Large Eddy Simulation and Experimental Study of Flashback and Blow-Off in a Lean Partially Premixed Swirled Burner

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Abstract

Lean Premixed Prevaporized (LPP) combustion is a widely used concept for reducing pollutant emissions in gas turbines. In LPP systems, a mixing tube is added between the injector and the combustion chamber to promote mixing and combustion efficiency. These devices are efficient to reduce pollutant emissions but can be sensitive to complex transient phenomena such as blow-off or flashback which are still beyond the prediction capabilities of most numerical tools. The present study describes a joint experimental and numerical study to evaluate the capacities of Large Eddy Simulation (LES) for the prediction of flame dynamics in a swirl-stabilized LPP burner operated with propane. Combustion regimes are first identified experimentally: compact flames (the normal regime for LPP) but also flashback regimes (where the flame is stabilized in the mixing tube) as well as lean
blow-off situations are encountered. LES is then used to investigate each regime as well as the transition and the hysteresis phenomena between regimes. Flashback and blow-off limits are correctly reproduced and LES shows the crucial role of swirl and axial recirculation zones during flashback. More generally, this study demonstrates the potential of existing LES to study transient phenomena in flames.

*Key words:* Large-Eddy Simulation, Combustion, Flashback, Lean Premixed Prevaporized, Swirl

### 1 INTRODUCTION

The reduction of the pollutant emissions becomes one of the major stakes in the design of gas turbines combustors. In LPP systems (Lean Premixed Prevaporized) a mixing tube is inserted between the fuel injector and the combustion chamber. This tube allows a drastic reduction of the emissions because, as the mixing of the reactants is improved, the burnt gases temperature may be decreased and NOx emissions reduced (Fig. 1). On the other hand, LPP systems can be sensitive to combustion instabilities. They are also prone to flashback [1] as the flame may stabilize in the premixing zone, upstream of the combustion chamber. This regime of combustion can lead to severe damage of the injection device by increasing the wall temperature. Blow-off and reignition are also critical processes for gas turbine operation.

In this context, Large Eddy Simulation (LES) for combustion becomes a basic tool to understand, predict and prevent such phenomena [2-4]. This technique explicitly computes unsteady large turbulent structures of the flow and should be able to reproduce the dynamics of highly three-dimensional LPP burners.

This paper demonstrates the capacity of LES to predict transient combustion phenomena in a swirl-stabilized LPP system. The experimental configuration is a simplified 300 kW cylindrical LPP swirled burner operated at
Laboratoire EM2C. This burner, specifically designed to allow and visualize flashback, runs at atmospheric pressure. Propane is used to avoid vaporization effects and modeling in this preliminary study. Both experiments and numerical simulations are carried out in order to study the transitions between the various combustion regimes. Multiple papers have been devoted to detailed comparisons of velocity, species and temperature fields for one steady regime in various configurations [3, 5-8]. This will not be repeated here; instead of investigating one regime in detail, multiple regimes and the transitions between these regimes will be studied and less effort will be devoted to detailed analysis of one single case.

2 FLASHBACK

Flashback is an intrinsic behaviour of premixed systems as the flame may stabilize where fuel and oxidizer mix, upstream of the combustion chamber. Several explanations of flashback can be found in the litterature but none of them is universal and the occurrence of flashback depends mainly on the experimental device [9]. Flashback occurs when autoignition takes place in the mixing zone [1] or when the flow velocity is of the same order than the combustion velocity (fresh gases consumption velocity) so that the flame is able to propagate upstream. The low flow velocity relatively to the flame speed may be induced by the proximity of a solid wall, low turbulence levels, instability, or vortex breakdown. Flashback mechanisms are now briefly discussed.

- Flashback by autoignition
  Autoignition does not involve flame propagation and occurs when the gas residence time exceeds the fuel ignition delay time, leading to the ignition of the mixture in the mixing zone. Autoignition delays depend mainly on local temperature, pressure and equivalence ratio [10].
- Flashback in boundary layers
In boundary layers, the velocity is sufficiently low to allow upstream propagation of the flame. However, this propagation is limited by wall quenching. Lewis and von Elbe [11] have proposed a criterion for the laminar flame, which relies on a comparison between the wall velocity gradient and the ratio of the laminar flame speed $s_L$ over quenching distance $d_q$:

$$g = \frac{\partial u}{\partial r} \bigg|_{wall} \leq \frac{s_L}{d_q} \quad (1)$$

This criterion states that flashback occurs when the flow velocity at a distance $d_q$ from the wall is lower than the flame speed (at distances smaller than $d_q$, the flame cannot survive). This classical point of view is not satisfying for many of the observations of flashback in industrial and turbulent configurations [1, 9]. Flashback in boundary layers seems to be predominant in non-swirling low turbulent flows [12] or low speed catalytic combustion [1].

- **Turbulent flame propagation in the core flow**
  
  This propagation is possible when the turbulent flame velocity $s_T$ becomes higher than the local flow velocity. Such a situation may occur in swirling flames, where turbulence is intense and the flame surface available is significantly larger than the flame surface of a laminar flame leading to a possible flashback on the burner axis [9].

- **Combustion instabilities leading to flashback**
  
  Combustion instabilities are due to a coupling between heat release, pressure fluctuations and flow hydrodynamics. The velocity fluctuations induced by an instability can be as large as the mean flow velocity and lead to a transient flashback during the oscillation cycle. A classical example of such flashback is the turbulent premixed flame behind a step [13-16] where coherent structures control flashback. Since swirled burners are sensitive to combustion instabilities, these scenarios may trigger flashback in these combustors. However, such flashbacks require a high level of fluctuations to appear [12] which is beyond the acceptable noise levels in most combustion systems.
Flashback induced by vortex breakdown

Various mechanisms control the behavior of swirling flows. One of them is vortex breakdown [17]. It can be defined as an abrupt change in the jet topology and can take several forms. Phenomenologically, the breakdown of a vortex occurs when its azimuthal velocity is larger than its axial velocity. This complex and highly 3D phenomenon depends on the flow circulation (or the swirl number) and the Reynolds number [18]. In combustion chambers, vortex breakdown is accompanied by a large recirculation zone with high reverse flow velocities, of the order of the outgoing exit velocity [19]. In a swirled stabilized flame, these reverse velocities can promote upstream flame propagation and flashback [1]. This type of flashback has been experimentally observed and identified in a swirled burner [12] and a radial-type swirled stabilized flame in [9].

This short review of flashback suggests that it can be triggered by multiple causes. The type of flashback occurring in LPP systems is not clearly defined. Understanding flame propagation and stabilization in the mixing zone of LPP devices is essential to avoid flashback. The practical solutions chosen to stabilize the flame in the chamber will be different to avoid a boundary layer flashback or a flashback due to vortex breakdown. Visualizations with a high-speed camera on the experimental device studied here show an upstream propagation of the flame during flashback. These images, presented in the next sections, suggest that flashback is not due here to boundary layer propagation. Recent experiments [12], two-dimensional RANS [20], or two-dimensional LES [21] show that flashback in swirled flows occurs because of vortex breakdown but the interaction between the flow (the recirculation zones) and the flame is still unclear.

In this work, large eddy simulations and experiments are combined to provide new insights on flashback in a well-controlled case. The configuration and the experimental setup are presented in section 3. Section 4 describes the
numerical solver used to simulate the unsteady turbulent reacting flow. The various combustion regimes found experimentally are presented in section 5 and compared to the numerical results in section 6.

3 CONFIGURATION AND EXPERIMENTAL SETUP

A laboratory-scale gas turbine combustion chamber has been designed and operated at atmospheric pressure by Laboratoire EM2C (Fig. 2). The air flow is introduced in the mixing tube through a swirl generator and shears a central jet of propane (Fig. 3). Fuel and air mix in the so-called mixing tube before entering the combustion chamber itself. The underlying principle of LPP techniques is to add such a mixing zone in order to produce a well-premixed prevaporized mixture and control the flame temperature. The swirling flow generated in the mixing tube both enhances the mixing of reactants and allows the flame stabilization in the combustion chamber. The sudden change of section between the mixing tube and the combustion chamber reinforces the central recirculation zone characterizing swirling flows [19]. This recirculation zone maintains hot burned gases in contact with fresh gases and stabilizes a very compact flame.

Purified air is provided under 6 bars by a compressor. Commercial propane is delivered at 6 bars by a pressurized tank. Before entering the mass flow meters each flow is purified through filters. The maximum capacities of each mass flow meter are $300 \, m^3/h$ for air and $15 \, m^3/h$ for propane, which leads to a maximum heat release of about 300 kW.

The radial-type swirl generator (Fig. 4) is composed of eighteen constant-section vanes whose angle with the local radial direction is $35^\circ$. Mixing tube and combustion chamber are made of high quality quartz (fused silica) allowing visible and UV optical access.

The mixing tube is 100 mm long, with an inner diameter of 25 mm. The
Reynolds number in the mixing tube (based on the mixing tube diameter and the bulk velocity) varies between 40,000 up to 280,000. The combustion chamber is 300 mm long and has a diameter of 150 mm. The exit of the combustion chamber is connected to a large dimension room bounded by non-reflecting material walls. We assume that the interaction between the burner and its surrounding is weak, so that the pressure at the outlet plane is constant and equal to 1\text{atm}. The mixture is ignited in the combustion chamber by a spark plug, located at the rear face of the combustion chamber, 50 mm from the combustion chamber axis.

Combustion regimes can be identified by a direct observation of the flame. Spontaneous emission of the $OH^*$ radical have also been recorded using a ICCD camera (PI-MAX 512x512 Princeton Instrument) with adequate filters (WG305 and U340). Flame front dynamics have been recorded using a high-speed camera (Photron Fastcam APX) operating up to 10,000 frames per seconds in 256x512 pixels.

4 LES FOR TURBULENT REACTING FLOWS

The LES calculations are carried out with the LES parallel solver AVBP developed by CERFACS [22]. The full compressible Navier Stokes equations are solved on structured, unstructured or hybrid grids allowing the simulation of reactive turbulent flows on complex geometries by using refined grid cells only in the mixing and reactive regions of the flow.

The numerical scheme provides third-order spatial accuracy on hybrid meshes [23]. This point is important because high-order numerical schemes (required to perform precise LES calculations) are particularly difficult to implement on hybrid meshes. Time integration is done by a third-order explicit multistage Runge-Kutta scheme. The Navier-Stokes characteristic boundary conditions (NSCBC) are used for inlets and outlets [2, 24] to ensure a physical represen-
tation of the acoustic wave propagation.

The objective of LES is to compute the large scale motions of the turbulence while the effects of small scales are modeled. The WALE model \cite{25} is chosen to estimate subgrid scale stresses whereas the flame-turbulence interaction is described by the dynamic thickened-flame model (DTF) \cite{26-29}.

The grid used for this simulation is very fine in the mixing tube so that a small thickening factor $F = 5$ can be used in the DTF model: the thickness of the resolved flame front is about five times the unstretched laminar flame thickness. This low value is required to allow flashback since a thick flame would not be able to penetrate in the mixing tube. When the flame flashes back, it transitions from a partially premixed mode to a diffusion mode. The DTF model can capture this effect at least qualitatively. Tests \cite{21, 29} show that the DTF flame conserves the overall consumption rate of diffusion flames (within 10 to 20 percent) when it is thickened because only the reaction zones are thickened: the diffusion layers are not modified and hence the global consumption rate is conserved. The use of a small thickening factor increases the accuracy of the thickened flame model and reduces the importance of the subgrid scale model.

For the present study, an non-structured grid of tetrahedral elements is used with a total of about 700,000 cells (Fig. 5). The walls are assumed to be adiabatic and the gaseous fuel issuing from the injector is pure propane. A single step chemical scheme is used to describe air/propane chemistry:

\begin{equation}
C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O
\end{equation}

The rate of this reaction is given by:

\begin{equation}
q = A \left( \frac{\rho Y_{C_3H_8}}{W_{C_3H_8}} \right)^{n_{C_3H_8}} \left( \frac{\rho Y_{O_2}}{W_{O_2}} \right)^{n_{O_2}} e^{-\frac{E_a}{RT}}
\end{equation}

where $A = 3.2916E + 10$ cgs, $E_a = 31126$ cal/mol, $n_{C_3H_8} = 0.856$ and $n_{O_2} = 0.503$. 
The total physical time simulated for each transition is about 0.05s corresponding to 3000 hours CPU time on a SGI O3800 R14000 500Mhz. The computations are typically performed on 32 processors.

5 EXPERIMENTAL IDENTIFICATION OF COMBUSTION REGIMES

Similarly to gas turbine burners, the present combustion chamber exhibits various stabilization modes. The normal operating point corresponds to a compact flame stabilized in the combustion chamber by the swirling flow (Fig. 1 and 6). When flashback occurs, the flame enters the mixing tube (Fig. 7) where it stabilizes near the fuel injector. Starting from a compact flame and decreasing equivalence ratio leads to a lifted flame, stabilized downstream in the combustion chamber (Fig. 8). Decreasing the equivalence ratio even more leads to lean blow-off.

The experimental setup is designed to resist flashback without damage for a long time. In this situation, the flame is stabilized a few centimeters downstream of the propane injector. Since both compact and flashback flames can be (safely) investigated, this facility gives the opportunity to understand both regimes and the transitions between them. A map of the flame regimes is plotted in Fig. 9 as a function of the air flow rate and the equivalence ratio.

For low and intermediate equivalence ratios (and intermediate air flow rates), the flame is stabilized in the combustion chamber due to the central toroidal recirculation zone. For higher values of the equivalence ratio, the structure of the flame can be either flashback or compact, depending on initial conditions and operating procedure. This is a hysteresis region. The transition from flashback to compact flames takes place at approximately the same equivalence ratio $\Phi_g = 0.68$, independently of the air flow rate. This transition is not smooth and is associated with high fluctuations of the flame shape and position.
Figure 9 shows that the dynamics of the burner are mainly controlled by the overall equivalence ratio since, for intermediate air flow rates, transitions between different regimes occur at constant equivalence ratios: $\Phi_g = 0.68$ for the flashback to compact flame transition, $\Phi_g = 0.54$ for the compact to lifted flame transition and $\Phi_g = 0.51$ for blow-off. For higher values of air mass flow rates (above 210 $m^3/h$) the bulk velocity in the premixing tube is very high (above 180 $m/s$) and the flame is lifted.

6 NUMERICAL RESULTS

The aim of this study is to investigate the ability of LES to predict the various flame regimes observed experimentally. Figure 9 shows the regimes computed using LES:

- **Regime I:** $Q_{\text{air}} = 60 \, m^3/h$ ; $Q_{\text{fuel}} = 2.25 \, m^3/h$ ; $\Phi_g = 0.9$
  
  These inlet mass fluxes are within the range of the hysteresis phenomenon: for regime I the flame can be either compact or flashback depending on its history.

- **Regime II:** $Q_{\text{air}} = 120 \, m^3/h$ ; $Q_{\text{fuel}} = 3 \, m^3/h$ ; $\Phi_g = 0.6$
  
  The equivalence ratio is weaker than for regime I. This regime corresponds to a normal operating mode of the LPP, leading to a compact flame.

- **Regime III:** $Q_{\text{air}} = 21 \, m^3/h$ ; $Q_{\text{fuel}} = 0.75 \, m^3/h$ ; $\Phi_g = 0.89$
  
  Flashback is expected for this regime corresponding to a high equivalence ratio and weak inlet flow velocities.

- **Regime IV:** $Q_{\text{air}} = 120 \, m^3/h$ ; $Q_{\text{fuel}} = 2.25 \, m^3/h$ ; $\Phi_g = 0.45$
  
  This regime corresponds to a lean blow-off.

In the following sections the transitions between these regimes are investigated according to the paths plotted in Fig. 9. The ignition is done for regime I and a compact flame is obtained. Travelling to regime II by increasing fuel and air
inlet flows but decreasing the equivalence ratio preserves the compact flame (section 6.1). A sudden decrease of inlet flows (increasing the equivalence ratio leading to regime III) induces flashback. This transition is discussed in section 6.2. Coming back to regime I evidences the hysteresis phenomenon: the flame remains in the mixing tube (section 6.3) instead of transitioning back to a compact flame. Finally, a lean blow-off sequence is investigated by simulating the transition between regimes II and IV (section 6.4).

In figures 10, 13 and 18, vertical cutting planes of axial velocity and a volumetric iso-surface of the temperature (1600 K) are presented in order to visualize the recirculating flow in the combustion chamber and/or in the mixing tube as well as the flame location and shape. Backflow zones are visualized by a black iso-line of zero axial velocity. The mixture fraction $z$ is used to visualize the stoichiometric mixing line $z_{st}$ in the central plane with a red line:

$$z = \frac{sY_F - Y_O + Y^0_O}{sY_F^0 + Y^0_O}$$

(4)

$$z_{st} = \frac{Y^0_O}{sY_F^0 + Y^0_O} = 0.059$$

(5)

where $Y_F^0$ and $Y_O^0$ are fuel and oxidizer mass fractions in pure fuel and oxidizer streams respectively, and $s$ is the mass stoichiometric ratio.

The flame structure (premixed vs diffusion flame) is a key issue in LPP devices. A simple local flame index (FI) [30, 31] can be used to identify the combustion regime:

$$FI = \nabla \cdot (\nabla \nabla (\tilde{Y}_{O_2}) \cdot \nabla \nabla (\tilde{Y}_{C_3H_8}))$$

(6)

where $\tilde{Y}_{O_2}$ and $\tilde{Y}_{C_3H_8}$ are the filtered mass fractions of the oxidizer and propane respectively. In the present study a modified flame index (MFI) is introduced to limit the visualization to reaction zones:

$$MFI = \frac{\bar{F}_I}{\omega_{F_{max}}}$$

(7)
where $\overline{\omega}_F$ is the instantaneous filtered reaction rate and $\overline{\omega}_{F_{\text{max}}}$ is its maximum value in the domain. In Fig. 11, 16 and 19 the white iso-surface corresponds to a positive modified flame index ($MFI = 0.01$), i.e. a premixed flame and the black iso-surface corresponds to a negative modified flame index ($MFI = -0.01$), i.e. a non-premixed flame. The volume integral of the positive or negative values of this index is used to quantify the relative weight of premixed and non-premixed flames for various combustion regimes. The temperature field is plotted both on the vertical cutting plane and the walls of the domain. In Fig. 17, 20 and 21 the red iso-line represents the $z_{st}$ line, the black iso-lines the non-premixed flame and the iso-lines the premixed flame.

### 6.1 Compact flame (Regime II)

Regime II corresponds to a compact flame at the mixing tube exit. The central recirculation zone induced by the swirling flow and evidenced by the iso-line of zero velocity (in black in Fig 10) is filled with burnt gases stabilizing the flame. Other recirculation zones are present behind the step, in the corners of the chamber. The flame topology revealed by LES (Fig 12 right) agrees with the experimental visualization (Fig 12 left). The experimental picture displays the OH radical spontaneous emission of the flame. The LES figure displays the integrated value of the mean reaction rate in the spanwise direction ($\int \dot{\omega} dy$). This comparison shows that both flame position and shape are correctly predicted by the simulations.

As expected, the combustion index for regime II corresponds essentially to premixed flames (95 %): only few non-premixed flames (5 %) are found in the combustion chamber (Fig. 11). This demonstrates the efficiency of the mixing tube combined with the swirling flow.
6.2 Flashback flame (regime III)

The transition from regime II (compact flame) to regime III (flashback) is now investigated (Fig. 13). Following the sudden change of the inlet boundary conditions (done at \( t = 0 \) s), the flame penetrates into the mixing tube after a delay of about 1s in the experiments, reduced to 0.03s in the simulation because the change of flow rates is more rapid in the simulation than in the experiment. Figure 14 shows the minimum axial position of the flame during the simulation. The position of the central recirculation zone is also plotted and defined here as the minimal axial position of an axis point with a negative velocity \( u = -22 \text{m/s} \). This velocity value is representative of the central recirculation zone and is a good criterion to detect its axial position. The calculated propagation velocity of the flame is approximately \( 11 \text{ m/s} \) (Fig. 14) while the experimental value obtained by image processing of a high speed camera is close to \( 12 \text{ m/s} \) (Fig. 15).

The flame dynamics during flashback are very similar to the results of [12] obtained with a high speed video camera coupled to an optical flame sensor placed in the mixing tube. First the flame exhibits a ”needle shape” (Fig. 13.2) whose oscillations are probably due to the presence of a precessing vortex core. The flame is located at the exit plane of the mixing tube \(( x = 0.145 \text{ m})\) as shown in Fig. 14 phase A. From 0.0 s to 0.013 s an intermittent recirculation zone appears in the mixing tube. The second part of phase A (0.013 s to 0.02 s) exhibits a strong correlation between the flame movement and the position of the central recirculation: the flame is now carried by the recirculation zone and follows its oscillations. Then, at \( t = 0.02 \) s, the flame needle penetrates towards the inlet of the mixing tube \(( x = 0.05 \text{ m})\), carried out by the expansion of the central recirculation zone at a speed close to \( U = -11 \text{ m.s}^{-1} \) as shown in phase B of figure 14. The propagation speed of the flame is the same as the one of the central recirculation zone: the flame flashback because
the recirculation zone enters the mixing tube. When flashback is installed, the
flame position (i.e. the minimum distance between the flame and the lips of
the injector) remains constant while the recirculation zone is ejected from the
mixing tube (Fig. 14 phase C, and Fig. 13.4).

The topology of the recirculation zones during flashback is shown in more de-
tails on Fig. 13. The first picture (just before decreasing the inlet mass flows
at  \( t = 0.0 \)  s) exhibits the classical topology found in swirled flows: a central
recirculation zone, expanding from the outlet of the mixing tube up to two
thirds of the chamber, stabilizes the flame in the chamber (Fig. 13.1). The
second snapshot corresponds to the onset of flashback ( \( t = 0.02 \)  s). The flow
is massively recirculating in the chamber and the central recirculation zone
penetrates into the mixing tube. The comparison of the zero-velocity iso-line
between the second and the third snapshot evidences a rotating movement
of this recirculation zone. In the third picture ( \( t = 0.0225 \)  s), the flame is
propagating inside the mixing tube. The recirculation zone in the chamber
becomes smaller. In the fourth snapshot, taken at  \( t = 0.0325 \)  s, the flame is
stabilized inside the mixing tube, it accelerates the flow and the central recir-
culation zone in the chamber vanishes. After flashback, the flame is stabilized
by a narrow recirculation located around the fuel injector. The position of the
flame with respect to the \( z_{st} \) line shows a rich flame near the injector.

Figure 16 and 17 show the combustion index (Eq. 7) when the flame is stabi-
lized inside the mixing tube. A non-premixed flame is found near the injector
lips where oxidizer and fuel are not mixed. In the chamber, islands of diffusion
flames are observed around the premixed flame. In the whole computational
domain, the combustion index indicates 15% of non-premixed flames and 85%
of premixed flames. The visualization of the flame index of Eq. 7 in the ax-
ial cross section \( Z = 0 \) shows that the diffusion flames are located along the
stoichiometric line while the premixed flames cross the \( z_{st} \) line (Fig. 17).
6.3 *Hysteresis phenomenon (Regime I)*

It is interesting to investigate whether the hysteresis phenomenon observed by the experiments is reproduced by the LES simulations. For example, regime I corresponds either to a compact or a flashback flame depending respectively whether the chamber is directly ignited at regime I or changes from regime III to I. When the transition between regimes III and I is investigated using LES, the flame remains stabilized in the mixing tube. Figure 18 displays the two different flame structures obtained for the same inlet flow conditions (regime I): compact flame after ignition in I (top) and flashback flame after transition from III (bottom). For the flashback flame, the flame is stabilized in the mixing tube by a small central recirculation zone. For the compact flame, contrarily to the one obtained for regime II (Fig. 11), the rich mixture pockets create small diffusion flame islands located around the premixed flame (Fig. 19, 20 and 21): this structure is similar to results obtained by DNS for lifted diffusion flames [32]. According to the volume integral of the flame index, this compact flame contains approximately 24% of non-premixed flames and 76% of premixed flames. The fuel burnt within the chamber accounts for only 83% of the fuel injected into the burner, showing that unburnt gases leave the combustor. Flashback or compact flames obtained for this regime ($\Phi_g = 0.87$) are particularly inadequate both for material damage and pollution.

As expected, if the inlet mass fluxes are increased in order to simulate the transition between regimes I and II, the flame goes out of the mixing tube and stabilizes as a compact flame again.

6.4 *Blow-off (Regime IV)*

The blow-off limit is studied by simulating the transition between regime II and regime IV. The temporal evolution of the flame is displayed in Figure 22.
The physical time required to simulate the total blow-off sequence is very long (of the order of 20 ms) because it is important to verify that no hot gases remain in the chamber, which may induce a re-ignition. The second snapshot of Fig. 22 shows that the flame is weakened: it is lean (the rich zone within the iso-line $z = z_{st}$ remains located in the mixing tube) and the structure of the iso-surface of temperature shows a decrease of the flame temperature. At the last instant shown in Fig. 22 after 20 ms, the maximum temperature in the recirculation zones of the chamber is reduced to 1000K so that the flame cannot reignite any more. Total blow-off follows. This sequence is very similar to the experimental one.

7 CONCLUSIONS

This joint experimental and numerical study demonstrates the capability of reactive LES to predict unsteady flame dynamics such as flashback or lean blow-off. Both phenomena are critical points for real gas turbines design. Numerical simulations evidence the flame behavior during flashback: the correlation between the central recirculation zone induced by the vortex breakdown and the upstream flame propagation is clearly shown. The flame is carried by a recirculation zone which enters the mixing tube and then disappears when the flame is stabilized. The transitions between the various combustion regimes observed in the experiment are well reproduced by the simulations and a cartography of these regimes can be established from LES results. Moreover, a simple flame index is used in order to determine the local flame regime. Some regimes, typically for an equivalence ratio above $\Phi_g = 0.8$, exhibit the presence of diffusion flames and unburnt gases damageable for pollutant emissions. The flashback regime is dominated by non-premixed flames while compact regimes exhibit only premixed flames as expected for the normal operating of LPP
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10 FIGURES

Fig. 1. Schematic flow.

Fig. 2. Experimental setup
Fig. 3. The LPP configuration.

Fig. 4. The radial-type swirl generator.
Fig. 5. 3D view of the mesh.

Fig. 6. Compact flame for regime A (air mass flow rate: $120m^3/h$; propane mass flow rate: $3.75m^3/h$): OH radical spontaneous emission recorded with a ICCD camera.
Fig. 7. Flashback flame for regime A (air mass flow rate: 120 m$^3$/h; propane mass flow rate: 3.75 m$^3$/h): OH radical spontaneous emission recorded with a ICCD camera.

Fig. 8. Lifted flame for regime B (air mass flow rate: 174 m$^3$/h; propane mass flow rate: 3.75 m$^3$/h): OH radical spontaneous emission recorded with a ICCD camera.
Fig. 9. Combustion regimes.

Fig. 10. Instantaneous visualization of the compact flame (Regime II). Iso-surface: temperature ($T = 1600$ K); vertical plane: axial velocity; black iso-line: zero axial velocity ($U = 0$); red iso-line: $z_{st}$. 
Fig. 11. Flame index for the compact flame regime (II). Iso-surface of Modified Flame Index (Eq. 7): black for non-premixed flames ($MFI = -0.01$); white for premixed flames ($MFI = 0.01$). Vertical plane and boundary: temperature. Only premixed flames exist in that case.

Fig. 12. Comparison of compact flame shape: experiment (left, OH radical spontaneous emission, regime A) and LES simulations (right, integrated averaged reaction rate, regime II).
Fig. 13. Transition to flashback (regime II to III). Vertical plane: axial velocity; iso-surface: temperature \((T = 1600K)\); black iso-line: zero axial velocity \((U = 0)\); red iso-line: \(z_{st}\). Corresponding times for snapshots 1 to 4: 0s; 0.02s; 0.0225s; 0.0325s.
Fig. 14. Axial position of the flame (Thick line) and the recirculation zone (Thin line) during flashback (regime II to III). The boundary condition is modified at $t=0$ s. The black circles localize the snapshots of figure 13.
Fig. 15. Compact to flashback flame transition visualization (regime C to D) using a high speed camera (10000 frames per second). Time between images: 500 microseconds (only one image over 5 is shown). Figure must be read from left to right and then, top to bottom.
Fig. 16. Flame index for the flashback regime (III). Iso-surface of Modified Flame Index: black for non-premixed flames ($MFI = -0.01$); white for premixed flames ($MFI = 0.01$). Vertical plane and boundary: temperature.

Fig. 17. Flame index for the flashback regime (III). Red iso-line: $z_{st}$; black iso-lines: non-premixed flame ($MFI < 0$); white iso-lines: premixed flame ($MFI > 0$).
Fig. 18. The hysteresis phenomenon (inlet mass fluxes are identical): compact flame after ignition at regime I (top) and flashback after transition from regime III to I (bottom). Vertical plane: axial velocity, iso-surface: temperature ($T = 1600 K$); black iso-line: zero axial velocity ($U = 0$); red iso-line: $z_{st}$. 
Fig. 19. Flame index for the compact regime (I). Iso-surface of Modified Flame Index: black for non-premixed flames ($MFI = -0.01$); white for premixed flames ($MFI = 0.01$). Vertical plane and boundary: temperature.

Fig. 20. Flame index for the compact regime (I). Red iso-line: $z_{st}$; black iso-lines: non-premixed flame; white iso-lines: premixed flame.
Fig. 21. Flame index for the compact regime (I), downstream location $x = 0.245m$.
Red iso-line: $z_{st}$; black iso-lines: non-premixed flame; white iso-lines: premixed flame.
Fig. 22. Blow-off sequence (regime II to IV). Vertical plane: axial velocity; iso-surface: temperature \((T = 1600 K)\); black iso-line: zero axial velocity \((U = 0 \text{m/s})\); red iso-line: \(z_{st}\). Corresponding times for snapshots 1 to 4: 0s ; 0.005s; 0.01s ; 0.02s.