Flashback Analysis for ULN Hydrogen Enriched Natural Gas Mixtures

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Objectives: Investigate Flashback phenomena for Hydrogen enriched Natural gas mixtures at gas turbine conditions.

Achievements:

- Developed flashback models capable of predicting flashback behavior for various Hydrogen/Natural gas fuel compositions.
- Analyzed the impact of fuel composition variability on combustion performance.
- Defined important combustion characteristics as key parameters for flashback model development.
- Investigated the effect of both laminar and turbulent flame speed on flashback behavior.

Spin-Offs:

- Hydrogen addition to Natural gas does not necessitate major modifications to the engine configuration as long as the the Wobbe index is within the range 30-50 Mj/m^3.
- At gas turbine conditions, the combustion is in the turbulent regime and therefore flashback was correlated with turbulent flame speeds and turbulence intensities.
- There is a lack of experimental data on turbulent flame speeds at gas turbine operating conditions, namely pressures of 16-20 atm and inlet temperatures of 800 K . As an alternative, Peters' correlation, which was derived from scaling arguments was employed for the purpose of flashback model development.
- The correlation with the Damkohler and Wobbe parameters leads to reasonable result, however considering the preferential diffusion effect by correcting for the equivalence ratio should result into a more accurate flashback model.

Comments on the UTSR Fellowship Program

- My fellowship at Siemens Power generation was a great opportunity to apply my learned academic knowledge on a real world application in the combustion field, notably, gas turbines.
- The Combustion group at Siemens was very helpful and supportive by all means. Everyone was ready to provide me with the background I needed to perform the project assigned to me.
- The project was definitely related to my field of research at UCF and being able to develop something that might be useful to the company and to the combustion community was very exciting.
- I had the greatest opportunity to attend the UTSR workshop in Anderson SC, where I presented my poster. I met with other UTSR fellows as well as the UTSR staff who were helpful throughout the process.
- The level of confidence I attained from this experience was nurtured by the overwhelming interest my project received. I am looking forward to take part of this experience next summer and would recommend this program to anyone who has interest in gas turbines in general.

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Abstract

The lean premixed gas turbine combustion system is particularly sensitive to variations in gas composition. Hydrogen addition to natural gas allows for reduced NOx and CO emissions, in addition to improving stability and extending the operability range to lower equivalence ratios. On the other hand, hydrogen is characterized by it high flame speed which renders the fuel mixtures susceptible to flashback and therefore serious hardware damage could result. Flashback constitutes an obstacle for lean premixed technology, which makes it one of the gas turbine industry priority issues that needs attention. Therefore a flashback model is introduced herein in order to predict flashback for any given fuel mixture at a given Wobbe range. The model is developed from parameters relevant to combustion properties of the fuel mixtures and is presented on multiple plots, in which safe and flashback regions are identified. Damköhler and Wobbe parameters can reasonably capture flashback behavior for a specific range of Wobbe numbers. Additional limits are needed for lower Wobbe ranges. The fuel mixtures analyzed herein were conducted at test conditions representative of turbulent combustion. Therefore turbulent parameters were employed as an attempt to correlate flashback with turbulent flame speed. The results obtained do not show strong variation from the Damköhler-Wobbe predictions qualitatively. The effect of various parameters on the flashback correlation are also investigated.

Nomenclature

AFR	Air to fuel ratio
C_p	Specific heat of mixture [J/(Kg.K)]
D	Characteristic Diameter [m]
Da	Damköhler number [-]
D_F	Mass diffusivity of fuel [m^2/s]
D_{ox}	Mass diffusivity of oxidizer [m^2/s]
k	Thermal conductivity of mixture [W/(m.K)]
Ka	Karlovitz number [-]
Ka_l	Ka based on l_l [-]
Ka_R	Ka based on reaction zone [-]
LHV	Low heating value [Mj/m^3]
l_K	Kolmogorov length scale [m]
l_l	Laminar flame thickness scale [m]
l_o	Integral length scale [m]
MW	Molecular weight of mixture [Kg/mol]
P	Combustor Pressure [Pa]
R	Universal gas constant [8.314 J/(K.mol)]
Re	Reynolds number [-]
Re_0	Reynolds number based on l_0 [-]
Re_K	Reynolds number based on l_K [-]
Ru	Specific gas constant [J/(Kg.K)]
S_L	Laminar flame speed [m/s]
S_T	Turbulent flame speed [m/s]
T	Combustor Temperature [K]
T_{ad}	Adiabatic flame temperature [K]
U	Fuel-Air mixture axial velocity [m/s]
u’	Turbulence intensity [m/s]
Wo	Wobbe number [Mj/m^3]
Ze	Zeldovich number [-]
ϕ	Equivalence ratio [-]
ε	Turbulent Dissipation [m^2/s^3]
κ	Turbulent kinetic energy [J/Kg]
α	Thermal diffusivity [m^2/s]
δ_L	laminar flame thickness [m]
ρ	Density of mixture [kg/m^3]
ρ_{air}	Density of air [kg/m^3]
ρ_{fuel}	Density of fuel [kg/m^3]
υ	Kinematic viscosity [m^2/s]
τ_K	Kolmogorov time scale [s]
τ_l	laminar flame thickness time scale[s]
τ_{mix}	Mixing time or residence time [s]
τ_R	Reaction zone time scale [s]
τ_{reac}	Reaction time or chemical time [s]
τ_0	Integral time scale [s]

I. Introduction

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. Special interest has been given to coal-derived Syngas or fuels from other sources such as biomass, landfill gas, or process gas (Richards, 2001).

The gas turbine industry is primarily affected by the challenges set to develop combustion systems that not only ensure low levels of emissions, but also has minimum impact on gas turbine operation and component life. To comply with the legislative demands, attention is shifted toward lean premixed technology including Dry Low NO_x (DLN), and even Ultra Low NO_x (ULN) combustion systems. Lean premixed combustion with minimum emission levels, below 5ppm, can be achieved by burning hydrogen, which makes hydrogen the preferred alternative fuel. 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. Syngas and hydrogen fuels differ considerably in combustion characteristics and composition than natural gas; therefore, there is a growing interest in developing fuel flexible gas turbine combustors that can tolerate a broad range of fuel compositions without sacrificing low emission and high efficiency.

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 and the need to operate near lean flammability limits to reduce emissions by lowering the flame temperature.

Fuel Variability

There is general agreement from the gas turbine industry that varying the fuel composition affects the successful operation of originally designed natural gas engines (King, 1992). Alternative fuels such as syngas and hydrogen enriched fuels are primarily composed of H2, CO, and N2, in addition to small amounts of methane and higher order hydrocarbons. Diluents such as N_2, CO_2, Ar, and H_2O are often added for the purpose of reducing the flame speed (Moliere, 2002). The fuel composition also varies from region to region depending on the source and the processing technique. This variability constitutes a significant problem to the operation of gas turbines because low emission combustion systems were designed to operate on a relatively consistent fuel composition to maintain acceptable hardware life and to ensure low emissions. Significant changes in fuel composition beyond what the equipment is tuned to receive may have lead to engine failure.

Variations in the fuel composition result in changing the combustion characteristics of the fuel which introduces substantial modifications in flame speed, flame shape and combustion dynamics and therefore the system becomes more susceptible to potential problems such as flashback, blowoff, and instabilities (Lieuwen, 2006) (Richards, 2001).

The objective of this study is to 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. These characteristics are determined to 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.

Flashback

Flashback occurs when the gas velocity becomes smaller than the burning velocity and the flame propagates upstream into the premixer passages, since these passages cannot withstand high temperatures, hardware damage results from flashback (Law, 2006). Flashback phenomena has been widely investigated (Wohl, 1952) (Putnam, 1948). In Swirling flows, in particular, several potential modes of flashback can occur (Kroner, 2002) (Kieswetter, 2003). The first mode is that of flashback in the boundary layer due to the low velocity in the boundary layer. The second mode refers to flashback in the core flow. The two modes take place when local burning velocity exceeds the flow velocity, allowing the flame to propagate upstream into the premixer passages. In some cases, flashback can occur even though the local flame velocity is less than the flow velocity. The idea is that the flame causes the vortex upstream to breakdown and this creates a negative flow region ahead of it (adverse pressure gradients) which causes it to advance further upstream. This phenomenon is referred to "combustion induced vortex" (Kroner, 2002) and is caused by the temperature ratio across the flame (Brown, 1990). Lieuwen et al. concluded further that "combustion induced vortex breakdown" is not influenced by the chemical kinetic characteristics of the mixture (Lieuwen, 2006). Furthermore, Noble and coworkers related this phenomenon to the pressure rise upstream of the flame due to the divergence of the upstream flow caused by the inclined flame front (Noble, 2006).

In general, flashback is greatly influenced by the variations in fuel composition that affect the combustion properties of the mixture, notably, the local burning velocity.

II. Experimental Setup

The test data were obtained at initial inlet temperatures 700-800 K, inlet pressure of 15-20 atm, and equivalence ratios 0.46- 0.55. The approach was to keep the combustor pressure and temperature constant and increase the firing temperature by adjusting the fuel and air mass flow rates until flashback occurred. This data was obtained with the ULN combustion system. During some of the testing steam injection into the shell was used to control flashback. Flashback was recorded whenever the thermocouple temperature rose 50˚C degrees above the shell temperature.

Defining the flashback parameters

The combustion community is in need for models capable of predicting flashback behavior for varying fuel composition. Understanding the fundamental characteristics of the fuel mixtures, can significantly facilitate the development of such models. Recently, the characteristics of premixed hydrogen enriched methane fuels have been investigated (Slim, 2006) (Schefer R. W., 2003) (Schefer R. W., 2003) (Tuncer, 2006) (Wicksall, 2001) (Griebel P. B., 2006) .

Flashback has been a concern before the advent lean premixed technology. Interchangeability studies were performed extensively as early as the 1940s in an attempt to develop parameters to address this issue, including flame lifting, yellow tipping, but they were mostly focused on industrial flame burners and partially premixed home appliances . As a result, several empirical parameters were developed to address yellow tippping, flame lifting, and flashback and have been published in AGA Bulletin 36 (AGA, 1946) .

The flashback Interchangeability Index is given by:

$$I_F = K_s f_s \frac{\sqrt{\frac{h_a}{1000}}}{K_a f_a}$$

Subscripts "s" and "a" denote substitute and adjust gases respectively. K is the lifting limit constant and f is the primary air factor and h is the heating value. In the 1950s, E.R. Weaver expanded the AGA test regime on lifting, yellow tipping, and flashback by adding separate parameters for incomplete combustion, burner load and air supply (Weaver, 1951). These included values such as flame speed and incomplete combustion. The Weaver Interchangeability Index for flashback is given by:

$$J_F = \frac{S_S}{S_a} - 1.4\, J_A + 0.4$$

J_A is the weaver index for air supply

$$J_A = A_S \frac{\sqrt{D_a}}{A_a\sqrt{D_S}}$$

A is the cubic feet of air required for the complete combustion of 1 cubic foot of gas and D is the relative density of gas expressed as specific gravity referred to air as unity. S is the maximum flame speed in a mixture of fuel/Air, expressed as a fraction of the flame speed for Hydrogen:

$$S = \frac{aF_a + bF_b + cF_c + \cdots}{A + 5Z - 18.8Q + 1}$$

A, b, c, ... are the fractions by volume of various combustible constituents of the fuel gas. F is the flame speed factor, A is the volume of air required to burn one volume of gas, Z is the fraction by volume of inert gases, chiefly carbon dioxide and nitrogen, and Q is the percent of oxygen in the fuel.

However, it has been found that the above AGA and Weaver parameters, in addition to being complex, do not fully capture flashback behavior. Another important interchangeability parameter that has been used extensively throughout the world is the Wobbe Index (Kuipers). The Wobbe Index is a strong characteristic of the gas composition and its heating value, and moreover a measure of the overall fuel injection system to accommodate the fuel composition. It is also a measure of the jet penetration, so any deviation from the design causes poor mixing. The Wobbe number relates the energy content of the gas to the rate at which it passes through an orifice with subsonic flow. When the Wobbe index is varied greatly from the original design value, modifications to the entire fuel system are necessary to avoid hardware failure (AGA, 1946). To ensure that the Wobbe number of the fuel is within the operability range of the engine, usually the fuel gas is metered at an orifice in proportion to the mass flow rate of air. In 1927, Goffredo Wobbe, an Italian physicist was the first to derive the Wo relationship given below. Considering a specific fuel mixture, the Wobbe number is determined as such

$$i : Fuel\ component$$

$$x : mole\ fraction$$

$$LHV : Lower\ Heating\ Value$$

$$Wo : Wobbe\ Index\ or\ Wobbe\ number$$

$$LHV_{vol}\left(\frac{Mj}{m^3}\right) = \sum_{i=1}^{n} x_i \times LHV_i$$

$$Wo\left(\frac{Mj}{m^3}\right) = \frac{LHV_{vol}}{\sqrt{\frac{\rho_{fuel}}{\rho_{air}}}} = \frac{LHV_{vol}}{\sqrt{\frac{\frac{P}{Ru \times T_{fuel}}}{\frac{P}{Ru \times T_{air}}}}}$$

Assuming standard temperature and pressure conditions, the Wobbe number is given by:

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

$$Ru : Specific\ gas\ constant\ \left(\frac{J}{Kg.K}\right)$$

$$R : Universal\ gas\ constant = 8.314\ \frac{J}{K.mol}$$

$$MW : Molecular\ weight\ of\ species\ \left(\frac{Kg}{mol}\right)$$

However, the Wobbe index alone does not provide a good insight about other important combustion properties, such as flame speed and combustion chemistry, upon which the operability of lean premixed combustor systems strongly depend. The reason for this is that different fuel mixtures can have different combustion properties such as flame speed even at constant Wobbe index.

In addition to the Wobbe index, flashback correlations have considered parameters such as adiabatic flame temperature and laminar flame speed to average flow velocity ratio variations with hydrogen addition (Noble, May 2006), but theses parameters often do not lead to a good correlation of flashback.

The Damköhler is an important combustion parameter that relates the residence time of the flow to the chemical time (Glassman, 1996) and is also referred to as the loading parameter. Although it is more famous for correlating blowoff limits (Noble, May 2006) (Zhang, June 2005) than flashback, it remains an important parameter, especially considering all the relevant combustion physical properties that make it up. Laminar flame speed is one of these properties that provide a fundamental understanding of the combustion on the molecular level. Therefore, the Damköhler parameter, along with the Wobbe index, should provide some insight into the flashback limit variation with varying fuel composition. The Damköhler number can be scaled with different parameters that lead to the same basic definition of the Damköhler number which relates a flow time to a chemical time as shown below.

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

τ_{mix}: $mixing\ time,\ also\ refered\ to\ as\ residence\ time,\ flow\ time, and\ fluid\ motion\ time$

τ_{reac}: $reaction\ time\ or\ chemical\ time$

$$\tau_{mix}(\text{sec}) = \frac{D}{U}$$

D : $Characteristic\ diameter$

U : $fuel\ air\ mixture\ axial\ velocity$

$$\tau_{reac} = \frac{\delta_l}{S_l}$$

$S_L = Laminar\ flame\ speed$

δ_l : $Laminar\ flame\ \ thickness$

The laminar flame thickness is given by the ratio of the thermal diffusivity to the laminar flame speed

$$\delta_l = \frac{\alpha}{S_l}$$

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

Substituting this equation into the reaction time equation, $\tau_{reac} = \frac{\alpha}{{S_l}^2}$

The general form of the Damköhler number becomes: $Da = \frac{\tau_{mix}}{\tau_{reac}} = \frac{D\times S_l^2}{U\times\alpha}$

And the thermal diffusivity is determined by: $\alpha = \frac{k}{\rho\times c_p}$

$k \left(\frac{W}{m\,.K}\right)$: $mixture\ conductivity$

$\rho \left(\frac{Kg}{m^3}\right)$: $mixture\ density$

$c_p \left(\frac{J}{Kg.K}\right)$: $mixture\ specific\ heat$

Laminar flame speeds were calculated with the PREMIX application in CHEMKIN, using the GRI 3.0 Mechanism. In a recent study, it has been shown that the measured H2/CO flame speeds were in good agreement with the GRI 3.0 mechanism than the H2/CO mechanism (Natarajan, June 2005). The thermal diffusivity of the mixtures were determined from the transport properties of TRAN application in Chemkin which calculates the conductivity, viscosity and specific heat for each mixture at a given temperature and pressure. These properties were determined at the inlet combustion air conditions to be consistent with the laminar flame speed calculations.

To investigate the influence of hydrogen addition upon flashback, Fig. 1 shows the effect of hydrogen addition on the adiabatic flame temperature. The flashback data are given in open symbols and the non-flashback data are represented by the closed symbols. Two flashback limits are identified. The first limit is for the fuel mixtures without steam addition and the second limit represents steam addition. At 1800 K, flashback occurs around 47% hydrogen for the no steam fuel mixtures. As the adiabatic flame temperature is increased, the amount of hydrogen needed for flashback drops to 35%. With steam injection, the flashback limit shifts to higher hydrogen concentration. For instance, at 1800 K, flashback occurs at 60 % hydrogen compared to 47% without steam injection. Steam injection improves the resistance to flash back and the flashback limit is increased from 47 to 60 % hydrogen.

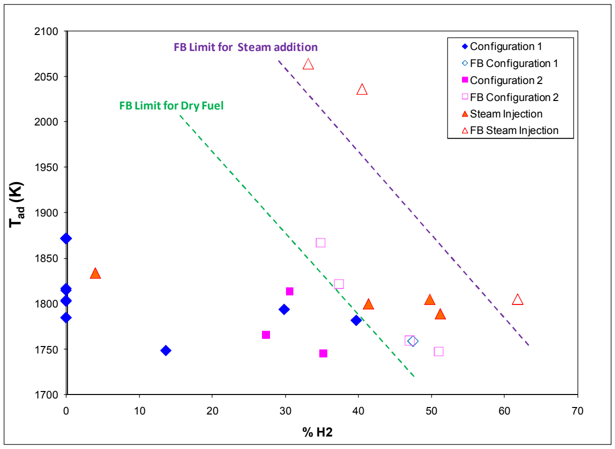

Fig. 1 Flashback limits for hydrogen fuel mixtures with and without steam injection. The correlation is given as a function of adiabatic flame temperature and % hydrogen added to natural gas mixture

Laminar flame speed is an important and fundamental property in combustion. Figure 2 shows the dependence of laminar flame speed on hydrogen addition. Similarly to Fig.1, flashback limits are determined for both cases. Laminar flame speed does not correlate well with % hydrogen, at least for the fuel mixtures considered in this study. Flame speed is strongly dependent on the equivalence ratio of the fuel mixtures. For the mixtures considered herein, although the amount of hydrogen is varied greatly, the heating value was kept constant by diluting the mixture with N2.

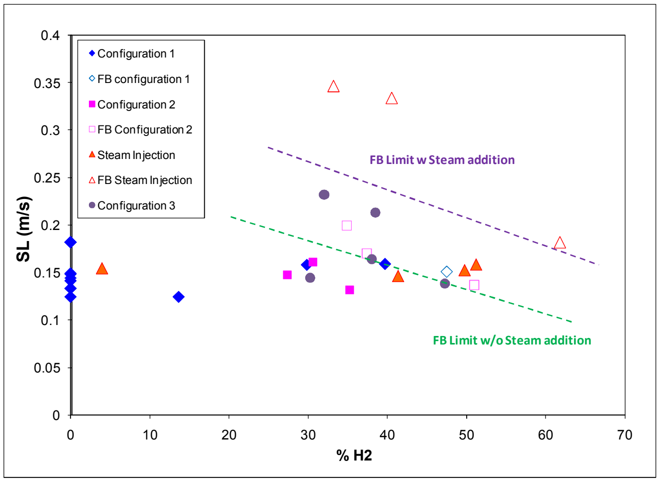

Fig. 2 Flashback limits for hydrogen fuel mixtures with and without steam injection. The correlation is given as a function of laminar flame speed and % hydrogen added to natural gas mixtures.

A better characteristic of the fuel composition is the Wobbe Index. To illustrate, two mixtures with the same percent hydrogen are selected. Figure 3 shows the % hydrogen plotted versus the Wobbe index. The two mixtures have different Wobbe values. A close look at the composition of the mixtures shows that the amount of nitrogen added to the mixtures is different. Therefore, % hydrogen is not sufficient to characteristic the fuel mixture composition and. This confirms the assumption made earlier on the effect of hydrogen on flame speed, where the heating value of the whole mixture should be considered.

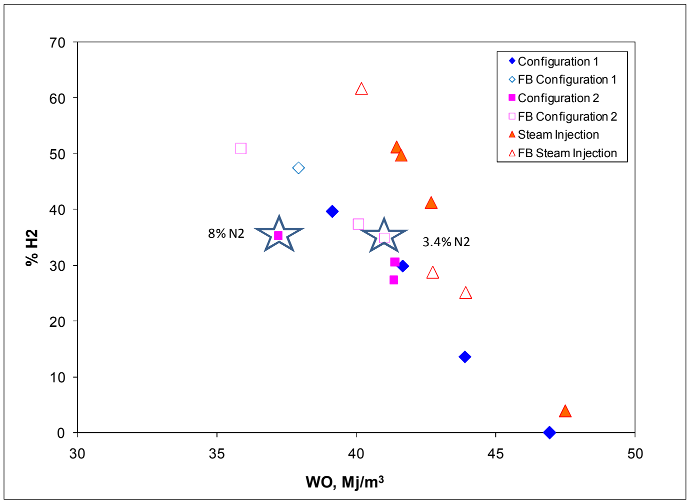

Fig. 3 Change of Wobbe index with % hydrogen

The next step is to correlate flashback with the Wobbe index and the Damköhler parameters. Figure 4 shows the results plotted on the Damköhler-Wobbe plot, where a flashback limit is identified. The flashback limit separates between the flashback data and the safe data.

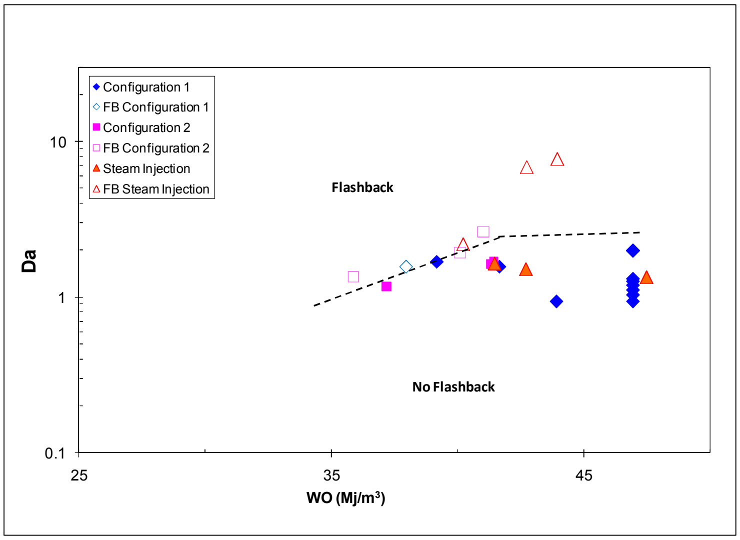

Fig. 4 Flashabck correlation with Damköhler and Wobbe parameters

The Damköhler –Wobbe plot displays two important results. The first one is characterized by a constant Da number and a varying Wo number. The variation in the Wo index is due to the variation in the fuel composition. The addition of hydrogen causes a decrease in the Wo number because the calorific value of pure Hydrogen ~ 13 Mj/m^3, which is one third the calorific value of natural gas ~35-40 Mj/m^3. The impact of change in gas composition on flame speed is mainly dictated by its impact on the equivalence ratio, which is dependent on the Wobbe index. Hydrogen addition causes a decrease in stochiometric air requirement, rendering the fuel mixture leaner. This effect on equivalence ratio yields only a modest change in laminar flame speed and therefore the Da number. The leaner mixture offsets the effect of the faster burning hydrogen on the burning velocity. Depending on the amount of hydrogen added, this offset can be so large that no change of the burning velocity is observed.

The second important result is for the case of constant Wo index but varying Da number. The Wo index can be held constant by adding other fuels such as higher order hydrocarbons or diluents to compensate for the effect of hydrogen; both the thermal input and the equivalence ratio remain essentially unchanged. In this scenario, the burning velocity of the mixture increases upon addition of hydrogen, due to the fast burning rate of hydrogen compared to natural gas.

A flashback limit is proposed and is characterized by a steeper slope for lower Wo ~35 Mj/m^3 and a practically zero slope for higher Wo ~ 50 Mj/m^3. Mixtures with lower Wo numbers tend to flashback more easily compared to high Wo mixtures.

To assess the validity of the correlation at even lower Wo values, other data from other tests are added to the plot. Figure 5 shows the data plotted for a broader range of Wobbe numbers. The blue dot data are hydrogen, methane and nitrogen mixtures for which hydrogen and nitrogen concentration is gradually increased, while methane is decreased. These mixtures have not been tested yet, so no information concerning the potential of theses mixtures to flashback is available. Also included on the plot are data form syngas mixtures from previous test programs.

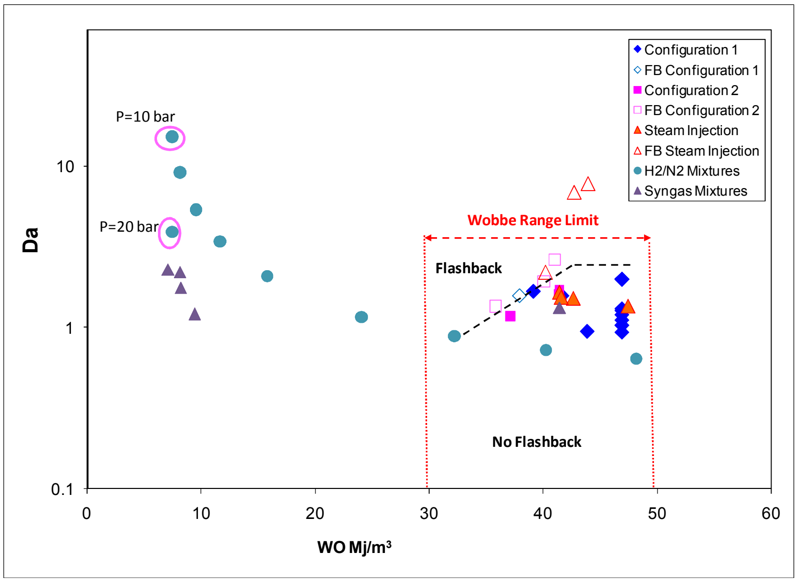

Fig. 5 Damköhler-Wobbe flashback limit correlation. Correlation is valid for Wo (30 -50 MJ/m^3)

Based on the results presented in Fig. 5, it is impossible to extrapolate the flashback limit to Wo values outside of the specified Wo range that is between 30 and 50 Mj/m^3. It is important to note that any given combustion nozzle is only valid for a limited Wobbe range. When the Wobbe index is varied greatly from the original design value, modifications to the entire fuel system are necessary to avoid hardware failure. Therefore Wobbe values outside of the range specified herein mean that modifications to the nozzle's design are required and additional flashback correlations are needed for each geometry.

Also, provided in Fig. 5, is the effect of pressure on the Da number. The flame thickness is inversely proportional to the pressure. An increase in pressure causes the flame thickness to decrease which then leads to a decrease in the flame area. Since the flame area is proportional to the flame speed, this latter one decreases. The Damköhler is a measure of a mixture's reactivity which strongly depends on the flame speed. Therefore, the Damköhler, similar to the flame speed, is inversely affected by the pressure. To illustrate, a fuel mixture with the same fuel composition for which the pressure is the only varying parameter is more reactive at 10 bars than at 20 bars.

Also provided in Fig. 6 are the computed low heating values in Mj/Kg and the corresponding Da numbers. The LHV of hydrogen is ~120 Mj/Kg and for methane is ~50 Mj/Kg. Note that the highly diluted mixtures have lower LHV values. The flashback data is dominant at high LHVs, due to the high amount of hydrogen present in the fuel mixtures; with the exception of steam-containing mixtures, for which the flashback resistance is improved due to steam addition.

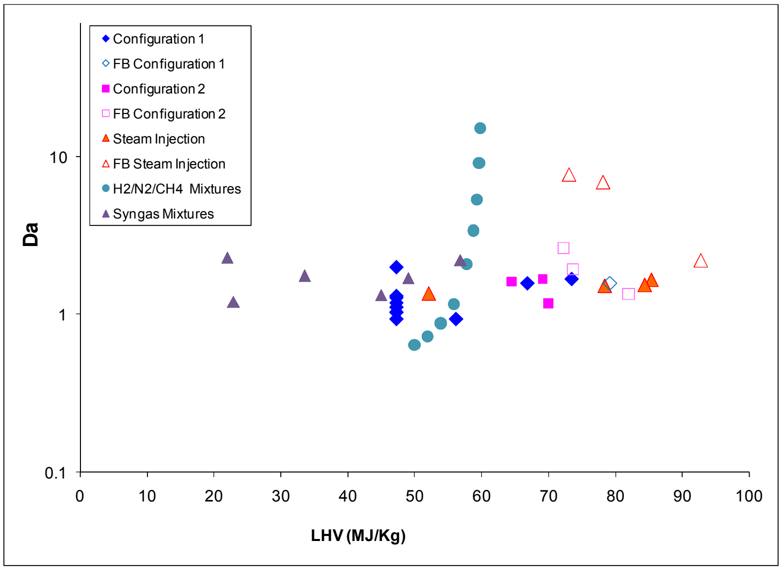

Fig. 6 Flashback correlation with Da and LHV (Mj/Kg)

The next section will investigate the effects of turbulent combustion on flashback and the possibility of identifying a flashback model with turbulent parameters.

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 and therefore a correlation for flashback should scale with turbulent parameters since the flame speed in no longer laminar. Turbulent burning velocity is strongly a function of the turbulence intensity u', the Reynolds number, and the laminar flame speed. It is often expressed by:

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

Important parameters needed to characterize the turbulent burning velocity are the turbulent length scales which can be measured for different turbulence intensities. Turbulent flow is characterized by the presence of eddies of various strengths and dimensions (Law, 2006). The turbulent kinetic energy and dissipation are expressed in function of integral length scale and turbulence intensity u', where,

$$k \approx \frac{3u_0^2}{2} \quad \text{and} \quad \epsilon \approx \frac{u_0^3}{l_0} \approx \frac{k^{\frac{3}{2}}}{l_0}$$

The turbulent parameters employed in this study were obtained from averaged CFD simulations. The average turbulent kinetic energy was estimated to be $k = 177.3\ m^2/s^2$ and the turbulence dissipation was found to be $\epsilon = 609537\ m^2/s^3$. The turbulence intensity u' was determined from:

$$u' = \sqrt{\frac{2}{3} \times k}$$

The integral length scale was estimated from the eddy dissipation equation to be 2.57 mm. And the turbulent Reynolds number is defined by:

$$Re_0 = \frac{u'_0\, l_0}{\vartheta}$$

Where ϑ is the kinematic viscosity and l_0 is the integral length scale. The turbulent time of the integral length scale is given by:

$$\tau_0 \approx \frac{l_0}{u_0} \approx \frac{k}{\epsilon}$$

When the intensity of turbulence increases, the amount of kinetic energy transfers at a rate ϵ to eddies of smaller sizes until they reach the minimum scale of eddies, called the Kolmogorov scale, l_k (Law, 2006).

$$l_k \approx \left(\frac{\vartheta^3}{\epsilon}\right)^{\frac{1}{4}}$$

The Kolmogorov length scale was calculated to be 3.67 microns.

To characterize the combustion regime of the tests performed, the Borghi diagram of Peters is employed (Peters N. , 2000), where $\frac{u'_0}{S_l}$ is plotted versus $\frac{l_0}{l_l}$ on a log scale (fig. 7).

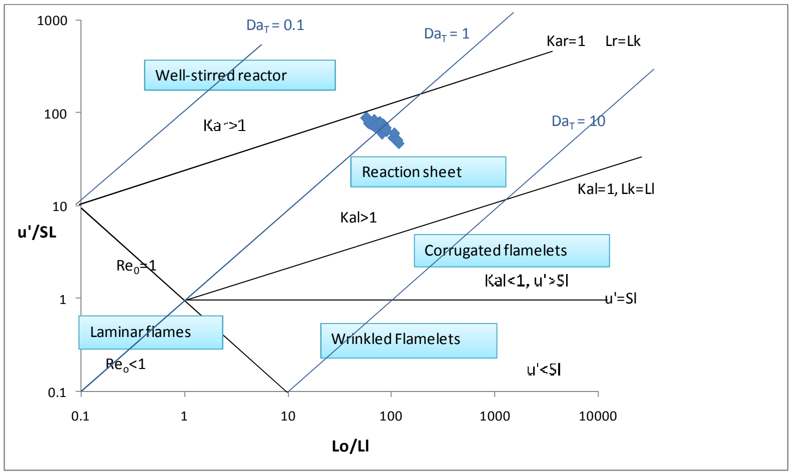

Fig. 7 Regime diagram for premixed turbulent combustion (Peters N. , 2000)

The Turbulent Reynolds number Re_0, the Karlovitz number Ka, and the Damköhler number Da are plotted on the Borghi diagram as transition boundaries between the different combustion regimes and are defined by:

$$Re_0 = \frac{u'_0 l_0}{\vartheta} = \frac{u'_0}{S_l}\frac{l_0}{\delta}$$

The Karlovitz number Ka determines wether a laminar flame structure can exist in a turbulent flow and is expressed in terms of the Kolmogorov scale , the smallest eddy scale (Law, 2006),

$$Ka_l = \frac{\tau_l}{\tau_k} = \left(\frac{l_l}{l_k}\right)^2 = \left(\frac{u'_k}{S_l}\right)^2$$

$$\frac{u'_0}{S_l} = Ka_l^{2/3}\left(\frac{l_0}{l_l}\right)^{1/3}$$

$\tau_l$and l_l are the laminar flame time and flame thickness respectively.

The Karlovitz number can also be expressed in terms of the chemical reactivity and is denoted by Ka_R

$$Ka_R = \frac{\tau_R}{\tau_k} = \left(\frac{l_R}{l_k}\right)^2 = \left(\frac{l_R}{l_l}\right)^2\left(\frac{l_l}{l_k}\right)^2 = Ze^{-2}Ka_l$$

Where Ze is the Zeldovich number and τ_R and l_R are the reaction zone time scale and thinckness respectively. The Damköhler used in the Borghi diagram has a slightly different definition than the Damköhler introduced earlier and is given by

$$Da_T = \frac{l_0}{l_l}\frac{S_L}{u}$$

Where l_0 and l_l are the integral length scale, and laminar flame thickness respectively. The subscript T was added to Da to differentiate between the two Damköhlers.

The results are provided in Fig. 7. The data lie well within the thin Reaction sheet regime. This regime is characterized by a high turbulent Reynolds number, high Karlovitz numbers and a Damköhler number ~ 1. This is typical for gas turbine combustors (Griebel P. s., 2003). In this regime, the smaller eddies can penetrate into the preheat zone flame structure and therefore enhance the heat and mass transfer rates. As a result, the preheat zone of the flame is broadened. However, the reaction zone is thinner than the smallest eddies, Kolmogorov scales, which causes the flame to wrinkle only without affecting its structure (Law, 2006).

Attempts to develop turbulent flame speed correlation were introduced as early as 1940 by Damköhler. While turbulent flame speed correlations for natural gas fuels exist extensively, hydrogen enriched natural gas mixtures have not benefited yet of such luxury, with the exception of a semi empirical correlation proposed by Kido et al. for hydrogen-methane, and hydrogen-propane mixtures (Kido H. N., 2002) but is only valid for $0<Ka<0.5$, and was developed for atmospheric conditions, while gas turbines operate at high inlet temperatures, high temperatures, and high intensities.

For the purpose of formulating a flashback correlation as function of turbulent flame speed, two turbulent flame speed correlations were carefully selected with respect to the appropriate turbulent combustion regime considered in this study. Peters developed a correlation for the thin reaction regime to be applied to 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). The turbulent combustion regime of this study falls well within the region for which Peters correlation was developed. Furthermore, Peters correlation was derived based on scaling arguments from the kinematic G equation. Its solution well shows the bending effect and even depicts the preferential diffusion effect described by Kido et al (Kido H. N., 2002) as will be show later. Peters correlation is expressed as:

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

S_T and S_L are the turbulent and Laminar flame speeds respectively; u' is the turbulence intensity; l_0 and l_l are the integral length scale and laminar flame thickness respectively.

The second Correlation employed for turbulent flame speed predictions is that of Gülder (Gülder, 1990). Gülder proposed an expression of the turbulent flame speed as a function of the turbulent Reynolds number Re_t, the laminar flame speed, and the turbulence intensity and is given by:

$$\frac{S_T}{S_L} = \left\{1 + 0.62 \times {Re_t}^{1/4} \times \left(\frac{u'}{S_L}\right)^{1/2}\right\}$$

When the Reynolds number based on the Kolmogorov length sacle, $Re_\eta \geq 1.5\ u'/S_L$, and he the Reynolds number based on the integral length scale $Re_L \leq 3200$, the Turbulent flame speed is calculated based on the Kolmogorov length scale. For this study, Re_η and Re_0 (Re_L) are around 9 and 6500 as shown in table 1.

Turbulent flame speeds were obtained from Gülder and Peters correlations. The ratio of turbulent flame speed to laminar flame speed is plotted versus the turbulence intensity scaled by the laminar burning velocity. The results are presented in Fig. 8. Some differences exist in the predicted results. Peters correlation shows more scatter in the data than Gülder's. The scatter is mainly due to the changing composition of the fuel mixtures, while Gülder's correlation shows minimum scatter as if the variation in the mixture composition is not important. Also both correlations predict an increase in turbulent to laminar flame speed ratio with pressure. The trend by which the pressure increases is shown in the Fig.8.

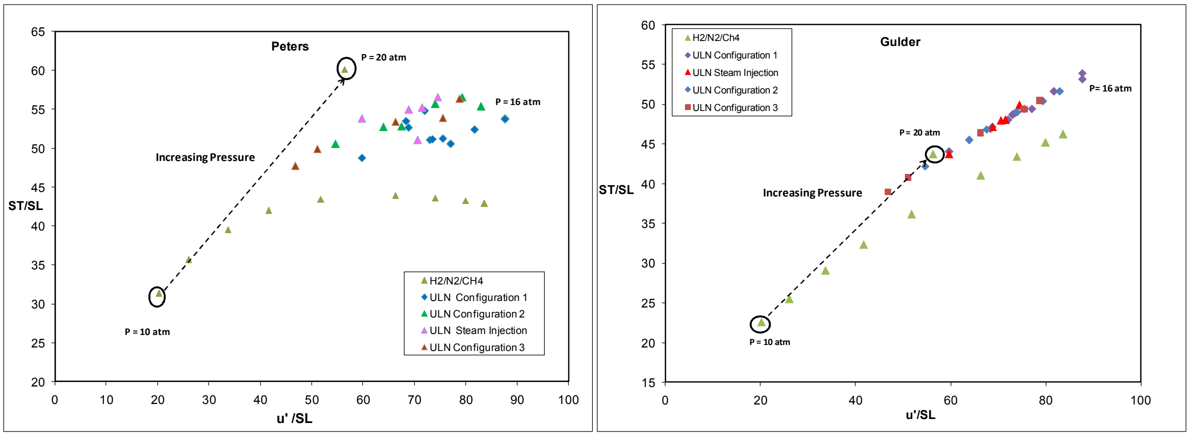

Fig. 8 Turbulent-laminar flame speed ratio versus turbulence intensity-laminar flame speed ratio. Predictions obtained from Peters and Gülder correlations.

To further examine the differences between Peters and Gülder correlations, a fuel mixture of 62% hydrogen and 38% methane and Air in which steam was injected was considered at a pressure of 16 atm, temperature of 696 K, and equivalence ratio of 0.5 and is presented in fig. 9. Both correlations predict an increase in turbulent flame speed with increasing intensity. At first, at very low intensities, the curves are identical, and then as the intensity increases gradually, the curves start to diverge and show the bending effect. Overall, there is a general agreement in the predicted results qualitatively.

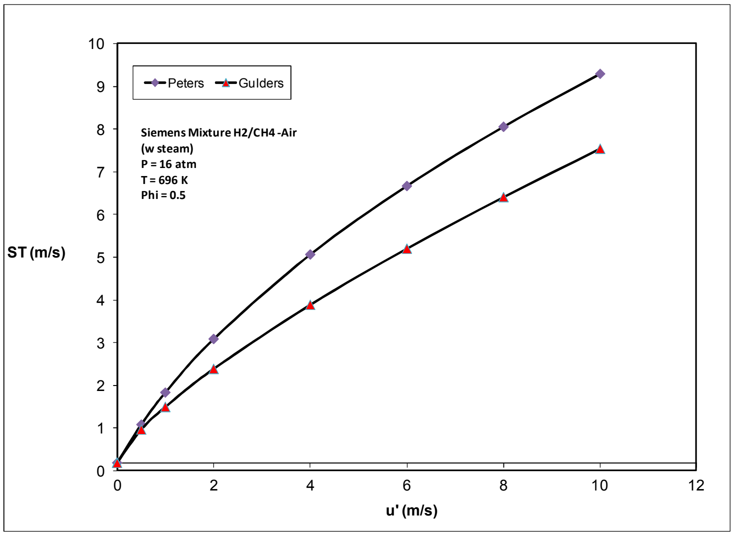

Fig. 9 Turbulent flame speed versus turbulence intensity predictions from Gülder and Peters correlations. Peter predicts slightly higher flame speeds that Gülder

Effect of hydrogen addition

The ratio of turbulent to laminar flame speed is plotted versus % hydrogen added to the fuel mixtures. Figure 10 shows that hydrogen addition has no effect on turbulent to laminar flame speed ratio for the ULN mixtures, while the effect is strong for the H2/N2/CH4 mixtures. The reason being is the Wobbe index of the mixtures which does not vary much for the ULN data compared to the H2/N2/CH4 data as is shown in Fig. 10.

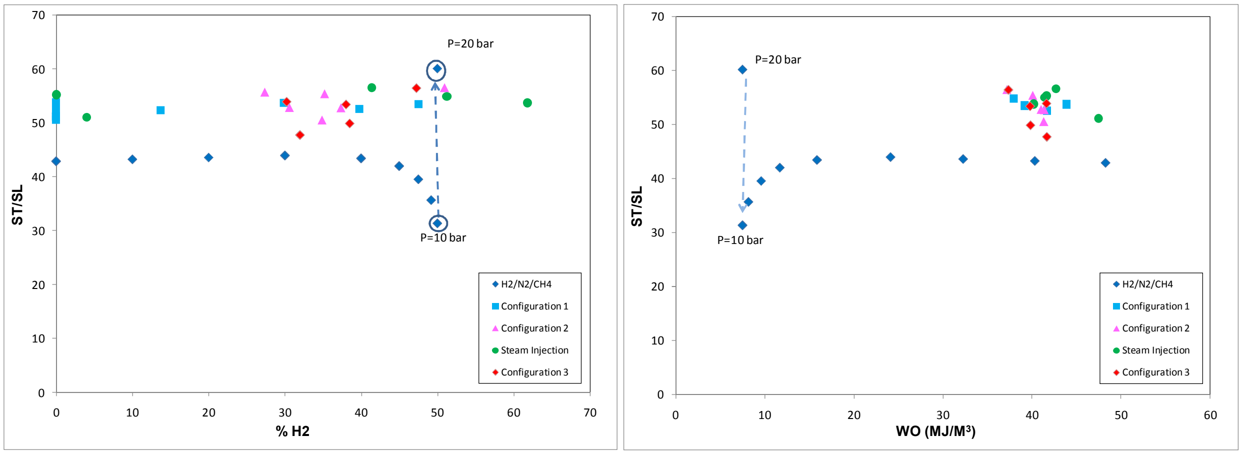

Fig. 10 Effect of % (volume) hydrogen on turbulent to laminar flame speed ratio. The ratio decreases with hydrogen for H2/N2/CH4 mixtures but shows no variation for the ULN data due to the small Wobbe range considered.

To further investigate the effect of hydrogen addition on turbulent flame speed, the H2/N2/CH4 mixtures were chosen for the purpose of comparison. The mixtures were prepared by gradually adding equal amounts of hydrogen and nitrogen and reducing methane. This produced a broad range of Wobbe values. The results are given in Fig. 11. As the turbulence intensity increases, the turbulent flame speed increases with increasing hydrogen almost linearly up to a turbulence intensity of ~2 m/s, then the shape of the curve starts to bend as the intensity is increased further. Eventually, at high intensities, the curve should plateaus and any hydrogen addition will cause a decrease in the turbulent flame speed (Kido H. N., 2002). The differences between the two correlations lie in the predicted turbulent flame speeds, where Peters predicts slightly higher values than Gülder, however, the trend and effects of hydrogen and turbulence intensity is the same. Hydrogen addition makes the fuel mixture more susceptible to flashback due to an increase in turbulent flame velocity that could exceed the flow velocity.

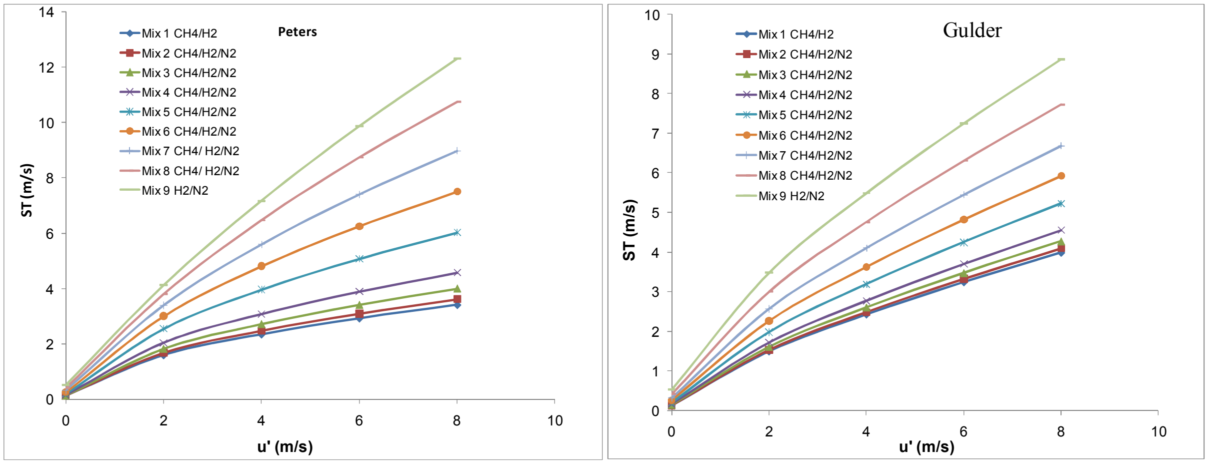

Fig. 11 Effect of hydrogen addition on turbulent flame speed. Turbulent flame speed increases with hydrogen addition due to the increase in laminar flame speed. Results are given for Peters and Gülder correlations

Effect of Pressure

Earlier, the effect of pressure on ST/SL was investigated and it was concluded that the turbulent to laminar flame speed ratio increases with pressure and turbulence intensity. However, it should not be assumed that an increase in ST/SL implies an increase in the turbulent flame speed as well. Figure 12 below shows the effect of pressure on turbulent flame speed. Initially, at zero turbulence intensity, the flame speed is laminar and it is higher at 10 atm than at 20 atm. As the intensity increases up to 2 m/s, the difference between the turbulent flame speeds is kept constant, then as the intensity increases further, the curves diverge gradually from each and the difference between the flame speeds is no longer constant. In addition, Gülder's correlation shows more divergence and bending compared to Peters. The turbulent flame speed is strongly dependant on the laminar flame speed. An increase in pressure causes the flame thickness to decrease and therefore the flame area, consequently, the laminar flame speed goes down. Therefore it can be concluded that the effect of pressure on turbulence flame speed is predetermined by its effect on laminar flame speed. The divergence in the predicted values reported below can be explained by the increasing turbulence intensity. One explanation is that pressure could have an indirect effect on turbulent flame speed through influencing the turbulence intensity, which then affects the turbulent flame speed by generating more wrinkles in the flame leading to an increase in the flame's area and therefore its flame speed. Unfortunately, very few literature results exist on this matter. Griebel et al investigated the effect of pressure on turbulent flame speed at an inlet temperature of 673 K, equivalence ratio of 0.5, and bulk velocity of 45 m/s. Pressure was increase from 1 to 10 bars, which caused the turbulent Reynolds number and the Karlovitz number to increase and the Damköhler to decrease. OH-PLIF measurements showed no significant influence of pressure on mean flame front position and concluded that turbulent flame speed is independent of pressure (Griebel P. s., 2003).

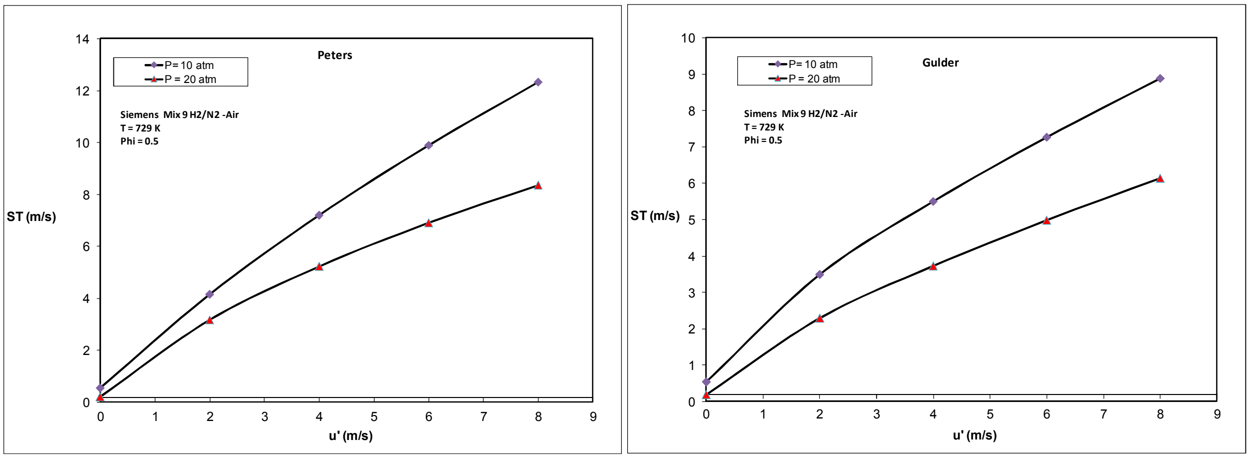

Fig. 12 Effect of Pressure on turbulent flame speed is predetermined by its effect on laminar flame speed. Results are shown for Peters and Gülder correlations.

Effect of preferential diffusion

The effect of fuel composition on flame speed can lead to wrinkles in the flame even in the absence of turbulence. This is explained by the "preferential diffusion" effect, by which the molecular diffusivity can change the local equivalence ratio causing a change in the mean value of the local burning velocity (Kido H. N., 2002). To explain further, in another study conducted by Kido et al. (Kido H. N., 2002) , hydrogen, methane, and propane mixtures were carefully chosen with the same laminar velocity (15 m/s) to investigate the influence of the kind of fuel and the equivalence ratio on the local flame properties. Turbulent flame speed of the fuel mixtures were measured at the same intensity. Results showed a divergence between the turbulent flame speeds with hydrogen having the highest speed and propane the lowest speed. These discrepancies are due to the differences in the thermal and mass diffusivities of the components of the fuel mixtures that cause the flame to spontaneously wrinkle even in the absence of turbulence. Preferential diffusion has been proven by kido and coworkers to affect not only the laminar flame speed but the turbulent flame speed as well. As an attempt to reproduce a plot similar to the one given by Kido and coworkers using Gülder and Peters correlations, two mixtures with different fuel compositions but having the same laminar flame speed (0.18 m/s) were selected. Some interesting results are presented in Fig. 13. At zero turbulence, the flame speed is totally laminar. Upon increasing the turbulence intensity, discrepancies between Peters and Gülder predictions appear. Gülder shows no variation in the turbulent flame speed with increasing intensity, while Peters exhibits the same effect seen by Kido and coworkers. Mixtures with different fuel compositions and the same laminar flame speed can have different turbulent velocities at the same intensity. Although it is not mentioned by Peter that his correlation accounts for preferential diffusion, there is a strong possibility that this behavior is due to this effect.

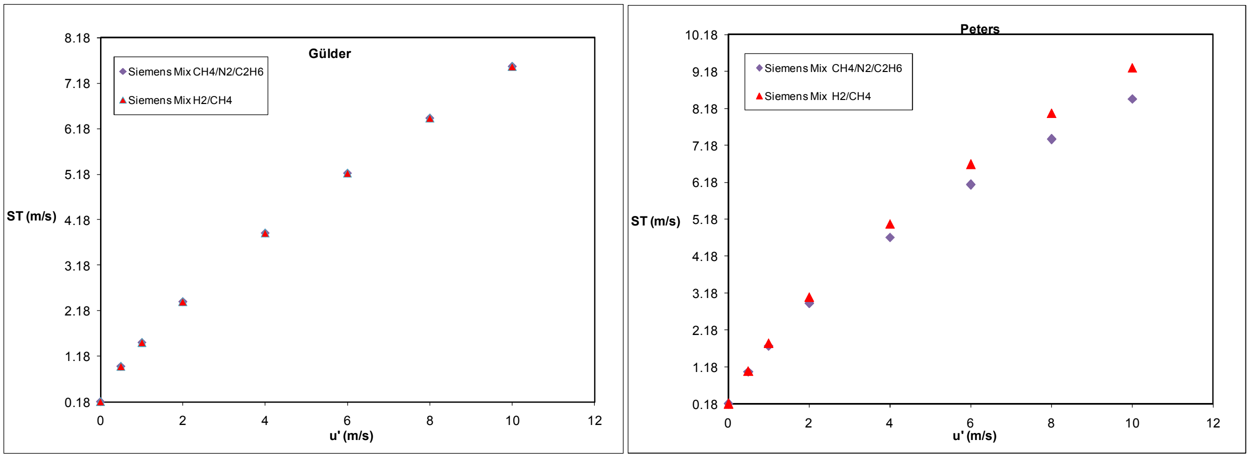

Fig. 13 Effect of preferential diffusion on turbulent flame speed. Peters correlations depicts this effect, while Gülder does not.

The comparisons presented above showed that both Gülder and Peters agree on the predicted turbulent flame speed results qualitatively and quantitatively to a certain degree. However, Contrarily to Gülder's correlation, Peters' was able to depict the preferential diffusion effect; therefore it was selected as the correlation of choice to correlate a flashback model. Figure 14 shows the calculated turbulent flame speeds scaled with the turbulence intensity (left plot) and with the flow velocity (right plot) plotted versus the Wobbe number. Both plots predict the same results. A reasonable flashback correlation is determined for the ULN data with the exception of one safe data point (blue diamond) that falls in the flashback region. However, the limit cannot be extrapolated to Wobbe values outside of the range 30-50 Mj/m^3.

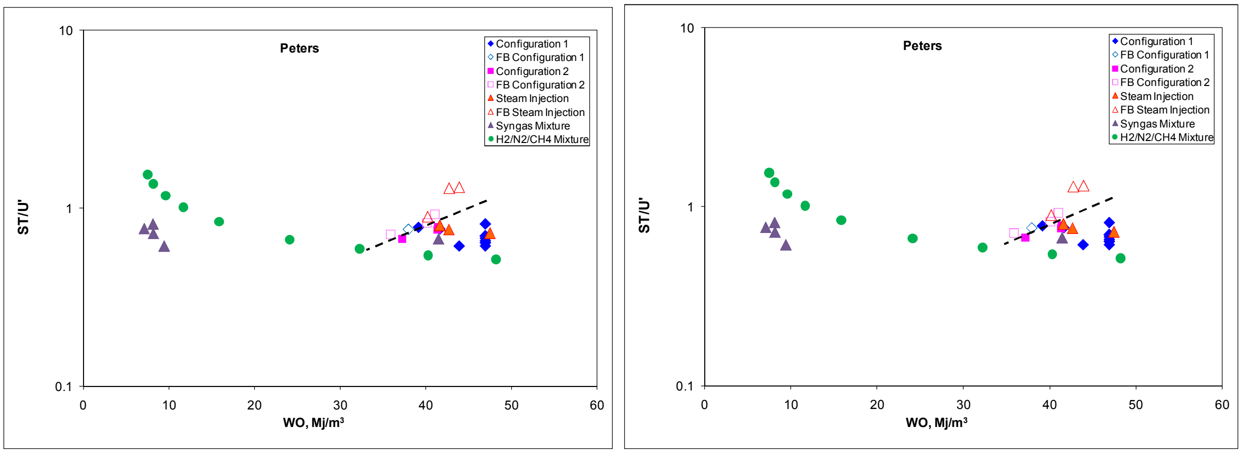

Fig. 14 Flashback model correlation with turbulent flame speed predicted from Peters correlation. The correlation is valid for the Wobbe range (30-50 Mj/m^3)

It is very important to choose the right parameters in order to determine an accurate correlation for flashback. The purpose behind correlating flashback with the turbulent flame speed is to be able to collapse the data into an almost constant value, no matter what the Wobbe value is. Although the ST/U'-Wo correlation was able to collapse the flashback limit given earlier in Fig. 4, into a one slope line, the ultimate goal is to find a correlation that is valid for a wider Wobbe range. In a blowoff study conducted by Noble and coworkers (Noble, 2006), the Damköhler parameter was chosen at first to correlate the blowoff data, but it was noticed that for high hydrogen concentration mixtures (>50%), the Damköhler was changing by 100 even though the equivalence ratio changed by 0.1 only. It was concluded that the change in the blowoff Da might be due to preferential diffusion effects such that the equivalence ratio can vary along the flame between high and low, and therefore the equivalence ratio should be corrected for. Kido and Nakahara (Kido H. a., 1998) proposed an expression for adjusting the equivalence ratio and is given by:

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

D_F and D_{OX} are the mass diffusivity of fuel and oxidizer respectively, and C is a constant equal to 0.3. The constant can be varied to find the best correlation. Noble and coworkers found that a constant value of 0.1 gave a nearly constant blowoff Da.

By the same mean, this approach could be applied to the flashback correlation. Mass diffusivities can be obtained from Chemkin and new flame speeds with the adjusted equivalence ratios should be recalculated.

III. Future Work

Future work will include considering the preferential diffusion effect in the parameters employed for the flashback correlation. One approach is to adjust for the equivalence ratio by using the expression proposed by Kido and Nakahara (Kido H. a., 1998). Laminar flame speed will be resimulated using the corrected equivalence ratio and a new Damköhler number should be obtained. A flashback correlation will be determined based on the corrected Damköhler values. Although Peters and Gülder correlations can predict turbulent flame speed with confidence to a certain degree, they were not validated against the type of mixtures studied herein. Semi-empirical correlations for hydrogen enriched natural gas mixtures exist, like that of Kido et al., (Kido H. N., 2002) but are not valid for gas turbine conditions. Therefore, turbulent flame speeds for hydrogen enriched natural gas and syngas mixtures will be measured experimentally at gas turbine conditions, mainly high pressures and high inlet temperatures. Once turbulent parameters, such as length and turbulence intensities are determined experimentally, a correlation for turbulent burning velocity should be developed. In addition to preferential diffusion effect, flame stretch is crucial to accurately predict the turbulent flame speed, notably the Markstein parameter which is required in flame front tracking methods such as the G-equation formulation of Peters (Chen J. H., 2000) (Chen J. a., 1998). The effect of pressure and hydrogen addition on turbulent flame behavior needs be reinvestigated. The purpose is to develop the best flashback prediction model for gas turbine engines.

IV. Conclusion

The impact of the fuel variability in composition on combustion performance has been reviewed and analyzed. Fundamental combustion properties, including heating values, laminar and turbulent flame speeds have been obtained in order to investigate flashback phenomena in ultra lean premixed combustion systems. First, Laminar flame speeds were simulated for recent test data and were formulated into in the Damköhler parameter using the test geometry. The results were presented in Damköhler-Wobbe plots and a flashback limit with two slopes was determined. In order to extrapolate the limit to lower Wobbe numbers, additional data from other tests were added to the Da-Wo plot, and it was concluded that the flashback limit given herein should be applied to the Wobbe range specified (30-50 Mj/m^3) and that additional limits are needed for lower Wobbe numbers. The effects of adiabatic flame temperature, hydrogen addition, and laminar flame speed were investigated in addition to the influence of steam addition on the mixture, which resulted in improving the flashback resistance.

Due to the turbulent conditions present in gas turbine combustion, turbulent length scales and intensities were determined and turbulent flame speeds were obtained from previously derived correlations of Peters and Gülder, valid for the thin reaction regime. Both correlations predicted turbulent flame speed values ~ 9 m/s at an intensity ~ 10 m/s. The effect of hydrogen addition and pressure on turbulent flame speed was examined. 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 not clear for turbulent flame speed. Pressure causes the flame thickness to become thin and therefore its area reduces leading to a decrease in the laminar flame speed. Until confirmatory high pressure experimental evidence is forthcoming, the effect of pressure on turbulent flame speed is unknown. It is important to note that the ratio of turbulent to laminar flame speed increases with pressure. One explanation is that the rate by which the laminar flame speed decreases is greater than the rate by which the turbulent flame speed decrease upon increasing the pressure resulting in an increase of their ratio. The preferential diffusion effect was also investigated, where two fuel mixtures with different compositions were carefully chosen to have the same laminar flame speed. At zero intensity, u'=0, the curves were converged at a laminar flame speed of 0.18 m/s, and upon increasing the intensity gradually, the curve showed a divergence for Peters correlation. Although this is similar to what Kido and coworkers observed, it cannot be concluded that this effect is due to preferential diffusion because it was not mentioned by Peters. An additional flashback limit was determined from the turbulent flame speed scaled by the turbulence intensity and the Wobbe number. It was again found that the limit is only valid for the Wobbe range (30-50 Mj/m^3).

The changes in the Damköhler values can be explained by the preferential diffusion effect. The mixtures are composed of different constituent whose diffusivities vary from component to component. Assuming an average equivalence ratio for all the constituent is not the best approach. The equivalence ratio can be corrected for by applying Kido's expression. This would at least result in a nearly constant Damköhler value which could render the flashback limit valid for all the Wobbe range. Although this approach has worked for blowoff correlation, it remains a hypothesis for flashback correlation. Further studies are needed to investigate this hypothesis.

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