STABILIZATION OF A DILUTED H₂ LIFTED JET FLAME: NUMERICAL STUDY AND CONTROL

CHRISTOPHE DUWIG
Research & Development Division
Haldor Topsøe A/S - DK- 2800 Lyngby
Tel:+45 4527 2252 – Email: chdu@topsoe.dk

ABSTRACT
The secondary reformer stage of an ammonia plant includes a syngas/air flame. Indeed, our current technology favours a collection of small high-speed air jet issuing into a hot low-heating value fuel co-flow. Such a combustion system involves several lifted flames and is a challenge for modelling activities. Because of the large size and high operating pressure, simulation is the only eligible avenue for understanding and optimizing secondary reformers. The present paper is well in line with this goal and uses a well-documented flame that emulates the secondary reformer jet flames. The simulation results are in excellent agreement with the available experimental data, indicating that the present Large Eddy Simulation (LES) based tool is accurate and captures the important features of the flame. Based on these results, the dynamics of the vortices are highlighted. Furthermore, the sensitivity of the flame to small perturbations at the inlet is presented with emphasis on the flame stabilization. Different strategies are followed trying to promote different azimuthal Fourier modes. It was found that high azimuthal Fourier modes are the most efficient for controlling the flame stabilization opening an avenue for passive vortex and flame control in secondary reformers.

KEY WORDS
Ammonia production - reforming – lifted flame – hydrogen combustion – vitiated gas combustion

1 Also with Div. Fluid Mechanics, Dept. Energy Sciences, Lund University, Lund, Sweden
INTRODUCTION

Syngas/air flame in ammonia technology
In many industrial applications, for example ammonia production, low heating value fuels (also referred to as syngas) are intermediates in hydrogen production. Figure 1 presents a layout of the conversion of natural gas, steam and air into ammonia. Firstly, the natural gas is cleaned and mixed with steam. In a second stage (referred to as reforming), the syngas is obtained by steam reforming, i.e. endothermic catalytic conversion of methane and water into hydrogen and carbon monoxide. Additional heat is given to the mixture by heating of the reactor tubes allowing the reaction to proceed. However, the steam reforming reaction is definitely not complete resulting in a hot mixture of methane, water, carbon monoxide/dioxide and hydrogen, so further treatment is needed before utilization. A secondary reforming operation is performed within the ammonia synthesis. Air is added to the syngas in appropriate proportions (we seek a stoichiometric mixture hydrogen/nitrogen ~3 in mol.). The oxygen will react further with methane, hydrogen and carbon monoxide increasing the mixture temperature and enabling reforming reactions to continue (i.e. converting the remaining methane). This step features a syngas/air flame. Figure 2 presents a ‘maintenance-free’ Topsøe designed nozzle-burner with a large number of small air nozzles (right-hand side of the picture) that inject the oxidant as a collection of small air jets (Vang-Christensen, 2001b). As a result, we have high-speed jet flames involving diluted reactants at relatively high temperature. A successful operation involves optimal fuel/air mixing and flame stability downstream of the nozzle. These aspects will be studied in the present paper.

Finally, the remaining carbon monoxide is converted to carbon dioxide (water-gas-shift) which is removed (CO₂ removal + methanation) together with the excess steam. The resulting mixture contains 25 mol% nitrogen and 75 mol% hydrogen which is appropriate for the ammonia synthesis.
Overview of vitiated lifted flame

The present study focuses on understanding of flame/turbulence interaction in a lifted jet flame corresponding to an idealized secondary reforming process with the aim of improving the flame stability. We target a syngas/air flame and decrease the heating value of the hydrogen by dilution with nitrogen (40 mol%). We also a pre-heat significantly the oxidant, i.e. use vitiated air at 1045K. A small nozzle is used ensuring a large strain rate when having a jet velocity above 100 m/s. It indeed emulates a reforming-like process, including realistic temperature levels, molar fraction of inert compounds and strain rates since these aspects contribute to the lifting of the flame above the nozzle exit. Consequently, it is believed that the stabilization mechanisms are very relevant to secondary reformer operation.

Despite more than 50 years of research in turbulent combustion, modelling even a single jet flame is a difficult topic which involves non-linear multi-scale phenomena. As a result, turbulent flames are complex and often difficult to stabilize in practice. Indeed, state-of-the-art techniques (numerical and experimental) are to be used to address the stabilization problem.

In order to have a flame, one also needs to have enough fuel, oxidant and heat (high enough temperature). If one of the ingredients is missing, the oxidation cannot proceed and there is a risk of flame blow-out. At high Reynolds numbers, the co-existence of these three factors depends highly on the turbulent micro-mixing. Consequently, the flame location is unsteady in nature and very sensitive to perturbations; (Poinsot and Veynante, 2001). Such an example is given by Cabra et al. (2002) for a non-premixed lifted jet flame where the flame starts at some 10 pipe-diameters downstream of the nozzle. However, the flame anchoring points move with time and are indeed very sensitive to external perturbations such as minor variations in the co-flow temperature. The high sensitivity of the flame stresses the importance and the need for a better understanding of the flame dynamics and stabilization.

In the present paper, we investigate a non-premixed lifted flame corresponding to the vitiated co-flow burner (VCB) experiment conducted by Cabra et al. (2002) emulating a secondary reformer jet flame. The flame is well documented thanks to advanced non-intrusive laser measurement techniques (Cabra et al., 2002) as well as numerical simulation (Duwig and Fuchs, 2007 and 2008). However, the unsteady features of the stabilization and underlying mechanisms have not been explored in detail, so far. Since we focus on the unsteady features of the turbulent flame, we use reacting Large Eddy Simulation (LES) to study the lift-off and stabilization of the VCB flame. Firstly, we present the LES governing equations. Secondly, the combustion model is described together with the chemistry tabulation technique. Thirdly, we
present the computational case and boundary conditions. In the result section, the numerical predictions are compared with the experimental data. The result section also discusses the influence of external forcing upon the flame and highlights the underlying mechanism of the flame stabilization.

GOVERNING EQUATIONS FOR TURBULENT FLOWS

Momentum equations and closure
The basic equations describing the motion of a fluid are the conservation of momentum, mass, species and energy (Poinsot and Veynante, 2001). The system of equations has to be closed with an equation of state. In LES, one applies a low-pass filter to the dependent variables so that the filtered governing equations only describe the larger turbulent fluctuations. They read:

\[
\frac{\partial \overline{\rho}}{\partial t} + \nabla \cdot \overline{\rho \mathbf{u}} = 0
\]

\[
\frac{\partial \overline{\rho \mathbf{u}}}{\partial t} + \nabla \cdot (\overline{\rho \mathbf{u} \mathbf{u}}) = -\nabla \overline{p} + \nabla \cdot \left( \overline{\rho \mathbf{u} \mathbf{u} \mathbf{u}} - \overline{\rho \mathbf{u} \mathbf{u}} + \mu \nabla \mathbf{u} \right)
\]

The filtering operator is linear and is assumed to be commutative with time and space derivatives. The filtering operation is not commutative with non-linear terms. Thus, the non-linear terms lead to expressions that cannot be expressed in terms of the filtered quantities. These terms are gathered on the right-hand side of the equations above and are collectively called the subgrid scale (SGS) term. We model the SGS term by a classic gradient expression with an effective ‘eddy’ viscosity \( \mu_\Delta \) based on the Filtered Structure Function Model (Ducros et al., 1996) so that:

\[
\mu_\Delta = C \Delta \sqrt{\left(F_2(\overline{\mathbf{u}})\right)}
\]

where \( F_2 \) denotes the structure function computed from the filtered, resolved flow field, \( C \) is a constant and \( HP \) is a high-pass filter.

Combustion closure
Incorporation of combustion chemistry into LES involves finding a suitable reaction mechanism and solving a reduced set of filtered species equations. Here, we follow the technique presented by (Duwig et al., 2006; Duwig and Fuchs, 2007 and 2008). For non-premixed flames, one conveniently introduces the mixture fraction \( Z \) (Poinsot and Veynante, 2001) to describe the fuel air mixing (\( Z = 1 \) in the fuel and \( Z = 0 \) in the oxidant). Considering fuel fluid parcel exiting the nozzle, a typical scenario is as follow:

- The fuel fluid parcel is convected and travels downstream.
- The fuel fluid parcel mixes with the hot oxidant. The fluid parcel composition changes as fuel and oxygen are diluted and the local temperature increases. \( Z \) decreases during the mixing process. No reactions occur at this stage.
- The fluid parcel composition and temperature are such that auto-ignition occurs.
- The combustion proceeds in the parcel. The flame may interact with neighbouring parcels.
- The parcel leaves the combustor.
One represents the scenario as an unsteady Perfectly Stirred Reactor (PSR) (Duwig et al., 2006; Duwig and Fuchs, 2008). The set of equations describing the idealized process are:

\[
\begin{align*}
\frac{dY_i}{dt} &= \dot{w}_i, \quad i = 1, \ldots, N, \\
\rho \frac{dT}{dt} &= \dot{w}_T
\end{align*}
\]  

(4)

The initial conditions for the N species and temperature are:

\[
X(t=0) = \left[ \begin{array}{c} Y_i \\ T \end{array} \right] = Z \cdot X_{FUEL} + (1-Z) \cdot X_{OXIDANT}
\]

(5)

where the subscripts \textit{FUEL} and \textit{OXIDANT} denote the cold fuel and vitiated air, respectively. Equations (4) are ODEs (Ordinary Differential Equations) and are solved using chemical packages together with detailed reaction mechanisms. In the present work, a comprehensive \textit{H}_2/\textit{O}_2 mechanism is used (Li et al., 2004) together with the software CANTERA (2005). The solution to the ODEs is mapped in a \([Z, T]\) coordinate system providing a complete description of the chemical state (species mole fractions and reaction rates) as function of two scalars only (Duwig et al., 2006; Duwig and Fuchs, 2008).

As a consequence, only two scalar transport equations are needed. Firstly, the mixture fraction transport equation reads:

\[
\rho \partial_t \bar{Z} + \rho \bar{u} \cdot \nabla \bar{Z} = \nabla \cdot (\rho \bar{D}_\alpha \nabla \bar{Z}).
\]

(6)

Secondly, the corresponding filtered temperature equation is:

\[
\rho \partial_t \bar{T} + \rho \bar{u} \cdot \nabla \bar{T} = \nabla \cdot (\rho \bar{D}_\tau \nabla \bar{T}) + \bar{\dot{w}}_T(Z,T)
\]

(7)

Among the different closure options (Poinsot and Veynante, 2001), we use a presumed filtered density function (FDF) approach so that the closure reads:

\[
\bar{\dot{w}}_T(Z,T) = \int \int \hat{\dot{w}}_T(Z,T) \cdot P(\bar{Z}, \bar{T}, Z, T, \sigma_Z, \sigma_T) dZdT
\]

(8)

where \(P\) is the FDF taken to be a top-hat function and the local SGS variances (\(\sigma_Z\) and \(\sigma_T\)) are computed analytically (Pierce and Moin, 1998). Note that the modelling of the FDF was discussed by Duwig and Fuchs (2008) and it was found that it does not significantly affect the LES results which supports the choice of simple closures as done in the present work. The reaction rate \(\dot{w}_T(Z,T)\) is obtained from the tabulation of the solution of Equation (4).

**COMPUTATIONAL TOOL AND CASE DESCRIPTION**

**LES code**

We use a high-order finite difference code that solves a low-Mach number formulation of the Navier-Stokes equations on Cartesian grids (Gullbrand et al., 2001). The spatial discretization is done using a fourth-order centred scheme except for the convective terms in Equations (6-7) that are treated using fifth-order Weighted Essentially Non Oscillatory scheme (Jiang and Shu, 1996) that ensures stability and high-order accuracy. A second order-finite difference scheme is used for time discretization; the time integration is done implicitly. Locally refined grids are employed in regions with large gradients. Multi-grid iterations are used to solve the implicit
parts of the system. More details can be found in Gullbrand et al. (2001). The use of Cartesian finite difference techniques provides fast and accurate results. These advantages make the present approach suitable for LES of turbulent flows e.g. (Duwig and Fuchs, 2007 and 2008).

**Geometry and computational grid**

The combustor consists of a high-speed fuel jet (of diameter \( d = 0.00457 \) m) surrounded by a low velocity vitiated co-flow, i.e. a hot oxidant (Cabra et al., 2002). The diameter of the co-flow is 0.21 m so that interaction with the surrounding air can be neglected (Cabra et al., 2002). The operating conditions as well as the molar fractions of the fuel and oxidizer are summarized in Table 1.

The computational domain is a \( 22d \times 11d \times 11d \) box starting at the exit of the fuel nozzle. The coordinate system consists 3 dimensions: \( X = (x, y, z) = (x, r, \theta) \) with \( x \) being the streamwise direction. The origin of the coordinate system is taken at the centre of the fuel nozzle. Since the mean flow field is axi-symmetric, it is sometimes convenient to replace the \( y \) and \( z \) directions with the radius \( r \) and the azimuthal coordinate \( \theta \). The computational grid contains \( \sim 2 \times 10^6 \) mesh-points with \( \sim 20 \) cells across the fuel nozzle. The resolution is adequate for studying the large scales in this type of problem as shown by Duwig and Fuchs (2008).

The time step is set by ensuring that the Courant number does not exceed 0.3. The following results are normalized by the fuel jet bulk velocity \( U_0 = 107 \) m/s and the fuel pipe diameter \( d \) with a corresponding time unit \( \tau = d/U_0 = 4.3 \times 10^{-5} \) s.

The vortex core has been visualized using a criteria based on the second largest eigenvalue of the second invariant of the velocity derivative tensor proposed by Jeong and Hussain (1995) (the so-called \( \lambda_2 \) technique). In the following figures, the vortex core corresponds to a region where the eigenvalue \( \lambda_2 \) is negative.

Since the fuel and oxidant have different temperatures, it is convenient to introduce the *frozen* temperature \( T_F \) and *excess* temperature \( T_E \). The frozen temperature describes a pure mixing state where fuel and oxidant are mixed without reactions. Accordingly, we have \( T_E = T - T_F \) so that the excess temperature is non-zero only when burnt gases are present, i.e. it marks the flame front.

### Table 1: Boundary conditions for the H\(_2\)/N\(_2\) flame including species molar factions (Cabra et al., 2002).

<table>
<thead>
<tr>
<th></th>
<th>( U [\text{m/s}] )</th>
<th>( T [\text{K}] )</th>
<th>( \text{H}_2 )</th>
<th>( \text{H}_2\text{O} )</th>
<th>( \text{N}_2 )</th>
<th>( \text{O}_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (jet)</td>
<td>107.0</td>
<td>305</td>
<td>0.25</td>
<td>0.00</td>
<td>0.75</td>
<td>0.00</td>
</tr>
<tr>
<td>Oxidant (co-flow)</td>
<td>3.5</td>
<td>1045</td>
<td>0.00</td>
<td>0.10</td>
<td>0.75</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Boundary conditions**

The boundary conditions are essential for all computational results and for LES in particular. Ideally, one would set the boundary conditions far enough from the region of interest trying to minimize their influence. However, increasing the domain size without reducing the resolution increases the computational cost dramatically. Additionally, in many experimental data, the inlet conditions are not fully developed or ideal. Actually, it has been noted that small
variations in inflow conditions have significant impact upon the results, e.g. (George and Davidsson, 2004).

These points have two major implications. Firstly, small amplitude (but well chosen) actuation enables the control of the coherent structure development in the jet shear-layer (hence, mixing and flame stabilization). This is exemplified by DaSilva and Métais (2002) and will be developed in the result section. Secondly, an exact reconstruction of the inflow boundary is not feasible. Instead, one should find a compromise so that the modelling of the inflow boundary ensures a reasonable approximation of the experimental set-up. In the present case, we start the LES computation at the end of the fuel pipe. For any velocity component, \( u \), the inflow boundary is obtained as a weighted average of the jet and the co-flow so that:

\[
u(x = 0, r, \theta, t) = (1 - \gamma)u_{\text{JET}}(r, \theta, t) + \gamma u_{\text{COFLOW}}\]

with

\[
\gamma = 0.5 + 0.5 \cdot \tanh \left( \frac{\gamma}{\sqrt{\delta}} \cdot \left( \frac{r}{d} - \frac{r_{t}}{\delta} \right) \right)
\]

The thickness \( \delta \) is taken to be \( d/20 \) which is commonly used for LES of turbulent jet e.g. (DaSilva and Métais, 2002). One may, then, approximate the turbulent jet flow using a well-defined (mean) velocity profile and adding artificially generated turbulent fluctuations. We consider the decomposition using the time averaging operator \(<,>\):

\[
u_{\text{JET}}(X, t) = A(t) < u > (X) + u'(X) \cdot F(t)
\]

Here we set \(<u>(X)\) and \(u'(X)\) in order to recover the mean velocity and fluctuation profile of a fully developed pipe flow. \( A(t) \) represents the profile modification or excitation as listed in Table 2. It also requires the function \( F(t) \) providing a seemingly turbulent fluctuation. We used a digital filter-based technique (Klein et al., 2003) where the fluctuations are computed to mimic a given Reynolds stress tensor (from a pipe flow).

At the outlet, all variables are assumed to have zero gradient.

Table 2 summarizes the different inflow variations (temporal and spatial) tested presently. The base case corresponds to the experiments by Cabra et al. (2002) and will be used for a brief comparison with the experimental data. Further, we tested an axi-symmetric forcing (jet mass flow harmonic modulation), an asymmetric forcing (referred to as VariFlap) and a steady perturbation of the velocity (Star). The perturbation amplitudes were chosen to be 5% while the excitation frequency \( f \) was set so that \( St_p = f \cdot \tau = 0.4 \) (frequency of the preferred mode) as recommended by DaSilva and Métais (2002). Here, the axi-symmetric corresponds to an azimuthal Fourier mode \( m = 0 \). The VariFlap corresponds to an azimuthal Fourier mode \( m = 1 \). Finally, the Star is a perturbation of azimuthal Fourier mode \( m = 5 \).

When the axi-symmetric and VariFlap excitations are applied, the turbulent fluctuation amplitude \( u'(X) \) is reduced to keep the inflow turbulent kinetic energy constant.

<table>
<thead>
<tr>
<th>Case</th>
<th>( A(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not excited - base</td>
<td>1</td>
</tr>
<tr>
<td>Axi-symmetric</td>
<td>1+0.05\sqrt{2}\cos(2\pi St_p t/\tau)</td>
</tr>
<tr>
<td>VariFlap</td>
<td>1+0.05\sqrt{2}\cos(2\pi St_p t/\tau)+0.05\sqrt{2}\cos(\pi St_p t/\tau) \cdot (2y/d)</td>
</tr>
<tr>
<td>Star</td>
<td>1+0.2 \cdot \cos(5\theta) \cdot (2r/d)</td>
</tr>
</tbody>
</table>
RESULTS

Base case

Figure 1 shows the instantaneous temperature field as predicted by the LES computation. The flame consists of a cold jet surrounded by hot gases. The flame is irregular with steep gradients. Close to the fuel nozzle, the jet is weakly wrinkled. Further downstream, the jet pattern changes, exhibiting larger wrinkles. Downstream of the lift-off height, the shape of the jet is somehow spiral-shaped with turbulent structures of the order of the jet diameter. High temperatures (i.e. above the frozen temperature) are seen relatively far downstream of the fuel nozzle exit indicating that the flame is lifted. Figure 3 also shows that the flame is located on the lean side of the jet and not on the stoichiometric line. This behaviour is well in line with previous findings; see (Duwig and Fuchs, 2008).

Figure 3: 2D cut of the instantaneous temperature [K] field (right) and OH molar faction. The stoichiometric line ($Z_{ST} = 0.47$) is shown as a dashed line. The jet flame flows from left to right.

Figure 4 plots the mean temperature field together with experimental data. Here, we follow Duwig and Fuchs (2008) analysis to compare the two data sets and use a reduced coordinate system of streamwise component ($x-x_{IG})/d$. Following Cabra et al. (2002), the lift-off height $x_{IG}$ is defined as $<T(r/d = 1.53,x_{IG})> = 1200K$ where the operator $<>$ indicates time averaging. The two data sets agree very well with the differences below the experimental uncertainty. Similar agreement regarding OH molar faction, mixture fraction and temperature was reported previously (Szasz et al., 2008; Duwig and Fuchs, 2008) and is not repeated here. As a consequence, the present simulation captures the flame and flame dynamics accurately and is a suitable base for the study of the sensitivity of the flame to small modifications of the inflow conditions.

Figure 4: Mean temperature along different radial lines from LES (line) and experiments from Cabra and Dibble (2002) (symbols). Two coflow temperatures ($T_c$) were used in the simulations.
Figure 5 is a snapshot of the jet core and flame location (iso-levels $T = 400K$ and $T_E = 100K$, respectively). One clearly sees on this snapshot that the vortex rings develop at the base of the jet core i.e. downstream of the nozzle. They are axi-symmetric and extend down to $x/d \sim 3$. Further downstream, the relatively well ordered rings bend and might pair up. As a consequence, the jet core ends with a wrinkle tip. The tip of the core is engulfed around helical vortex tubes. In between two helices, short, streamwise vorticity tubes are seen. In other words, vorticity is concentrated into randomly distributed tubes that are aligned with the axis (referred to as braids). Indeed the breakdown of the rings into helices and braids also affect the turbulent scales distribution by promoting small-scale mixing. Small-scale mixing efficiently mixes fuel and oxidant as already reported by Liepmann and Gharib (1992) and enables chemical reactions. As a consequence of this scenario, the flame stabilizes a few pipe-diameters downstream of the nozzle.

It is worth noting that the intermittent occurrence of helices and streamwise vorticity is responsible for the unsteady motion of the leading edge of the flame reported by Duwig and Fuchs (2007) and also the particular noise generated by this flame (Szasz et al., 2008).

Effect of inflow modification upon the vortex dynamics

Figure 6 shows the flame location (OH field) and vortex tubes in the axisymmetric pulsed case. A distorted vortex ring is seen at $x/d \sim 2$ resulting from a combination of the excitation and the turbulent inflow fluctuations. At $x/d \sim 7$, combustion starts with high an OH concentration and the small branches of the flame scattered azimuthally. We note that the branches are $\sim 6$ and that the vortex ring breaks upstream from the flame, giving raise to small vortex tubes at $x/d \sim 5$. The mechanism is similar compared to the non-excited case but the ring vortices are breaking down faster.
Figure 6: Axisymmetric case: 3D snapshot of the vortex tubes (iso-$\lambda_2$ surfaces) and axial cut of the OH mole fraction.

Figure 7 (left) shows the vortices and OH field when using the VariFlap excitation. Again, vortex tubes are seen close to the nozzle and get distorted as they reach $x/d \sim 3$. The breakdown into small-scale tubes $x/d \sim 5$ and enable fuel air mixing. Again, the flame is starting $x/d \sim 7$ (Figure 7 right). The vortex dynamics does not differ much qualitatively from the other cases. However, the jet core (Figure 7 right) is much shorter and significantly distorted by the VariFlap excitation. While the rings do not alter the axisymmetry of the jet core, the helical ($m = 1$) excitation breaks the symmetry. A seemingly spiral shape is already seen around $x/d = 3$ while the jet core was $\sim 3-4d$ longer in the two other cases.

Figure 7: Variflap case. Left: 3D snapshot of the vortex tubes (iso-$\lambda_2$ surfaces) and axial cut of the OH mole fraction ($X_{OH}$). Right: longitudinal cut of the temperature field [K] and $X_{OH} = 0.001$-isoline.

Figure 8 shows a snapshot of the flame in the ‘star’ case. The vortex rings are not visible close to the nozzle and small vortex tubes (often aligned with the x direction) are dominant almost everywhere. As a result, the flame is attached to the nozzle despite the high speed of the jet. The jet core extends in the flame down to $x/d > 10$. The helical mode is also seen, as previously, but less pronounced. Indeed for $x/d > 15$, pockets of unburnt (indeed unmixed) fuel are still
visible along the centreline while in the other cases, burnt hot gases were dominant at this location. The early development of small vortex tubes enables rapid fuel/air micro-mixing and the flame can settle in the strong shear-layer. The heat release (i.e. thermal expansion) affects the vortex development and consequently the dynamics. As a result, the flame stabilization is improved by decreasing the fluctuation of the flame leading edge.

![Figure 8: Star case. Left: 3D snapshot of the vortex tubes (iso-λ_2 surfaces) and axial cut of the OH mole fraction. Right: longitudinal cut of the temperature field [K] and X_{OH} = 0.001-isoline](image)

**CONCLUSION**

Large Eddy Simulation of a lifted turbulent flame was performed using a two-scalar approach accounting for complex chemistry effects. The results were shown to be well in line with the experimental data with discrepancies below the experimental uncertainty. Further, the LES tool analyzed the effect of the large-scale turbulent structures on the flame stabilization and listed the different modes, namely: rings, helices and braids. Among these structures, only the braids seem to provide the micro-mixing necessary for obtaining an ignitable mixture (hence stabilize the flame). Different excitations were used to separately promote each mode. As a result, it appears that:

1. The axi-symmetric excitation and vortex rings do not shorten the jet core or promote the flame, unless the vortex rings breakdown into braids.
2. The VariFlap excitation or helical mode strongly shortens the jet core but does not promote the flame. Again, only the helical mode may break into braids and enable the flame to settle.
3. The star profile promotes small-scale turbulent with a dramatic influence upon the flame that attaches to the nozzle. The appearance of helical modes is also delayed resulting in a longer jet core.

The significant sensitivity of the flame stabilization to minor modifications of the inflow enables the design of control strategies. In the present case, a steady azimuthal perturbation enables the control of the flame lift-off, i.e. maintain the flame close to the nozzle. Mechanical solutions to do so are already available and have been successfully applied to jet noise reduction (Callender et al., 2005). They could be advantageously adapted for passive control of jet flames.
ACKNOWLEDGMENTS

The author want to thank Dr. Markus Klein for kindly providing the code for generating the unsteady inflow conditions.

REFERENCES


GEORGE W. K., DAVIDSSON L., (2004), Role of initial conditions in establishing asymptotic flow behavior AIAA J., 42(3), 438-446


