Flashback Analysis for ULN Hydrogen Enriched Natural Gas Mixtures

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Gas Turbine Need

✓ The growing concern over the rising prices of natural gas and oil and the stricter legislations to reduce emission of NO_x and CO, have sparked an increasing interest in alternative fuel programs and the development of low emission combustion systems such as lean premixed technology including Dry Low NO_x (DLN), and even Ultra Low NO_x (ULN) combustion systems.

✓ Burning hydrogen not only results in no CO_2, but also when added to natural gas, extends the lean operating limit allowing a reduction in both CO and NO_x.

✓ Gas turbines are generally optimized to operate on natural gas and were not initially designed to operate on either syngas or hydrogen fuels.

✓ With the benefits of hydrogen addition that allows for the operation under leaner conditions for effective NO_x control, come potential problems such as **Flashback** and combustion instability, due to the high turbulent flame speed of hydrogen

Objectives

✓ Understand the impact of the variability in fuel composition on combustion performance by understanding the fundamental combustion properties of these mixtures, including heating values, laminar and turbulent flame speeds.

✓ Investigate flashback phenomena in ultra low NO_x premixed systems upon the addition of hydrogen to natural gas.

✓ Flashback is an important issue in lean premixed combustion systems that use hydrogen as an additive fuel due to the widely varying flame speeds of the mixtures considered. As such, the effect of fuel composition variation upon flashback depends upon the corresponding change in local flame speed, both laminar and turbulent.

✓ Develop models capable of predicting flashback behavior for varying Hydrogen/ Natural gas fuel composition using laminar and turbulent flame speeds

✓ Utilize existing combustion parameters such as the Damköhler and the Wobbe index to develop flashback correlations and introduce new parameters that lead to even more accurate predictions.

Approach

Testing

ULN Combustion System
Inlet Temperatures: 700-800 K
Equivalence ratios: 0.46- 0.55

Inlet Temperatures: 700-800 K
Inlet pressure:15-20 atm
Mixtures: Hydrogen/Natural Gas with Steam injection

Flashback Parameters

❖ Wobbe Index: Characteristic of gas composition and its heating value

$$Wo\left(\frac{Mj}{m^3}\right) = \frac{LHV_{vol}}{\sqrt{\frac{Ru_{fuel}}{Ru_{air}}}} = \frac{LHV_{vol}}{\sqrt{\frac{R/MW_{fuel}}{R/MW_{air}}}} = \frac{LHV_{vol}}{\sqrt{\frac{MW_{fuel}}{MW_{air}}}}$$

❖ Damköhler parameter: Relates the residence time of the flow to the chemical time (loading parameter)

$$Da = \frac{\tau_{mix}}{\tau_{reac}}$$

$$\tau_{mix}\,(\text{sec}) = \frac{D}{U}$$
$$\tau_{reac} = \frac{\delta_l}{S_l}$$
$$\delta_l = \frac{\alpha}{S_l}$$
$$\alpha = \frac{k}{\rho \times c_p}$$

$S_L = Laminar\ flame\ speed$

$\delta_l : Laminar\ flame\ thickness$

$\alpha\left(\frac{m^2}{s}\right) : Thermal\ diffusivity$

Laminar flame [PREMIX application in CHEMKIN, GRI 3.0 Mechanism]

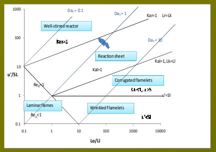
The thermal diffusivity [Chemkin Transport properties gives conductivity, viscosity and specific heat.

Turbulent Combustion

Gas turbines operate in a very turbulent flow regime, where flashback could occur as a result of turbulent burning velocity exceeding the local flow velocity

$$S_T = S_l \times f\{u', Re\}$$

Turbulent parameters [averaged CFD simulations]
Turbulent Kinetic energy k= 177.3 m^2/s^2
Turbulence dissipation ϵ = 609537 m^2/s^2
Turbulence Intensity u' $u' = \sqrt{\frac{2}{3} \times k}$
Integral Length Scale l_0 ~ 2.57 mm
Kolmogorov Length Scale l_k ~ 3.67 microns
Turbulent Reynolds Number Re_o
Karlovitz Number Ka



Regime diagram for premixed turbulent combustion (Peters N. , 2000)

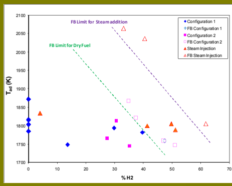
Turbulent Flame speed Correlations

Thin reaction regime in premixed turbulent combustion characterized by small eddies that can penetrate into the preheat zone but not small enough to enter the reaction zone (Peters N. , 1999).

$$\frac{S_T}{S_L} = 1 - \frac{0.39}{2}\frac{l_0}{l_l} + \left[\left(\frac{0.39}{2}\frac{l_0}{l_l}\right)^2 + 0.78\frac{u' l_0}{S_l l_l}\right]^{1/2}$$

Results

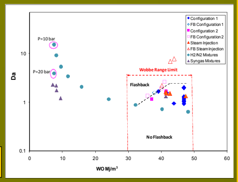
Flashback Limit correlation with Adiabatic Flame Temperature and % H2 in mixture.



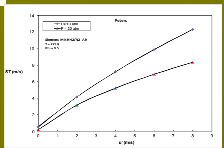
Steam Injection improves the resistance to flashback

Wobbe values outside of the range mean that modifications to the nozzle's design are required and additional flashback correlations are needed for each different geometry.

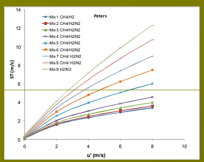
Flashback Limit correlation with Da and Wo parameters. Correlation valid for Wo range 35~50 Mj/m³



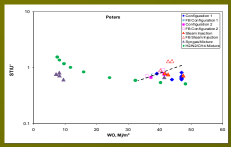
Effect of Pressure on Turbulent Flame Speed



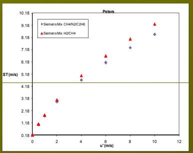
Effect of Hydrogen addition on Turbulent Flame Speed



Flashback Correlation with Turbulent flame speed and Turbulent Intensity



Effect of Preferential Diffusion on Turbulent Flame Speed



Conclusions

➢ The impact of the fuel composition variability on combustion performance has been reviewed and analyzed

➢ The flashback limit given herein should be applied to the Wobbe range specified (30-50 Mj/m³) and additional limits are needed for lower Wobbe numbers [different nozzle configurations]

➢ Hydrogen addition causes an increase in laminar flame speed and therefore turbulent flame speed

➢ Although the effect of pressure is well defined for laminar flame speed, it is yet not known for turbulent flame speed

➢ The ST/U'-Wo correlation was able to collapse the flashback limit into a one slope line, however, the ultimate goal is to find a correlation that is valid for a wider Wobbe range.

➢The changes in the Damköhler values can be explained by the preferential diffusion effect. Assuming an average equivalence ratio for all the mixture constituents is not the best approach. The equivalence ratio can be corrected for by applying Kido's expression, which has been verified and successfully applied to Blowoff correlations (Noble 2006)

$$\Delta\phi = C \times \ln\left(\frac{D_F}{D_{OX}}\right)$$