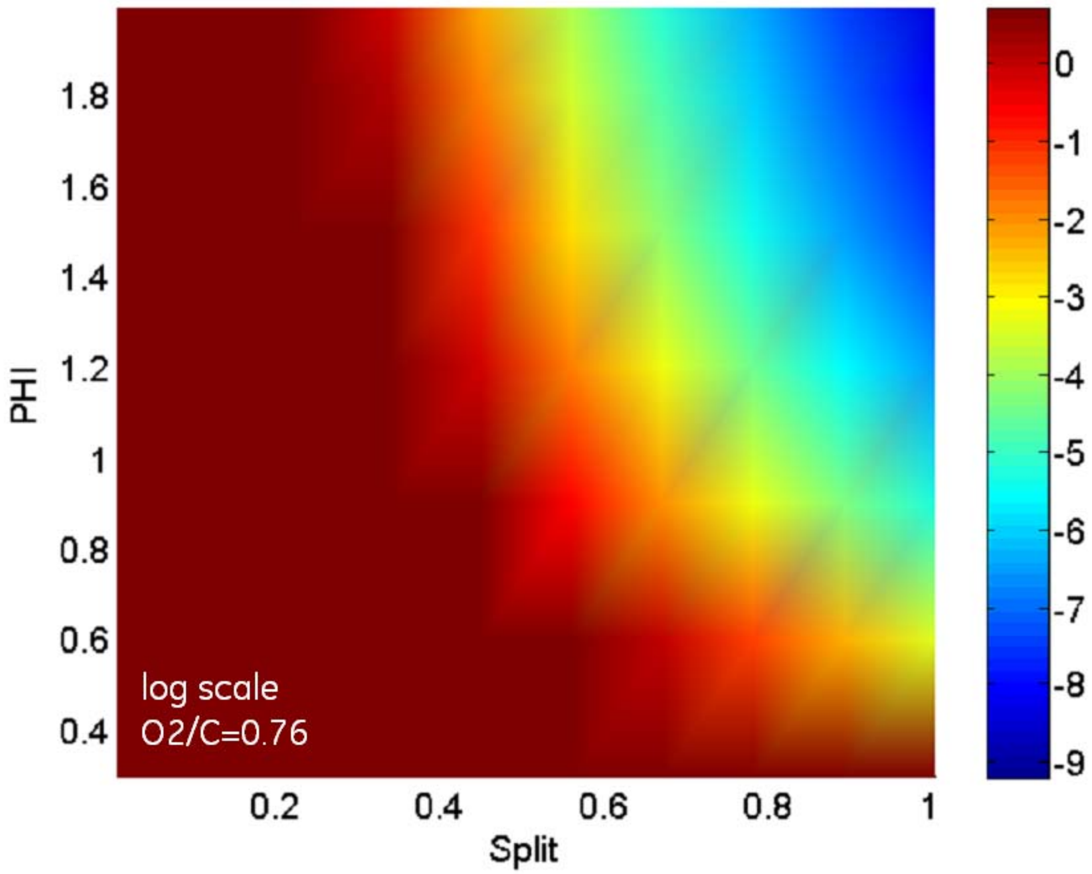

Figure 7 Auto-ignition time of mixture with various amount of pre-oxidation at oxygen to carbon ratio of 0.76 and equivalence ratio.

In addition to fuel quenching, quick fuel air premixing can lower auto-ignition, as lean mixtures are less likely to auto-ignite. On the other hand, increased fuel preprocessing will lower weak extinction limits and improve dynamics. The more the fuel is preprocessed the more weak extinction limits can be improved. With improved weak extinction limits pollutant reductions and premix combustion turn down improvements can be made.

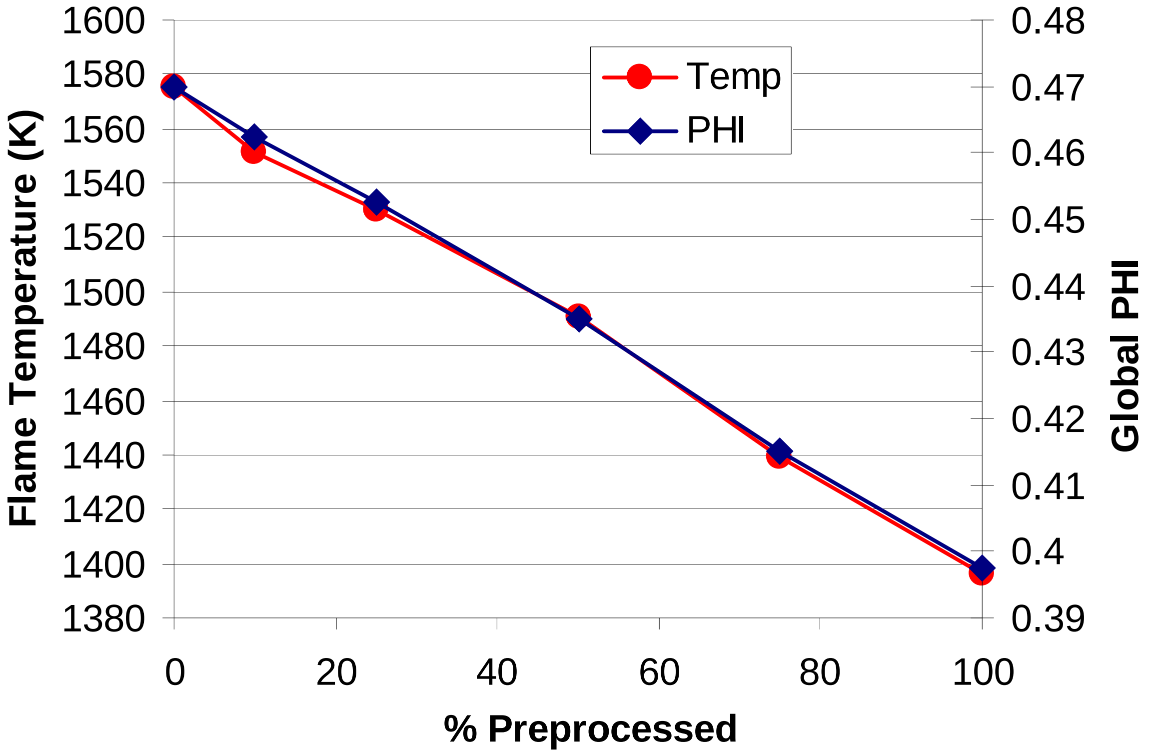

Figure 8 Flame temperature and equivalence ratio (phi) at lean blow out for various amount of fuel preprocessed at oxygen to carbon ratio of 0.76.

Analysis Application on Fuel Flexibility and Control:

It is desired to preprocess the fuel to increase the fuel reactivity before lean premix combustion. In addition, to valve actuation and pressure drop effects of fuel variations captured by the Wobbe index, lean premix combustion fuel flexibility is limited by potential problems in auto-ignition, flame holding and emissions guarantees. Induction time provides a first order approximation to flame holding. Simulation results shown in Figure 9 indicate fuel properties can substantially affect induction time elucidating potential flame holding problems.

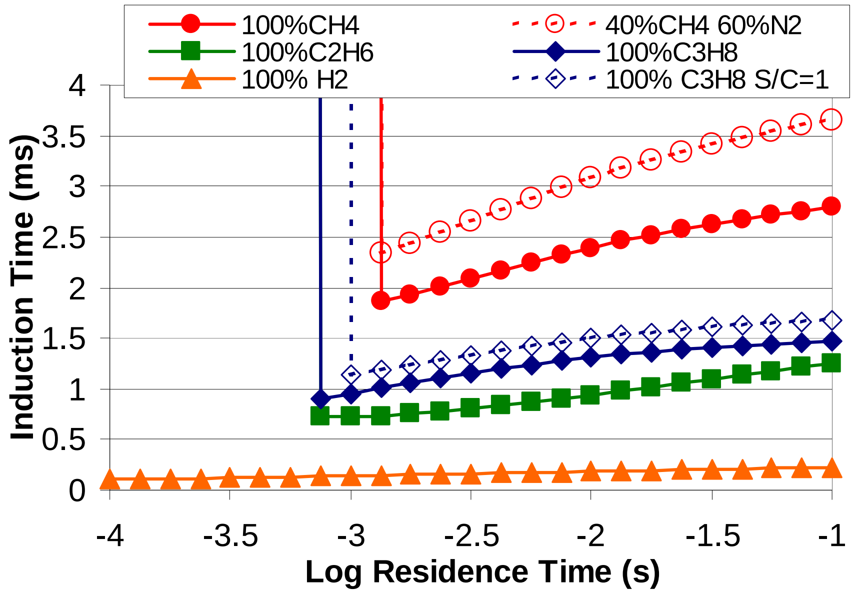

Figure 9 Fuel variation and residence time effect on induction time.

The same limitations in fuel flexibility may exist in fuel preprocessing. It may however be possible to suppress the problems by varying the combustor temperature. Simulation results shown in Figure 10 indicate the fuel induction time of propane can be tailored close to that of methane by manipulating the combustor temperature. System controls can potentially be used to vary the equivalence ratio to maintain flame stability, and emissions guarantee depending on the inlet fuel or amount of fuel preprocessed.

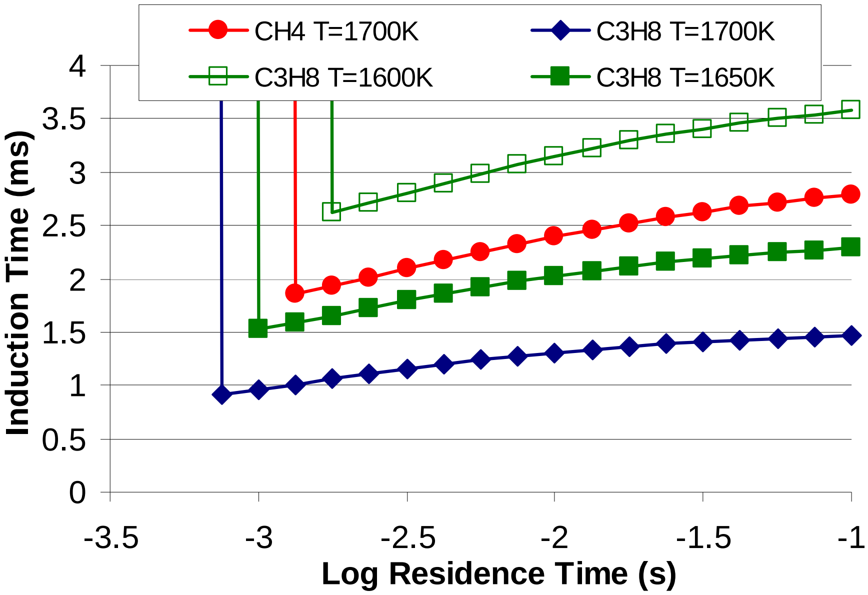

Figure 10 Combustor temperature induction time adjustments.

Effects of fuel preprocessing on Emissions:

By increasing the mixture reactivity lean blow out and dynamics margins should increase. Improvements in weak extinction limits can be used to reduce combustions pollutant emissions. The concept is similar to rich burn, quick mix, lean burn (RQL) used in propulsion engines. In traditional RQL the flame is not fully quenched before mixing resulting in emissions generation during mixing. In the investigated concept, the partially preprocessed mixture is quenched with fuel and rapidly premixed with air prior to lean combustion. As shown in Figure 11, the fuel is preprocessed in rich conditions, cracking the methane with minimal nitrous oxide formation. Preprocessing the fuel then allows for leaner combustion where NOx emissions are suppressed.

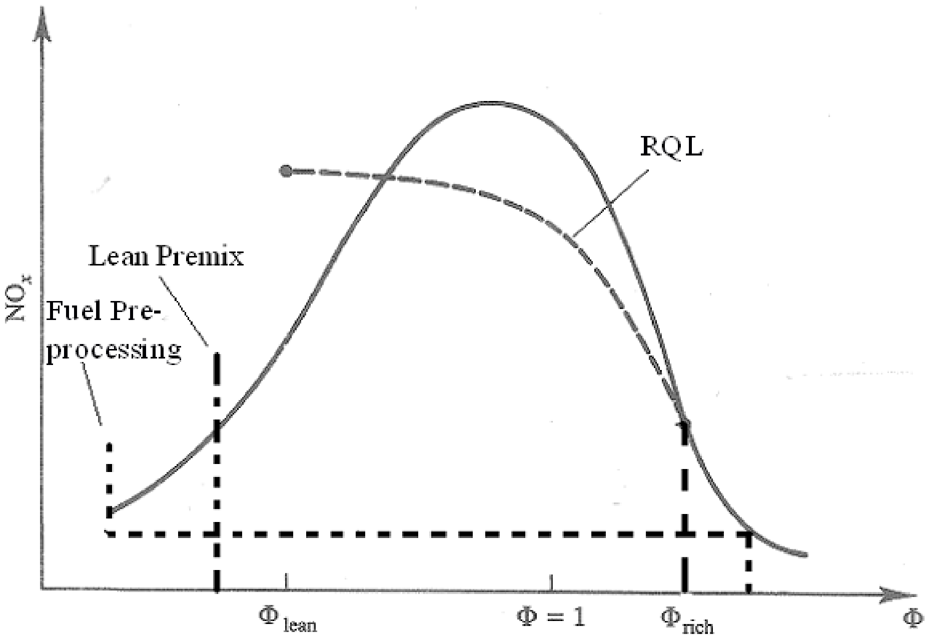

Figure 11 Concept of rich fuel pre-oxidation prior to premix lean combustion compared to RQL and lean premix combustion for pollutant reduction.

Furthermore, increased fuel reactivity can lead to lowered carbon monoxide emissions at leaner conditions. Consequently, reduced combustor temperatures can be established reducing thermal NOx emissions, potentially creating more pollutant emissions margins relative to guarantees.