ABSTRACT
The NOx formation within a practical lean premixed gas turbine combustor concept has been investigated. The effects of chemical kinetics and fuel/air mixing have been isolated, by adopting an approach, which combines high pressure combustion testing, CFD and chemical reactor modelling. Given the complexities of the underlying fluid dynamic and chemical processes and their interactions, consistency has been sought between experimental and numerical approaches, prior to drawing any conclusions.

Two variants of Siemens Industrial Turbomachinery’s dry low emissions combustor have been investigated, one exhibiting near-ideally premixed combustion over a wide range of combustor pressure drop. Perfectly Stirred Reactor analysis, utilising the GRI 3.0 NOx mechanism, shows that NOx formation is dominated by the N2O and Zeldovich routes, with the N2O route being the larger at flame temperatures below 1800-1900K, for systems operating at 14bars, 400°C inlet temperature and at residence times of interest. Other reactions involving H-N-O chemistry are also significant, however the C-H-N-O chemistry has a negligible impact.

INTRODUCTION
Guarantees of <25 ppmv NOx (@15% O2) emissions are now commonplace for land-based gas turbines operating with natural gas. Furthermore, there is an increasing trend towards yet lower emissions, for example, some US states are legislating <3ppmv NOx emission, which gives a design target of <2ppmv. Presently, such low emissions are commercially achieved with post gas turbine cleanup systems, with the associated increase in capital and operational cost. Such costs are proportionately large in the case of small industrial gas turbines and prohibit the degree to which low emission legislation can be set for such machines.

By way of introduction, this paper describes Siemens Industrial Turbomachinery’s (the company’s) dual fuel dry low emissions (DLE) combustor, which forms the focus of the present work. The combustor is applied across the company’s range of small industrial gas turbines, from the Typhoon at ca. 5MW to the Cyclone at 13.4MW, and which has now accumulated >3 million hours of experience. In gas operation, the newest machines, the Tempest and the Cyclone, are offered commercially for certain markets at <10ppm NOx (@15% O2). The company is committed to further emissions reduction whilst meeting all other specifications, such as required life, availability, robustness, operability, cost and time-to-market. These more stringent targets necessitate a greater understanding of the fundamental processes of turbulent fluid dynamics, chemistry, thermoacoustics and their complex interactions, as well as their impact on the combustor and related components.

In this paper, focus is confined to the analysis of NOx formation, in particular the identification of the NOx formation kinetics and the impact of fuel/air ratio inhomogeneity. High pressure combustion tests have been performed on two variants of the company’s DLE combustor, having different fuel/air mixing characteristics but both being capable <15ppm NOx at normal gas turbine operating conditions. Analysis has been performed through a combined use of experiment, CFD and chemical kinetic modelling. Given the complex turbulent swirling flow, the high degree of local strain-induced flame quenching, and the importance of NOx mechanisms other than...
the well documented Zeldovich route, consistency between the
numerical models and test data has been sought prior to
drawing conclusions about the NOx formation process.

In the next section the DLE system is described. Then the
nature of NOx formation within lean premixed systems is
investigated, by way of analysis of the chemical kinetics and
fuel/air mixing processes. The high pressure rig facility at the
company’s Lincoln site, which has been used to undertake the
testing, is then described. Two variants of the combustor have
been investigated. These are analysed in the subsequent section
by way of experimental and numerical approaches.

The CFD analysis, which has been used to investigate the
fuel/air mixing in the case of non-reacting flow, has been
performed using the commercial code CFX4, from ANSYS
CFX [1]. The chemical reactor modelling assumes a single
Perfectly Stirred Reactor (PSR) and utilises CHEMKIN III [2].

NOMENCLATURE

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>DLE</td>
<td>Dry Low Emissions</td>
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<tr>
<td>F</td>
<td>Mixture Fraction</td>
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<tr>
<td>FAR</td>
<td>Fuel/air ratio</td>
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<tr>
<td>G</td>
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<td>H\text{act}</td>
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<td>Probability Density Function</td>
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<tr>
<td>P(F)</td>
<td>PDF of F</td>
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<tr>
<td>PSR</td>
<td>Perfectly Stirred Reactor</td>
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<tr>
<td>R\text{0}</td>
<td>Universal Gas Constant</td>
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<tr>
<td>T\text{act}</td>
<td>Activation Temperature = H\text{act}/R\text{0}</td>
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<tr>
<td>T\text{flame}</td>
<td>Adiabatic Equilibrium primary zone temperature</td>
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<tr>
<td>\Delta P</td>
<td>Pressure drop</td>
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<td>\overline{\phi}</td>
<td>Average of \phi</td>
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<td>\phi'</td>
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THE DLE COMBUSTOR

The dual fuel DLE combustion technology is applied
across the company’s range of small industrial gas turbines
from the Typhoon at ca. 5MW to the Cyclone at 13.4MW [3-5].
In order to cover this power range, rather than having a single
combustor design and applying different numbers of
combustors to each engine type, the combustors have been
scaled (figure 1). The Typhoon, Tempest and Cyclone have 6
combustors per engine and the Tornado has 8.

The combustor consists of three main sections (figure 2): [i] the pilot body, which houses the pilot fuel galleries and
injectors for both gaseous and liquid fuel, [ii] The main burner,
which houses the main air swirler and main gas and liquid fuel
systems and [iii] the combustor, which includes a narrow inlet
duct, called the prechamber. The combustor is of a double skin
construction and is cooled through impingement cooling. The
cooling air is then exhausted into the combustor through
dilution holes downstream of the main reaction zone. A
transition duct, located downstream of the combustor, conditions
the flow from the circular combustor exit to a sector of the
turbine entry annulus.

Figure 1: The Dry Low Emission combustor family.

Figure 2: The Dry Low Emission combustor construction.

Figure 3 shows a schematic of the combustion concept.
The main combustion air enters through a single radial swirler
at the head of the combustor. The flow then turns through a
right angle into the prechamber followed by a sudden
expansion into the combustion chamber. The swirl number is
sufficiently high to induce a vortex breakdown reverse flow
zone along the axis. This is termed the internal reverse flow
zone. In the concept, this reverse flow zone remains attached to
the back surface of the combustor, thereby establishing a firm
aerodynamic base for flame stabilisation. In the wake of the
sudden expansion, an external reverse flow zone is established.
The flame is stabilised in the shear layers around the internal
and external reverse flow zones.
Figure 3: Schematic of the Dry Low Emission combustor concept.

The fuel, both gas and liquid, is introduced, in two stages: the main, which results in a high degree of premixedness and hence low NO\textsubscript{x} emissions, and the pilot, which is steadily increased as the load demand decreases in order to ensure flame stability. The pilot is arranged, such that as the pilot fuel split increases, the fuel is biased towards the axis of the combustor.

**NO\textsubscript{x} FORMATION WITHIN LEAN PREMIXED COMBUSTORS**

In this section, background related to the formation of NO\textsubscript{x} in lean premixed combustion is given in order to aid the analysis of the high pressure combustion tests reported in the following sections. The chemistry of NO\textsubscript{x} formation is discussed briefly, however attention will be focused on the effect of inhomogeneity of the FAR. This is of significance, since practical lean premixed systems often do not operate under perfectly premixed conditions.

The main NO\textsubscript{x} formation mechanisms within combustion systems are the Zeldovich, Prompt and Nitrous oxide (N\textsubscript{2}O) routes. Fuel NO\textsubscript{x} may also be generated, when Nitrogen exists within the hydrocarbon fuel, in the form of e.g. ammonia. In lean premixed systems the N\textsubscript{2}O route is thought to be significant [6], whilst in rich combustion, given high concentrations of hydrocarbon radicals, the prompt NO\textsubscript{x} mechanism is significant.

The analysis of the NO\textsubscript{x} chemistry at the conditions of interest (14 Bars and 400°C inlet temperature) has been investigated by way of Perfectly Stirred Reactor (PSR) analyses, for which an extended version of the GRI 3.0 mechanism has been used. The mechanism has been extended to include species upto C\textsubscript{5} in order to address the natural gas composition used in the high pressure tests reported herein. This modification is of little importance to the chemical kinetic results presented, and has been implemented in order to model the stoichiometry and enthalpy correctly.

Figure 4: NO\textsubscript{x} and reactor temperature as a function of PSR residence time, for an equivalence ratio of 0.6, 14Bara and 400°C inlet temperature. NO\textsubscript{x} levels are presented for computations using the full GRI 3.0 NO\textsubscript{x} mechanism and where Zeldovich NO\textsubscript{x} has been neglected.

Figure 4 shows results of PSR calculations where the NO\textsubscript{x} emissions and reactor temperatures are plotted against reactor residence time for a constant equivalence ratio of 0.6. At the conditions investigated, the reactor temperature reaches the adiabatic equilibrium temperature, for residence times greater than approx. 1msec. Two curves are shown for NO\textsubscript{x}. One utilises the full GRI 3.0 NO\textsubscript{x} mechanism, whilst the other has the three reactions of the extended Zeldovich mechanism removed, and thus gives an indication of the importance of Zeldovich NO\textsubscript{x}. At 1msec, the Zeldovich NO\textsubscript{x} contribution is seen to be approximately 42%. This increases as a longer residence time is chosen for the reactor, reaching approx. 70% at 10msec. This is due to the relatively slow rate of the rate-limiting Zeldovich NO\textsubscript{x} reaction (R1).

Figure 5: Arrhenius-type plot of NO\textsubscript{x} levels derived from PSR computations, utilising full GRI 3.0 NO\textsubscript{x} mechanism, Zeldovich reactions, Zeldovich + N\textsubscript{2}O reactions, and full mechanism minus reactions involving C & N. Reactor residence time = 1 msec, unless otherwise stated. P=14Bara, 400°C inlet temperature.

Figure 5 shows the results of the PSR computations on an Arrhenius-type plot. The horizontal axis plots the reciprocal of the adiabatic equilibrium temperature, and thus the data are produced from a number of PSR calculations operating at
different equivalence ratios. The residence time for the reactors is kept constant. Four sets of data are presented for a 1msec residence time, for which different NO\textsubscript{x} reactions are activated. One shows the results of the full NO\textsubscript{x} mechanism, whilst the others show results using
- the extended Zeldovich reactions only
- the extended Zeldovich plus the N\textsubscript{2}O reactions
- all reactions bar those containing C & N species

The results show that Zeldovich NO\textsubscript{x} accounts for 15% and 40% of the total NO\textsubscript{x} at equilibrium flame temperatures of 1780K and 1950K respectively. If the N\textsubscript{2}O reactions are added, the percentage contribution is approximately 65% at 1780K and 1950K. The data for the case where all reactions containing C and N species are neglected, is seen to be very close to those resulting from the full mechanism. This shows that the difference in NO\textsubscript{x} between the full mechanism and the Zeldovich plus N\textsubscript{2}O routes is due mostly to additional H-N-O chemistry.

Figure 5 indicates the activation temperatures deduced from the slope of the lines, which give an indication of the temperature dependence of the NO\textsubscript{x} routes. In addition to the 1msec results, the figure also shows results for 5msec using the full NO\textsubscript{x} mechanism. For the longer residence time, as well as the NO\textsubscript{x} values increasing, the activation Temperature increases due to the increasing importance of Thermal NO\textsubscript{x}. Later, the high pressure test data will be plotted to determine the measured activation temperature. It should be noted that the activation temperatures, so deduced, are influenced by fuel/air ratio variations, which define the flame temperature.

For the investigation of fuel/air mixing quality on NO\textsubscript{x} formation, the following focuses on the two main Zeldovich reactions:

\[ O + N\textsubscript{2} \xleftrightarrow{K1} NO + N \] (R1)
\[ N + O\textsubscript{2} \xleftrightarrow{K2} NO + O \] (R2)

Assuming quasi-steady N concentration and sub-equilibrium NO, which are valid for many combustion circumstances, and noting that the first reaction is rate limiting, the NO formation rate is given by (See also [7]):

\[ \frac{d[NO]}{dt} = 2k_1[N_2][O] \] (1)

Where \( k_1 \) is the forward rate constant for reaction R1 and, using figures from [8], is given by:

\[ k_1 = 1.8 \times 10^{8} \exp\left(-\frac{38370}{T}\right) \text{ (m}^3/\text{mol.s)} \] (2)

The activation temperature for the reaction is seen to be 38,370K. This is a measure of the activation energy for reaction R1, and therefore does not consider the energy required to produce O from O\textsubscript{2}.

If the reaction

\[ 2O \xleftrightarrow{R3} O\textsubscript{2} \]

is assumed to be in equilibrium then the O radical concentration is given by (see [9])

\[ [O] = 3.97 \times 10^2 T^{-0.5} [O\textsubscript{2}]^{0.5} \exp\left(-\frac{31090}{T}\right) \] (3)

(mol/m\textsuperscript{3})

The effective activation energy of Zeldovich NO formation is therefore the sum of the activation energies from equations (2) and (3), giving an activation temperature of 69,460K.

In order to investigate the impact of unmixedness on NO\textsubscript{x} formation, the NO formation rate given by eqn. (1), has been deduced for different values of mixture fraction, assuming adiabatic thermodynamic equilibrium for the main combustion process. The formation rate is shown in figure 6.

![Figure 6: Zeldovich NO\textsubscript{x} formation rate (eqn.1) and sample PDFs of F plotted against F. G=0.001. P=14Bara, 400°C inlet temperature.](image)

Also shown are a series of PDFs of mixture fraction for a range of mean mixture fractions, in the lean region, and a constant value of G, which is a normalised variance, defined by:

\[ G = \frac{F^{1/2}}{F(1-F)} \] (4)

i.e. the variance divided by its maximum possible value. The PDFs are generated from the mean and variance, assuming a beta function form. The mean NO\textsubscript{x} formation rate has then been deduced for a range of means and variances of F from:

\[ \frac{d[NO]}{dt} = \int_0^1 \frac{d[NO]}{dF}P(F)dF \] (5)
The results of this analysis are plotted in figure 7 by way of an Arrhenius plot, where best-fit lines are plotted for a number of different values of \( G \), one being \( G = 0 \), representing perfect premixing. The results are of the natural log of the mean NO formation rate against the reciprocal of the adiabatic equilibrium temperature calculated at the mean value of mixture fraction.

![Figure 7: Arrhenius plot produced from Zeldovich mechanism (reactions R1 and R2) for different values of G.](image)

For the lean mixtures in question, as the value of \( G \) decreases, the NO formation rate decreases and the apparent activation temperature increases. For the case of ideal premixing (\( G = 0 \)), the activation temperature is close to the value deduced from eqns. 2 and 3. It is thus seen that the impact of unmixedness in lean systems, is to reduce the apparent activation temperature of the NO formation, as well as increasing the mean NO production rate.

### HIGH PRESSURE COMBUSTION TEST FACILITY

The company’s Lincoln site has two high pressure combustor test cells which are supplied with air from a five stage centrifugal compressor driven by an TB5000 3.5 MW gas turbine. The compressed air is heated by a gas-fired heat exchanger which is downstream of the air metering. The system is capable of delivering 4.6 kg/s of air at up to 18.9 bar and 500°C.

Each test cell houses two air supply legs to which can be connected a test rig assembly. A single combustor with can and transition-duct is mounted within the rig casing. The combustor exhausts to a water-cooled section of pipework which houses the hot pressurised-water-cooled bulk gas sampling probe of the EPA cruciform type. The downstream pipework terminates at a rig pressurising valve which, in conjunction with a rig inlet valve, regulates the pressure and mass-flow of the combustor inlet air.

The rig data logging system is linked to a semi-automated gas-analysis system to allow on-line monitoring of the emission characteristics. Regularly updated fuel files are read in from a dedicated Gas Chromatograph for accurate calculation of equilibrium flame temperature based on pre-test measurements of component effective flow area. The flame temperature is based on the deduced air flow through the swirler. The wall pressure-drop is measured, and overall flow area checked and monitored, using surface pressure-tappings in the rig headplate and downstream sections of the can.

In one of the configurations tested, confirmation of flame temperature has been obtained by post-processing of species data from sample gas drawn from the centre of the combustion zone through a very small, choked, wall drilling. Switching from bulk gas sampling to local gas sampling is performed manually by the rig operator.

### THE ANALYSIS OF NOX FORMATION WITHIN THE DLE COMBUSTOR

The NO\(_x\) formation within the DLE combustor is investigated in this section, by combining information obtained from CFD, PSR computations and high pressure combustion tests. Given the complexities of the fluid dynamics and combustion within lean highly-swirled combustors, consistency between numerical and experimental data is sought wherever possible. To aid the analysis two variants of the combustor have been studied which exhibit different aerodynamic and fuel distribution characteristics, but have been designed to have the same effective areas. These are termed Variant A, which is the design currently used in the 4.9MW Typhoon Gas Turbine and the second, termed Variant B, is a modification that has been developed within an in-house low NO\(_x\) technology programme.

The investigation is performed at 14 bara and 400°C inlet temperature, which is close to full load conditions for the Typhoon engine, and focuses on zero pilot operation (i.e. all the fuel being supplied through the main fuel ports).

![Image of Combustor](image)

Figure 8: Predicted fuel distribution at the exit of the swirler channels

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CFD results of fuel/air mixing are shown in figures 8 and 9. The figures each contain an insert, in the form of the schematic introduced in figure 3, which indicate the planes at which the CFD results are plotted.

Figure 8 shows CFD results of the fuel distribution and the secondary flow pattern at the exit of the swirler. The fuel distribution is very different in the two variants and results from the different secondary flow patterns, which have resulted through modifications to the swirler geometry. The most significant observation is that Variant B exhibits a rich region at the bottom of the swirler channel (i.e. back face of the combustor).

Figure 9 shows the computed fuel distribution, predicted by the present non-reacting CFD analysis, at a radial plane through the combustor front end. Variant A shows that the fuel distribution within the combustor is outboard-biased. In Variant B, though the flow exiting the swirler show rich regions at the swirler base and tip, these regions merge rapidly. This results in near ideal premixing, at the shear layer around the central and external recirculation zones, where the combustion is stabilised. This suggests that Variant B should yield lower NOx values than Variant A.

In an effort to part-validate the CFD analysis, a high pressure combustion test was conducted on Variant B, where a gas sample port was bored into the centre of the pilot body to allow gas extraction, and subsequent analysis, from the base of the central recirculation zone. The CFD analysis of Variant B indicates that the FAR at the centre of the pilot face is close to the average FAR in the primary zone (see figure 9). Figure 10 shows the mixture fraction, measured at the centre of the pilot face, plotted against the average primary zone mixture fraction, deduced from the fuel flow rate and the air flow through the swirler. Points are plotted for zero pilot and finite amounts of pilot gas. All the zero pilot points indicate that the mixture fraction at the centre of the pilot face is indeed close to the average primary zone mixture fraction, which is in agreement with the CFD analysis. The points for finite amounts of pilot gas show the mixture fraction at the centre of the pilot face to be richer than the average primary zone mixture fraction, which is expected given that the pilot gas is arranged to enrich the central recirculation zone to aid low load stability.

Figure 11 shows the NOx emission plotted against flame temperature measured in the high pressure combustion tests. Several curves are plotted, each for a different combustor pressure drop, which is controlled by altering the mass flow rate through the combustor. The Variant A results show that as the combustor pressure drop increases, the NOx emission decreases. The Variant B results do not indicate any pressure drop dependence, even for a 2.2 fold increase in pressure drop (i.e. ca. 50% increase in mass flow rate). By comparing the Variant A and B results, it can be seen that Variant A only approaches the Variant B results for the highest pressure drop tested (4.4%).
Figure 12 shows Arrhenius-type plots of the NO\textsubscript{x} data, where the natural log of the NO\textsubscript{x} emission is plotted against the reciprocal of $T_{\text{flame}}$. The Variant A data shows that as the pressure drop increases, the gradient of the lines and hence, the apparent activation temperature, increases. The maximum apparent activation temperature is 34,300K. The figure also shows similar data for Variant B, where apparent activation temperatures between 33000K and 37,000K are observed.

It is to be noted that the Variant A results, for increasing pressure drop, are consistent in trend to the effect of increasing mixedness shown in figure 7. In the present DLE system, the fuel distribution is dominated by the air flow, e.g. the secondary flow induced in the swirler channel, rather than the momentum flux ratio between fuel and air. As the pressure drop, and hence mass flow rate is varied, therefore, the fuel distribution remains largely unaffected. This characteristic is also indicated through investigating the governing transport equations for the unreacting flow. At high Reynolds number, the integral turbulent length scale remains constant, being governed by the global dimension of the domain, and both the mean and fluctuating velocity scale linearly with the inlet velocity. The latter in turn is linearly related to the mass flow rate, given that the density is kept constant i.e. constant Pressure and preheat temperature. In this case, one observes that the balance equations for the mean and higher moments of mixture fraction yield the same scalar field, for a given overall AFR. Thus it is found, that at any point within the combustor, the PDF of mixture fraction is relatively independent of combustor pressure drop. The parameter that does change however, is the strain rate. The integral strain rate is proportional to the mean velocity (i.e. to $\Delta P^{1/2}$) and the Kolmogorov strain rate is proportional to the mean velocity to the power 3/2 (i.e. to $\Delta P^{3/4}$). As the pressure drop increases, the strain rate increases and hence the degree of local extinction in the flame zone will increase. As this occurs, the reaction zone will broaden and be shifted downstream, further away from the fuel injection ports.

In the case of Variant A, this shift moves the flame into regions where the mixing quality is higher, which, it is argued, leads to the NO\textsubscript{x} dependence upon $\Delta P$. The changing strain rate will also affect the Variant B flame in a similar manner, however there, the fuel distribution becomes near-uniform very rapidly, such that near-perfectly premixed circumstances arise even for the lowest $\Delta P$ tested.

The activation temperatures for the PSR utilising the full GRI 3.0 NO\textsubscript{x} mechanism for 1 and 5msec, shown in figure 5, are close to those observed for Variant B and the minimum NO\textsubscript{x} curve of Variant A. This gives credence to the suggestion that near-ideal premixing occurs in these cases. The activation energy is less than the values suggested for Zeldovich NO\textsubscript{x}, indicating the significance of alternative pathways.
The vertical axis of figure 12 plots the natural log of the NO_x emission rather than the emission divided by a suitable residence time. However, each line that is plotted is for a single mass flow rate through the combustor and hence the residence time can only be affected by the varying flame temperature. This however amounts to a 12-15% variation in residence time and therefore, though the deduced activation temperature would then be larger, the increase is relatively small. In terms of comparing the ∆P characteristics with one another, it could be argued that the change in mass flow rate and hence residence time should be considered. However, it is felt that such a simple view is not realistic. At the low values of NO_x considered (2 to 20ppm) a significant amount of NO_x is likely to be formed close to the main reaction zone, the volume of which increases with increasing ∆P, due to increased local extinction. Therefore, as ∆P increases, both the velocity through the reaction zone and the reaction zone volume increase. The balance between the slow post flame Zeldovich NO_x and faster chemistry NO_x formation paths are the focus of further work.

CONCLUSIONS

The NO_x emission from two variants of the company’s DLE combustion system have been investigated, by way of high pressure combustion testing, where the emissions have been mapped as a function of primary zone flame temperature and combustor pressure drop. The fuel/air mixing has been characterised using CFD and the NO_x chemistry analysed using chemical reactor modelling.

Given the complex fluid dynamic and chemical processes underlying the behaviour of highly-swirled lean premixed combustors, consistency has been sought between the experimental and numerical techniques, in order to give credence to the analysis.

The CFD analysis suggests that one of the variants has a combustion zone that operates at near ideally premixed conditions, a characteristic which has, in part, been verified through gas sampling in the primary zone. This combustor exhibited the lower NO_x against flame temperature characteristic which was independent of combustor pressure drop, over a range from 2 to 4.4%. The other variant, for which the fuel distribution is outboard-biased as indicated by CFD, showed a decreasing NO_x emission for increasing pressure drop. Pressure drop influences the combustion process through flame-zone straining. It is argued that pressure drop will only influence NO_x emission if any displacement or broadening of the flame zone, through strain-induced local flame quenching, shifts the mean reaction zone to regions of different fuel/air ratio.

The impact of unmixedness on NO_x emission has been investigated by way of Arrhenius-type plots, where it is shown that increasing unmixedness leads to a reduction in the apparent activation energy.

PSR analysis, utilising the NO_x mechanism of the GRI 3.0 reaction scheme, indicates an activation temperature close to the values obtained from the high pressure tests for the near-ideally premixed combustor. Investigation of the mechanism, shows that the NO_x emission is dominated by the Zeldovich and N_2O routes, with the N_2O route becoming the greater at temperatures below approx. 1800-1900K for residence times between 5 and 1msec. The kinetic model suggests that other NO_x forming reactions, involving H-N-O chemistry, are also significant, but reactions involving C-H-N-O chemistry are negligible.

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REFERENCES