An Experimental Investigation on the Dynamics of Lean Premixed Swirl Flames

Dissertation by
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In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy

King Abdullah University of Science and Technology
Thuwal, Kingdom of Saudi Arabia

April, 2020
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ABSTRACT

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Gas turbine engines are an efficient and flexible way of power generation and aircraft propulsion. Even though different combustion systems can be implemented in these engines, more stringent regulations on pollutant emissions have been imposed throughout the years, especially in regard to nitrogen oxides (NOx). A very promising technology to reduce NOx emissions is lean premixed combustion (LPC), however, it is plagued by intense flame dynamics. Thermoacoustic instabilities, lean blow-off and lean instabilities are examples of dynamical phenomena that are detrimental to the gas turbines. In view of this, the present thesis presents the experimental investigation of the response of lean premixed swirl flames to acoustic perturbations at atmospheric and elevated pressures. The results of this investigation may be used to understand the thermoacoustic instabilities and further could be helpful in their prediction. Moreover, this work addresses the effects of non-thermal plasma discharges on the lean blow-off and stability limits of premixed swirl flames at elevated pressures. For the analysis of the flame response to acoustic fluctuations, the flame transfer functions, the flame dynamics, phase-locked velocity fields, and phase-locked measurements of flame curvature are collected through heat release and velocity fluctuations measurements, phase-locked images of the flame, particle image velocimetry, and planar laser-induced fluorescence, respectively. For the analysis of the effects of plasma discharges on the stability limits, electrical measurements and direct imaging of the flame are performed. The results include the development of an empirical
relation based on the laminar burning velocity and on the circulation of the acoustically generated vortex to predict the response of the flame to acoustic fluctuations in different operating conditions. Moreover, the results show that the pressure has a strong impact on the response of lean premixed swirl flames to acoustic oscillations and on the flame-plasma interactions. Therefore, extrapolating results obtained at atmospheric conditions to elevated pressures may result in erroneous conclusions. Furthermore, it is shown that non-thermal plasma discharges can effectively extend the stability limits of lean premixed swirl flames at elevated pressures, underlining the potential of these discharges at conditions relevant for gas turbines.
ACKNOWLEDGEMENTS

First of all, I would like to thank my two advisors, Professor Deanna Lacoste, and Professor William Roberts, for their guidance and support during these four and a half years. I would like to thank Professor Omar Knio and Professor Nicholas Worth for accepting to be part of my dissertation committee. I would like to thank Dr. Thibault Guiberti and Professor Jonas Moeck for their advice and support. I am looking forward to our collaborations in future years. I would like to thank the past and present technical staff of the clean combustion research center, in particular Issam, Andrew, Zhen, and Adrian, who made all this work possible keeping the laboratories to the high standards that they deserve. I would like to thank KAUST and the other funding sources, the Deutsche Forschungsgemeinschaft, and the Agence Nationale de la Recherche, through the GECCO project, for giving me the opportunity to carry out the studies presented in this thesis.

Thank you to Sumit that encouraged and supported me inside and outside the laboratory, especially at the beginning of my experience at KAUST. Thank you to my KAUST family, Joshua, Eshan, Monika, Ponnya, Ramgopal, Gustav, Anthony, Joel, Wesley, Sylvain, and many others that I do not have space to list here. Their support has been very important to me throughout these years.

Thank you to my family, Carlo, Alberta, Valentina, Daniele, and Annamaria, who helped and encouraged me throughout my life in Italy and Saudi Arabia. Last but not least, I would like to thank my wife, Valentina, whose support, patience, and love made all of this possible.
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Chapter 1

Introduction

Abstract

This chapter describes the general context of this study. The lean premixed combustion and its effects on the nitrogen oxides emissions are detailed. Therefore, two of the main drawbacks of this technology, thermoacoustic instabilities, and lean blow-off, are discussed. Further, the mitigation and control strategies to overcome these drawbacks are presented. The objectives of this work and the structure of the thesis end the chapter.

1.1 General Context of this Work

Gas turbine-based power plants are widely spread around the globe to generate electricity. In recent years, there has been a substantial increment of interest of the general public on the environmental impact of these systems. Consequently, more stringent regulations on pollutant emissions have been established. Therefore, gas turbines have been extensively engineered to reduce their pollutant emissions, especially nitrogen oxides (NO\textsubscript{x}), and increase their efficiency. Several strategies have been considered throughout the years to reduce NO\textsubscript{x} concentrations in flue gases such as water injection or lean premixed combustion (LPC) \cite{5}.

Lean premixed combustion demonstrated to be very efficient in reducing NO\textsubscript{x} \cite{5,19}. However, it also generates flames with very intense dynamics that can seriously affect the efficiency and integrity of the whole engine \cite{19}. Thermoacoustic instabili-
ties, lean blow-off and instabilities are examples of dynamical phenomena that need to be considered and analyzed when LPC-based gas turbines are designed.

### 1.2 Nitrogen Oxides and Lean Premixed Combustion

Nitrogen oxides emission can be very harmful to human health and the environment. For instance, they can aggravate or even induce lung diseases, and they can lead to the formation of acid rains \[20\]. Several chemical mechanisms lead to the formation of \( \text{NO}_x \) in hydrocarbon flames, such as thermal and prompt mechanisms \[5\] \[21\]. Specifically, the thermal mechanism is controlled by the elevated temperature of the flame. Whereas, the prompt mechanism is governed by the interactions between nitrogen and hydrocarbon radicals.

Since the use of LPC, with a very lean equivalence ratio, leads to a cooler flame \((T_{\text{Flame}} < 1800K)\) compared to the non-premixed counterpart, the thermal \( \text{NO}_x \) is practically eliminated \[22\], as shown in Fig. 1.1.

![Figure 1.1](image)

**Figure 1.1**: Forward thermal NO formation rate as a function of equivalence ratio for several operating conditions: laboratory scale burners (1 atm, 300 K), utility gas turbines (10 atm, 600 K), and aero-propulsion gas turbines (30 atm, 900 K) \[5\]. Figure adapted from \[5\].
The prompt mechanism remains active at low equivalence ratio, but the NO\textsubscript{x} created by this pathway is less compared to the one generated by the thermal mechanism. This results in a significant reduction of the overall NO\textsubscript{x} produced by the lean premixed combustion process, as shown in Fig. 1.2.

![Figure 1.2: Uncorrected NO concentration as a function of equivalence ratio for different flameholders. Corrected values of NO concentration implies a correction to constant oxygen level [5]. The velocity of the approaching flow is 10 m/s, while its temperature is 560 K. The average thermal power of the considered flames is 100 kW. Figure adapted from [5].](image)

As previously stated, such an advantage in NO\textsubscript{x} emissions comes with serious drawbacks such as thermoacoustic instabilities and lean blow-off and instabilities.

### 1.3 Thermoacoustic Instabilities

Thermoacoustic instabilities in gas turbine combustors are characterized by high-amplitude self-sustained oscillations of pressure resulting from the positive feedback loop between the heat release from the flame and the acoustic modes of the combustor. These oscillations might lead to serious damages to the combustor and even to the
structural failure of the whole gas turbine engine [6, 23, 24, 25, 26, 27]. A schematic of the feedback loop that may lead to these instabilities is presented in Fig. 1.3.

![Thermoacoustic Loop Diagram](image)

Figure 1.3: Example of thermoacoustic loop. Figure inspired by [6].

Generally, there are turbulent flames in the combustion chamber of gas turbines that can generate unsteady heat release. The thermal expansion of the gas surrounding the flame due to the unsteady heat release can create acoustic perturbations. These acoustic waves travel along the combustor and they can be reflected at the boundaries. Then, they propagate back to the flame and perturb the flow field and the mixture, generating a new fluctuation of heat release, that closes the thermoacoustic loop.

Inside a combustor of a gas turbine, a turbulent flame is always present, but thermoacoustic instabilities rarely appear. Therefore, some conditions need to be satisfied for these oscillations to grow [6]:

1. The difference of phase between the heat release fluctuations and the acoustic oscillations should allow a net transfer of the energy generated by the heat released by the flame to the acoustic field;

2. The flux of energy transferred to the acoustic field needs to be higher than the flux of energy removed from the acoustic field (acoustic losses).
Several strategies have been considered throughout the years to mitigate and control thermoacoustic instabilities, and they are briefly discussed in Sec. 1.5.

1.3.1 Flame Transfer Function

An essential feature that controls thermoacoustic instabilities is the flame response to acoustic perturbations. The flame transfer function (FTF) is extensively used to investigate this response \cite{28, 29, 30, 31}. This function is defined as the ratio of the relative heat release rate fluctuations of the flame, \( \dot{Q}' / \dot{Q} \), over the relative velocity fluctuations of the incoming flow \cite{30}, \( u' / \overline{u} \), as shown in Eq. 1.1:

\[
F(f) = \frac{\dot{Q}' / \dot{Q}}{u' / \overline{u}} = G(f) e^{i\Phi(f)}. \tag{1.1}
\]

Since it is defined in the frequency domain, it can also be described in terms of a gain, \( G(f) \), and phase, \( \Phi(f) \). An example of FTF for a laminar V-flame \cite{7} is reported in Fig. 1.4.

The gain represents the flame response to acoustic fluctuations. The flame amplifies or dampens the acoustic fluctuations for \( G(f) \) higher or lower than unity respectively, while for \( G(f) \) equal to unity, the flame stays neutral. The slope of the phase represents the time lag between the heat release and velocity fluctuations. The present study focuses on the experimental determination of the FTF for lean premixed swirl flames that can be commonly found in LPC-based gas turbines.

1.3.2 Flame Transfer Function of Premixed Swirl Flames

Swirlers, see Fig. 1.5, are widely used in combustors of gas turbines to stabilize powerful flame keeping short the length of the flame and the combustor. The characteristic flow field generated by the swirler in the combustor, (see Fig. 1.6), consists of annular jet (AJ), outer (ORZ) and inner (IRZ) recirculation zones, \textit{i.e.}, low-velocity zones, where the premixed flame can stabilize, promoting the recirculation of hot burnt gases.
Figure 1.4: Example of flame transfer function for a laminar V-flame, at different values of acoustic forcing amplitude, $u'/U_b$. Figure adapted from [7].

Figure 1.5: Example of axial (a) and radial (b) swirlers. Figure adapted from [8].
towards cold unburnt gases, that sustains the combustion of the incoming reactants.

The swirl flames that are bound to different recirculation zones follow the shapes

Figure 1.6: Example of velocity vector field generated after a swirler. The outer recirculation zone, the annular jet, and the inner recirculation zones are highlighted. Figure adapted from [1].

shown in Fig. 1.7. The type of shape that the flame can assume depends on the conditions inside the combustor, such as the temperature of the walls or the bulk velocity of the flow [9, 32, 33]. The presence of the swirler, the nature of the flow field determines the flame shape that, in turn, influences the gain and phase of the FTF [30, 31, 34, 35]. An example of FTF of premixed swirl flames is reported in Fig. 1.8.

The trend of gain and phase of the FTF is understood in a qualitative manner for burners operating at atmospheric conditions. The flame/vortex roll-up (FVR) and the fluctuations of the swirl number [10, 27, 34, 36, 37, 38, 39, 40, 41] control the gain and the phase of the FTF. Usually, the gain features two local maxima and a local minimum. The FVR is the primary mechanism controlling the FTF gain, but when the fluctuations of swirl number are strong, a minimum of the FTF gain is observed. On the other hand, when the oscillations of swirl number are weak, a maximum of the gain is issued [10, 42, 43]. Moreover, the gain approaches unity when the forcing
frequency approaches zero [44]. On the contrary, the gain approaches zero when the forcing frequency is increased above a certain value that depends on the specific
configuration of the combustor. In the case of the phase of the FTF, it shows a quasi-linear variation with the forcing frequency, highlighting that the time lag between the fluctuations of heat release and velocity remains almost constant \[7, 45\].

A flow chart of the mechanisms responsible for the generation of the FVR and the swirl number fluctuations is presented in Fig. 1.9. When an acoustic wave \(u'/u\) interacts with the swirler, it is transmitted as an acoustic wave \(u'\), and a vorticity wave \(v'\) that is convected by the flow towards the base of the flame. Therefore, the transmitted acoustic wave interacts with the shear layers between the annular jet and the recirculation zones (see Fig. 1.6), resulting in the shedding of a vortex. This vortex propagates along the flame generating the FVR and, consequently, a fluctuation of heat release rate \(\dot{Q}'/\dot{Q}\). On the other hand, the vorticity wave is convected towards the base of the flame, where it can interact with the transmitted acoustic wave. When these two waves are out of phase at the injection tube outlet/flame base, the swirl number fluctuations are maximum. Whereas, when they are in phase, the swirl number fluctuations are null. These oscillations generate fluctuations of the base of the flame resulting in heat release rate perturbations \(\dot{Q}'/\dot{Q}\) \[8, 10\].

Figure 1.9: Diagram of the mechanisms generating heat-release rate fluctuations in premixed swirl flames. Figure inspired by \[8\].

The FTF is extensively used in low order modeling and in the analysis of flame-acoustic interactions. Therefore, there is a need for FTF measurements at conditions relevant to gas turbines engines. Moreover, the development of relations to predict
FTF based on parameters that can be easily measured is essential. This will be one of the objectives of this work.

### 1.4 Lean Blow-off and Lean Instabilities

The lean blow-off (LBO) and, consequently, the lean instabilities (LI) are examples of additional dynamical phenomena that are characteristic of lean premixed swirl flames. The main governing parameter for such instabilities is the equivalence ratio ($\phi$) of mixture, in addition to the bulk flow velocity and the combustor temperature. As $\phi$ is reduced below a certain threshold, the flame might experience intermittent local extinctions at its base and anchoring point, see Fig. 1.10 (a), which is referred to as the lean instability [11, 46, 47, 48, 49, 50, 51]. The extinction of the base of the flame might be determined by the elevated strain and stretch generated by the high velocity of the annular jet in that region and by the presence of several shear layers (IRZ to AJ and AJ to ORZ). Moreover, the extinction stretch rate of lean premixed methane-air flame decreases with decreasing $\phi$, promoting the extinctions of the base of the flame [11, 52].

With further reduction in $\phi$, these extinctions events might persist. Therefore, the flame might completely be blown-off from the combustor leading to the so-called lean blow-off [11, 46, 47, 48, 49, 50, 51, 53, 54] (see Fig. 1.10 (b)). Indeed, these two events must be controlled since they can lead to unstable operations and even to the
complete shut down of the gas turbine engine. Even though LBO and LI cannot be avoided, the equivalence ratios at which these events can appear could be extended to lower values. These values of equivalence ratio are called stability and blow-off limits for LI and LBO, respectively. Several strategies have been considered throughout the years to obtain the extension of these stability limits, and they are briefly discussed in the following sections.

1.5 Mitigation and Control Strategies

Several strategies used to mitigate the thermoacoustic instabilities and to extend the LBO and LI limits are briefly presented in this section.

1.5.1 Mitigation and Control Strategies for Thermoacoustic Instabilities

The main control strategies for thermoacoustic instabilities can be divided in two groups, passive and active [27]. Passive strategies include:

- Acoustic dampers such as Helmholtz resonators and quarter-wave tubes. These devices are cavities connected to the combustor that are designed to specifically dampen a range of frequencies of instabilities [6];

- Fuel staging and pilot flames, where the fuel injection in different locations inside the combustor is utilized to reduce pressure oscillations generated by thermoacoustic instabilities [6, 55]. Moreover, it has been shown that pilot flames can also mitigate these instabilities [6, 56];

- Fuel injectors and burner geometry, where the fuel injectors or the whole burner geometry are adjusted to avoid thermoacoustic instabilities [6, 57].

Active controls include:
• Sensors and actuators, where the pressure oscillations generated by the instabilities are measured by a sensor and an actuator is used to counteract the fluctuations. The sensors include several types of devices, such as pressure sensors, or photomultiplier tubes. While, actuators can include acoustic drivers, fuel injectors, or non-thermal plasma discharges [6, 15, 27, 58].

1.5.2 Mitigation and Control Strategies for Lean Blow-off and Lean Instabilities

The main strategies, considered throughout the years, to extend the stability limits are:

• Increase in the temperature of the unburnt gases which help in the ignition of the reactants at the base of the flame [53, 59];

• Pilot flames which help to ignite the mixture of reactants arriving at the base of flame [60];

• Addition of high reactive fuels such as hydrogen which leads to better flame stability [51, 61, 62, 63];

• Plasma-assisted combustion where plasma discharges are utilized to enhance the flame through several mechanisms that are described in the next section. [64, 65, 66, 67, 68, 69, 70, 71, 72].

1.6 Nanosecond Repetitively Pulsed Plasma Discharges and Their Effects on Combustion Processes

Nanosecond repetitively pulsed (NRP) plasma discharges belong to the type of plasma that remains in the state of non-equilibrium since the electron temperature is much
higher than the gas temperature. Therefore, it is far from thermodynamic equilibrium. These discharges are usually generated in the gap between two electrodes on which high voltage pulses (tens of kilovolts) are applied. The pulse repetition frequency (PRF) of these discharges is usually in the order of tens of kilohertz. Depending on different parameters, such as applied voltage, PRF, distance between electrodes, and gas temperature and pressure [73, 74, 75], different types of discharges such as corona, glow, and spark can be generated as shown in Fig. 1.11.

![Example of NRP plasma discharges generated between anode and cathode. Figure adapted from [12].](image)

Figure 1.11: Example of NRP plasma discharges generated between anode and cathode. Figure adapted from [12].

It is known from the literature that different types of discharges affect the combustion processes, i.e., the flame, in different ways: thermally, chemically, and hydrodynamically/transport (see Fig. 1.12) [13].

The propagation of the discharge can locally increase the temperature of the gas and even act as a source of ignition, i.e., thermally affect the flame. It has been shown in the literature [76, 77], that spark discharges have a strong thermal impact on the combustion processes, while it is negligible for corona and glow discharges [78]. The NRP discharges can generate radicals, excited species, and ions/electrons, and
therefore, chemically enhancing the combustion processes. The chemical effect of the glow and corona discharges is dominant when compared to the thermal and hydrodynamic ones. The generation of ionic wind, the enhancing of the mixing, and the change in fuel diffusivity due to generation of small fuel fragments by the discharge defines the hydrodynamic/transport effect \cite{13}. Sparks discharges also have a strong hydrodynamic impact on the flame, while it is negligible for corona and glow discharges \cite{78}.

It has been shown in literature that different types of discharges with different effects on the combustion processes can be used to enhance the ignition of combustible mixtures \cite{79, 81, 82, 83, 84, 85, 86, 87, 88}, extend the stability limits, \textit{i.e.}, LBO and LI limits \cite{64, 65, 66, 67, 68, 69, 70, 71, 72} at atmospheric pressure conditions, or even mitigate thermoacoustic instabilities \cite{15, 58}. For instance, Pilla \textit{et al.} \cite{14} investigated the effects of NRP plasma discharge on the LI limit of premixed propane-air swirl flames at atmospheric pressure. They showed that these discharges extended this limit for a broad range of air flow rate, \textit{i.e.}, range of bulk flow velocity (see Fig.
They related this extension to the combined chemical and thermal effects of the discharges on the flame.

Recently, Lacoste et al. [15] detailed the effects of NRP plasma discharges on the response of a lean premixed swirl flame to acoustic perturbations. They showed that the gain of the FTF was considerably reduced when NRP discharges were applied (see Fig. 1.14).

Moreover, they showed that the amplitude of the velocity fluctuations generated by self-sustained thermoacoustic instabilities could be greatly reduced by non-thermal plasma discharges (see Fig. 1.15). They associated these results to a partial suppression of the radial oscillations of the flame front.

Even though several studies have been carried out at atmospheric pressure, there is a lacuna in the literature on if and how NRP plasma discharges could be utilized to extend the stability limits or mitigate thermoacoustic instabilities of lean premixed swirl flames at elevated pressures. The possible extension of the stability limits by NRP plasma discharges will be one of the objectives of this work.
1.7 Objectives and Contributions

The main objectives of the present work are to investigate the dynamics of lean premixed swirl flames at elevated pressures and to understand if NRP plasma discharges
could be used to control and mitigate these dynamical phenomena. Moreover, as previously stated, there is a need for simple relations, based on parameters that are easy to measure, to quantitatively predict the FTF in different operating conditions. The main objectives of this study are summarized in the following:

- Analyze the effect of different fuels and equivalence ratios on the FTF of lean premixed swirl flame to develop an empirical relation to quantitatively predict the response of the flame in different operating conditions;
- Investigate the effect of pressure on the response of lean premixed swirl flames to acoustic perturbations, through the measurements of the FTF and the analysis of the flame dynamics;
- Investigate the effectiveness of NRP plasma discharges in the extension of the LBO and LI limits of premixed swirl flames at elevated pressures.

1.8 Structure of the Thesis

The thesis is structured as follows:

- Chapter 2 describes the test rigs that are used in this study. The diagnostic techniques utilized in this work are also detailed;
- Chapter 3 includes the experimental investigations of the effects of fuel and equivalence ratio on the response of lean premixed swirl flames to acoustic fluctuations at atmospheric pressure. The results comprise the measured FTF, phase-locked OH* chemiluminescence images of the flame during the forcing cycle, phase-locked velocity fields measured with particle image velocimetry (PIV), and phase-locked measurements of flame curvature collected with OH-planar laser-induced fluorescence (PLIF). This chapter has been published in [1], [2], and presented in [2, 89, 90];
Chapter 4 presents the experimental investigation of the effects of pressure on the response of lean premixed swirl flames to acoustic perturbations. This chapter includes results in terms of FTF and phase-locked OH* chemiluminescence images of the flame during the forcing cycle. This chapter has been published in [3], and a part of it has been presented in [16];

Chapter 5 includes the experimental investigation of the extension of the LBO and LI limits of lean premixed swirl flames by NRP plasma discharges at elevated pressures. The results are presented in terms of direct images of the flames with and without plasma discharges, and measurements of the electrical properties of the discharges. This chapter has been submitted to [4], and it is currently under review;

Chapter 6 presents the concluding remarks and future work.
Chapter 2

Experimental Setups and Diagnostic Techniques

Abstract

In this chapter, the experimental setups and the diagnostic techniques utilized in this study are described. In the first part of this chapter, the description of the test rigs is presented. While, in the second part, diagnostic techniques are described.

2.1 Experimental Setups

2.1.1 Swirl Stabilized Burner

The schematic of the swirl stabilized burner utilized in chapter 3 and 4 is reported in Fig. 2.1:

The gaseous fuel and air are premixed 2 meters before being injected into a plenum of 120 mm length. This ensures that no equivalence ratio fluctuations are present during the acoustic forcing of the flame. The flow of reactants is regulated by thermal mass flow controllers (Brooks SLA 58 Series) with around 5% accuracy. The reactants then flow through a honeycomb section and a perforated plate before entering a radial swirler. The swirler features a measured swirl number of 0.39 [16], following the definition of [91] (see also Appendix B). The injection tube has a diameter of 18 mm and includes a central rod with a diameter of 2.5 mm. A small diameter for the central rod is chosen to be close to a purely aerodynamically stabilized condition. The flame is stabilized downstream of the injection tube and a quartz tube of 100 mm length, and 70 mm inner diameter confines it [1].
Figure 2.1: Schematic of the swirl stabilized burner. All dimensions are given in millimeters. Figure adapted from [1].

The acoustic section of the burner is composed of a 900 W loudspeaker (Beyma 10LW30/N) mounted in a 15.4 L plastic enclosure and powered by a high-fidelity amplifier (QSC GX5). A signal generator (NF WF1973) connected to the amplifier allows the control of the frequency and the amplitude of the acoustic forcing of the
2.1.2 High-Pressure Combustion Duct

To investigate the effects of operating pressure on the response of lean premixed flames to acoustic fluctuations, the swirl stabilized burner described in Sec. 2.1.1 has been installed in the High-Pressure Combustion Duct (HPCD). A schematic of the swirl stabilized burner in the HPCD is reported in Fig. 2.2.

The HPCD is a 0.67 m³ cylindrical vessel featuring an inlet diameter of 0.4 m and a height of 5.3 m. Four fused-silica windows with a diameter of 150 mm provide optical access and allow visualization of the flame in the UV and visible range. The working flow of reactants [1].
pressure, controlled by a back pressure regulator installed on the exhaust line, can be set from 1 to 40 bar. Two additional ports of the HPCD are used to feed the swirl stabilized burner with fresh gases and water cooling and send the electrical signals for hot wire and the loudspeaker [3]. A detailed description of the HPCD can be found in [92].

2.1.3 High-Pressure Swirl Combustor for the Study of the Flame/Acoustics/Plasma Interactions

To further investigate the interactions between flames, acoustic waves, and plasma discharges, a new high-pressure swirl combustor has been designed and commissioned at KAUST in collaboration with Tresch + Kieliger Engineering company. In this section, the main parts of the new test rig are described.

Overview of the Combustor

The schematic of the high-pressure swirl combustor is reported in Fig. 2.3, where the main modules and units are highlighted.

The test rig is positioned vertically, mounted on a stainless steel table. The rig is 2.1 meters tall, while the table is 1.4 meters wide. The modules and units that compose the combustor are:

- An acoustic module that encloses two loudspeakers for the acoustic forcing of the flame at elevated pressures. It also used for the injection of the mixture of reactants, such as methane and air, in the combustor;

- A supply module, where the air/nitrogen and water used for the cooling of several parts of the test rig are injected;

- A burner unit, including the swirler, the injection tube to the combustion chamber, and the plasma electrodes and insulation;
Figure 2.3: High-pressure swirl combustor shown in sectional view.

- A combustion chamber, that confines the flame providing optical access;
- A window module, that surrounds the combustion chamber;
- A cylinder module, that allows the cooling of the burnt gases;
- An outlet module, that allows controlling the pressure inside the combustor through a water-cooled back pressure regulator (BPR).
Each of these modules or units is detailed in the following sections. A picture of the test rig installed at KAUST is shown in Fig. 2.4.

Figure 2.4: High-pressure swirl combustor installed at KAUST.

Pressure Vessel

A schematic of the pressure vessel is reported in Fig. 2.5. It has been designed to sustain the elevated pressure and temperature during the operation of the test rig allowing optical access to the flame.
The pressure vessel has an average thickness of 43 millimeters and has been designed for a maximum operating pressure of 35 bar, allowing a maximum deflagration pressure of 52 bar. The components of the pressure vessel have been designed, manufactured, and tested in accordance with the European Community (EC) pressure equipment directive 97/23 as well as with the AD2000 2015 regulation of the technical inspection association "TÜV".

**Acoustic Module**

The schematic of the acoustic module is reported in Fig. 2.6.
The mixture of reactants is injected from the bottom of the module and flows along the acoustic main duct towards the burner unit. This module encloses two loudspeakers to acoustically force the mixture of reactants, and consequently, the flame. A stainless steel tube, defined as acoustic wave concentrator in Fig. 2.6, is utilized to merge the acoustic forcing generated by the two loudspeakers. Several measurement ports are available for microphones, static pressure sensors, and hot wire anemometer for FTF measurements.

On one of the enclosures of the loudspeakers, a burst disc is connected to avoid overpressures in the module. Moreover, purge air is injected from the back side of both acoustic drivers to reduce the risk of deflagration. The flow rate of purge air is defined as the 5% of the total flow rate of air injected in the combustor and it is
controlled by thermal mass flow controllers (Brooks SLA 58 Series).

**Supply, Window and Cylinder Modules**

The schematic of the supply, window, and cylinder modules is reported in Fig. 2.7.

Figure 2.7: Schematic of the supply, window, and cylinder modules.
The supply module contains the inlets for the cooling water for the combustion chamber, the window module, and the cylinder module. Moreover, it also contains ports for the air/nitrogen that is used for the cooling of the windows of the combustion chamber and the burnt gases.

The windows module allows the optical access to the flame through four orthogonal fused-silica windows. The thickness of the windows is 30 millimeters. Moreover, it hosts several measurement ports for pressure and temperature sensors, i.e., thermocouples.

The cylinder module allows the mixing between the cooling air/nitrogen and the burnt gases. It also has several measurement ports for pressure sensors and thermocouples.

**Combustion Chamber**

A close-up view of the combustion chamber and burner unit is reported in Fig. 2.8 and its schematic is shown in Fig. 2.9.

The combustion chamber confines the flame allowing optical access through four orthogonal fused-silica windows aligned with the ones of the window module. The thickness of the windows is 2.5 millimeters. The combustion chamber has a square section of 85 millimeters width and it is 150 millimeters long. An acoustic orifice is placed on top of the chamber to acoustically decouple it from the cylinder module. Four nozzles spray air/nitrogen to cool down the windows. The top and the bottom of the chamber, and the pillars sustaining the windows are water cooled (see Fig. 2.10). Moreover, the chamber is made of copper to enhance the heat transfer to the cooling medium. An external heat exchanger provides the pressurized and demineralized water used by the cooling system.
Figure 2.8: Close-up view of the combustion chamber.

Figure 2.9: Schematic of the combustion chamber.
Figure 2.10: Water cooling path in the combustion chamber.

**Burner Unit**

The schematic of the burner unit is shown in Fig. 2.11. This unit includes a flange that houses the burner inlet and allows to fix the plasma electrodes feedthrough. The burner inlet guides the rods for the plasma electrodes and sustains the swirler, the ceramic electrode holder, the minus electrode, and the burner unit top. The swirler generates the swirling flow, while the central rod connected to it, serves as a plus electrode. The ceramic electrode holder is utilized to electrically separate these electrodes inside the burner unit. The electrodes receive the high voltage from the plasma generator through stainless steel rods. The burner unit top serves as an electrical barrier for the plasma and thermal barrier for the flame. Most of the parts of this unit are made of plastic or ceramic to ensure electrical insulation between the electrodes. The configuration of this unit ensures the generation of plasma discharges between the electrodes only at the very top of the injection tube inside the combustion chamber.
Figure 2.11: Schematic of the burner unit.
Outlet Module

A schematic of the outlet module is presented in Fig. 2.12. The main component of this module is the back pressure regulator. This valve comprises a water-cooled piston that can be moved in such a way to increase the pressure of the test rig by decreasing the outflow section of the burnt gases and vice versa. The movement of the piston, and consequently the pressure of the combustor, can be controlled automatically by a DC-motor, or manually by a handwheel. A burst disc is also installed at the top of the module to avoid overpressures that can damage the test rig. Moreover, a deflection sheet is used to protect the BPR from big solid particles that can clog the outflow section. The BPR is water-cooled, as shown in Fig. 2.13, which allows a burnt gases
temperature up to 2000 K in the outflow section.

Figure 2.13: Water cooling path in the back pressure valve.

2.2 Diagnostic Techniques

The diagnostic techniques utilized in this work are presented in the following sections.

2.2.1 Particle Image Velocimetry

The particle image velocimetry (PIV) is a laser-based optical diagnostics utilized to visualize flows and measure two or three-dimensional velocity fields. For doing so, the flow is seeded with particles, such as oxides of aluminum, or titanium. A laser is used to illuminate these particles, and their Mie scattering is collected by a camera. Two laser pulses, separated by a specified time interval, are utilized, resulting in an image pair. Analyzing the two consecutive frames, the distance traveled by the particles can be estimated by correlation methods. Since the time interval between the two pictures is set, the velocity of the particles, and consequently, the velocity of the flow can be computed. More details of about PIV can be found in [93, 94]. Examples of
velocity field measured with PIV are shown in Figs. 1.6 and 1.6. The details of the specific PIV system utilized in this work are given in chapter 3. An example of a 2D-PIV setup is reported in Fig. 2.14.

![Figure 2.14: Example of 2D-PIV setup.](image)

The laser wavelength utilized for PIV is usually 532 nm, which is the second harmonic of the fundamental (1064 nm) of the Nd:YAG laser. These lasers are very reliable and then widely used for this technique. Cylindrical and spherical lenses are used to generate the laser sheet and focus it on the section of the burner where the velocity field needs to be obtained. The camera is usually equipped with a bandpass filter, center at the wavelength of the laser, i.e., 532 nm, to avoid interference from surrounding sources of light.

### 2.2.2 Planar Laser-Induced Fluorescence of Hydroxyl Radical (OH)

In combustion experiments, it is important to highlight the flame front. A technique that has been widely utilized for this purpose is the planar laser-induced fluorescence of OH radicals (OH-PLIF). During the combustion process, a range of radicals occurs
within the flame front. As a prominent flame marker, radicals such as OH* or CH* can be employed. Each of these radicals can be excited by a specific wavelength of the laser based on their absorption lines. As the excited radicals relax, it results in the emission of a photon of higher wavelength compared to the excitation wavelength. This rate of relaxation that occurs over a few 100 ns is termed as the laser-induced fluorescence (LIF). In this work, we utilized the planar LIF (PLIF) of OH* by forming a laser sheet similar to the PIV measurements to visualize the flame in the central section of the combustor. More details on this technique can be found in [95, 96]. An example of OH-PLIF images of lean premixed swirl flames can be found in Figs. 2.15 and 4.7. The details of the OH-PLIF system specific to this work are given in chapter 3. An example of a two-dimensional OH-PLIF setup is presented in Fig. 2.16.

Figure 2.15: Example of OH-PLIF images of lean premixed swirl flames.

The wavelength of the laser used for OH-PLIF is usually around 282-283 nm, which corresponds to the Q1(6) transition of (1,0) band of the $A^2\Sigma - X^2\Pi(1,0)$ system of OH. This transition is generally the one that results in a high signal to noise ratio, and it also has low sensitivity to temperature. Similar to PIV, the laser beam is converted in a sheet and focused on the measurement section of the burner, using cylindrical and spherical lenses. The camera is equipped with a bandpass filter, focused at the
emission wavelength of OH (around 310 nm), to avoid interference from other sources of light.

![Diagram of two-dimensional OH-PLIF setup]

Figure 2.16: Example of two dimensional OH-PLIF setup.

### 2.2.3 Heat Release Rate Measurements with Photomultiplier Tubes

As presented in chapter 1, it is necessary to collect the volumetric heat release rate fluctuations from the flame to measure the FTF. It has been shown by [97, 98] that this can be done by collecting the fluctuations of the emissions of excited radicals present in the flame, such as CH\(^*\) or OH\(^*\). For this, a photomultiplier tube (PMT) is used in this work to collect the emissions of OH\(^*\). This device is usually employed to detect weak signals. When a photon hits the photosensitive surface of the PMT, electrons are released and then multiplied along the photomultiplier. All these electrons are then collected at an anode, at the end of the PMT, and converted into a current that is proportional to the number of photons that hit the photosensitive surface. This current is then converted into a voltage signal that is read by oscilloscopes. In this work, the OH\(^*\) chemiluminescence of the full flame is focused on the PMT to get the
integrated signal, which would scale linearly with respect to the total heat release from the flame.

2.2.4 Flame Dynamics Visualization with ICCD or Intensified CMOS Camera

When studies on the response of flame to acoustic fluctuations are carried out, it is important to visualize the evolution of the flame surface area during this interaction. Similar to the heat release rate measurements, collecting the emission of OH* radicals from the whole flame can be used to highlight the flame surface area. In this study, the images of the flame surface area are collected using an Intensified Charge-Coupled Device (ICCD) or Complementary Metal–Oxide–Semiconductor (CMOS) camera. These devices couple an intensifier with a CCD or a CMOS camera. The intensifier enhances the OH* emission from the flame, similar to a PMT, while the CCD or the CMOS converts it in signals that are used to generates the images.

2.2.5 Velocity Fluctuations Measurements with Hot Wire Anemometer

For the estimation of the flame transfer function, it is necessary to measure the velocity fluctuations generated by the traveling acoustic wave. In this study, a hot wire anemometer (HWA) is utilized for this measurement, since it can "pointwise" measure flow velocity at very high sampling frequency [11, 3, 10]. The HWA is composed of a probe with a thin wire installed on its tip. The probe and the wire are connected to a power supply that maintains constant the temperature of the wire \( T_{HWA} \). When the probe is exposed to a flow of gases, the wire is cooled down by convection. Therefore, the electrical resistance of the wire \( R_{HWA} \) changes. Subsequently, the voltage applied at the extrema of the thin wire changes, resulting in an increase of the current that maintains \( T_{HWA} \) constant. The variation of voltage is proportional to
the velocity of the flow. This change in the applied voltage \( V_{HWA} \) is converted into a voltage signal \( V_{out} \) that can be read by oscilloscopes. The principle of operation of the HWA is summarized in the following.

At steady state, the thermal power of the wire \( P_{th} \), generated by Joule effect, is equal to the convective heat flux \( Q \), as shown in the following:

\[
P_{th} = \frac{V_{HWA}^2}{R_{HWA}} = Q = hA(T_{HWA} - T_{gas})
\] (2.1)

Where \( h \) is the heat transfer coefficient at the wire surface \( A \) and \( T_{gas} \) is the temperature of the gas. The Nusselt number \( (Nu) \) is generally utilized to determine \( h \):

\[
Nu = \frac{hD}{k} = f(Re)g(Pr)
\] (2.2)

Where \( D \) is a characteristic dimension of the wire, \( k \) is the mixture thermal conductivity, \( Re \) is the Reynolds number, and \( Pr \) is the Prandtl number. If it is assumed that \( Pr \) is a weak function of temperature and mixture composition, \( Nu \) is only depending on \( Re \):

\[
Nu = \frac{hD}{k} = f(Re) = f\left(\frac{uD}{\nu}\right)
\] (2.3)

Where \( u \) is the velocity of the flow and \( \nu \) is the kinematic viscosity of the mixture. Combining equation 2.1 and 2.3, it is possible to write:

\[
\frac{V_{HWA}^2}{R_{HWA}} = f\left(\frac{u}{\nu}\right)k\Delta T
\] (2.4)

Since \( R_{HWA} \) depends only on \( T_{HWA} \) that is kept constant, and \( T_{gas} \) is constant, Eq. 2.4 becomes:
\[ V_{HWA}^2 = f\left(\frac{u}{\nu}\right)k \quad (2.5) \]

Since \( V_{\text{out}} \) is a function of \( V_{HWA} \), it is possible to write for a fixed gas composition:

\[ V_{\text{out}}^2 = f(u) \quad (2.6) \]

Since it is complicated to determine \( h \), a calibration procedure is needed to convert \( V_{\text{out}} \) to the velocity (see Appendix A).

### 2.2.6 Electrical Measurements of Non-Thermal Plasma Discharges

To characterize non-thermal plasma discharges, applied voltage (\( V_{\text{disch}} \)) and current (\( I_{\text{disch}} \)), deposited energy (\( E_{\text{dep}} \)) and power (\( P_{\text{dep}} \)) should be measured. In this work, the voltage and current are measured with a voltage and current probes detailed in chapter [5]. First, the voltage and current are measured in a configuration in which no discharges are observed. This allows the measurement of the displacement current only. After synchronizing the voltage and the displacement current signals, the time delay between these two signals can be obtained. Therefore, this time delay is used to synchronize also the voltage and current signals during a discharge. The instantaneous power deposited by the discharge is then obtained multiplying the measured voltage and current:

\[ P_{\text{inst}} = V_{\text{disch}} \times I_{\text{disch}} \quad (2.7) \]

Integrating Eq. [2.7] over the pulse duration, the total energy deposited by the discharge can be obtained:
\[ E_{\text{dep}} = \int_{t_{\text{pulse}}} P_{\text{inst}} dt \] (2.8)

Therefore, the total deposited power can be evaluated multiplying the total energy by the pulse repetition frequency (PRF):

\[ P_{\text{dep}} = E_{\text{dep}} \times PRF \] (2.9)

A detailed description of the method utilized for the measurements of electrical properties of non-thermal plasma discharges can be found in [12, 77].
Chapter 3

Fuel and Equivalence Ratio Effects on Transfer Functions of Premixed Swirl Flames \[1, 2\]

Abstract

This chapter reports on the effects of fuel and equivalence ratio on the response of lean premixed swirl flames to acoustic perturbations of the flow, at atmospheric pressure. The response is analyzed using flame transfer functions. Two fuels, propane and methane, and five equivalence ratios are considered. The ten flames investigated are selected to exhibit the local maxima of the transfer function gain around the same frequency, 176 Hz and 336 Hz. The results show that changing fuel and equivalence ratio influences both the gain and the phase of the transfer function. The changes observed at 176 Hz and 336 Hz, where the dynamics of the flame is mainly controlled by the flame vortex roll-up mechanism, are discussed. Based on the analysis of the flow fields and the flame wrinkling, the laminar burning velocity and the flame temperature are identified as the main parameters controlling the gain. They have two competing effects: first, by enhancing the flame vortex roll-up and second, by affecting the strength of the vortex generated by the acoustic forcing due to changes in the height of the flame stabilization location. This entire chapter has been published in \[1, 2\].

3.1 Introduction

Several studies focused on the interactions between a swirl-stabilized flame and the acoustically generated vortex (AGV), that drive the flame vortex roll-up (FVR) and
control the maxima of the flame transfer function (FTF) gain \[37, 38, 99, 100\]. Palies et al. [99] showed that the fluctuations of the flame base angle may interact with the development of the AGV. In this case, the strength of the FVR is affected by this interaction. Similar to [99], Bunce et al. [37] suggested that when the position of the flame base fluctuates close to the shear layer at the nozzle tip, the strength of the AGV is reduced due to thermal effects. In both studies, even if different values of pressure, inlet temperature, and equivalence ratio are considered, their respective effects on the FVR are not analyzed. Oberleithner et al. [38] experimentally investigated the response of a swirl flame to acoustic forcing for different forcing amplitudes through the stability analysis of the shear layer from which the AGV is shed. They showed that the receptivity of the shear layer controls the size of the AGV and consequently the gain magnitude. However, the effects of fuel and equivalence ratio on the FVR are not analyzed in any of these studies.

Effects of fuel and equivalence ratio on the FTF of premixed swirl flames have also been the topic of a few studies \[36, 37, 101, 102\] but a satisfactory explanation of the observed trends is not always provided. The main challenge is that changing fuel or equivalence ratio affects important flame properties such as its length and, as a consequence, both the magnitude and the frequencies of the gain maxima usually change \[10, 42\]. It is then difficult to identify what the relevant fuel parameters are that should be considered for predicting the propensity of a fuel to promote thermoacoustic coupling. For premixed laminar flames, Gaudron et al. [103] have shown that, depending on the burner dimensions, the Lewis number, the laminar burning velocity, the flame thickness, and the flame temperature can play a role in the response of laminar flames to acoustic forcing. In a similar manner, it would be interesting to determine the relative impact of such properties on the FTF of turbulent premixed swirl flames.

In this context, the main objectives of the present chapter are: a) to analyze the
effects of fuel and equivalence ratio on the FTF of premixed swirl flames, and b) to identify the key parameters responsible for the fuel and equivalence ratio effects on the FVR. Understanding these effects could be of practical interest to engine designers. Indeed, changes in the fuel formulation or in equivalence ratio may have a dramatic impact on flame stability, and therefore on the behavior and performances of the gas turbine or aero-engine. Developing simple models for the effects of fuel and equivalence ratio on the flame response to acoustic perturbation could be a valuable tool.

### 3.2 Experimental Conditions and Diagnostics

The experimental setup utilized in this chapter consists of the swirl stabilized burner presented in Sec. 2.1.1 and diagnostics for flow and flame characterization described in Sec. 2.2.

#### 3.2.1 Experimental Conditions

The different fuels and equivalence ratios, and their corresponding thermal power ($P_{th}$), bulk velocity ($\bar{u}_{bulk}$), bulk Reynolds number (Re), laminar burning velocity ($S_L$), and adiabatic flame temperature ($T_{ad}$), examined in this chapter are summarized in Table 3.1. The values of $S_L$ are determined by averaging the values from [104, 105, 106, 107, 108, 109] with those calculated with Cantera [17] for a freely propagating flame with an initial temperature of 300 K using the USC-II mechanism [18] and a mixture-averaged mass diffusion model.

These ten flames are selected to exhibit the local extrema of the gain of the flame transfer function around the same frequencies. This is done to yield meaningful comparisons between all the cases. Indeed, if the extrema were not obtained for fixed frequencies, the driving mechanisms of the flame responses to acoustic modulation of the flow would have been combined in a different way for each condition. Conse-
<table>
<thead>
<tr>
<th>Fuel</th>
<th>$\phi$</th>
<th>$P_{th}$ (kW)</th>
<th>$\bar{u}_{bulk}$ (m/s)</th>
<th>Re</th>
<th>$S_L$ (m/s)</th>
<th>$T_{ad}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>0.65</td>
<td>3.8</td>
<td>6.4</td>
<td>7,400</td>
<td>0.15</td>
<td>1754</td>
</tr>
<tr>
<td></td>
<td>0.67</td>
<td>3.9</td>
<td>6.4</td>
<td>7,400</td>
<td>0.16</td>
<td>1788</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>4.0</td>
<td>6.4</td>
<td>7,400</td>
<td>0.19</td>
<td>1839</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>4.2</td>
<td>6.2</td>
<td>7,100</td>
<td>0.22</td>
<td>1888</td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td>4.2</td>
<td>6.2</td>
<td>7,100</td>
<td>0.25</td>
<td>1935</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>0.69</td>
<td>4.4</td>
<td>6.5</td>
<td>8,000</td>
<td>0.20</td>
<td>1863</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>4.4</td>
<td>6.5</td>
<td>8,000</td>
<td>0.22</td>
<td>1880</td>
</tr>
<tr>
<td></td>
<td>0.74</td>
<td>4.7</td>
<td>6.5</td>
<td>8,000</td>
<td>0.24</td>
<td>1947</td>
</tr>
<tr>
<td></td>
<td>0.79</td>
<td>4.7</td>
<td>6.3</td>
<td>7,600</td>
<td>0.30</td>
<td>2027</td>
</tr>
<tr>
<td></td>
<td>0.83</td>
<td>5.0</td>
<td>6.3</td>
<td>7,600</td>
<td>0.32</td>
<td>2087</td>
</tr>
</tbody>
</table>

Consequently, a quantitative analysis of the effect of fuel and equivalence ratio would have been extremely challenging. Direct time-averaged images recorded with a DSLR camera for all the flames investigated are shown in Fig. 3.1.

![Figure 3.1: Photographs of the flames considered in this study. The exposure time is 1.6 s for all these images.](image-url)
3.2.2 Diagnostics

The FTF can be evaluated from the velocity oscillations and the global heat release rate fluctuations of the flame subjected to acoustic forcing. A hot wire (Dantec miniCTA) is used to measure the velocity oscillations 1 cm upstream of the swirler, corresponding to about 7 cm upstream of the outlet of the injection tube. Although the velocity fluctuations should ideally be measured at the flame location, it has been shown in a previous study using a similar setup [10] that measuring them upstream of the swirler does not introduce significant modifications to the FTF for forcing frequencies smaller than 1 kHz. A difference in the magnitude of the gain of less than 10% and a difference in the slope of the phase of less than 5% are observed. These differences would apply equally to all the experimental conditions analyzed so the general trend of the results would be maintained.

A photomultiplier tube (Hamamatsu H10721), equipped with a 10 nm bandpass filter centered at 310 nm (ZBPA310 ASAHI Spectra Co.) is used to measure the fluctuations of OH$^*$ chemiluminescence. It has been shown in previous studies [10, 42, 110] that this technique can be used for non-adiabatic combustors to infer the heat release rate fluctuations and the errors introduced in doing so are not of the first order. The hot wire signal, the photomultiplier tube (PMT) signal, and the forcing signal are recorded using an oscilloscope (Agilent Technologies Infiniium 2.5 GHz).

The flame dynamics during acoustic forcing is captured by collecting the OH$^*$ chemiluminescence with an intensified CCD camera (Princeton Instruments PI-MAX) equipped with a UV lens (105 mm Coastal Optics) and a 10 nm bandpass filter centered at 310 nm (ZBPA310 ASAHI Spectra Co.). The exposure time is kept equal to 200 $\mu$s in all cases. The camera is synchronized with the signal generator controlling the acoustic forcing, allowing the collection of images during different specified phases of the forcing period.

The velocity fields are measured by particle image velocimetry (PIV). The PIV
system comprises a 10 Hz dual pulse Nd:YAG laser (Litron Nano L200-15 PIV), that
generates a laser beam of 26 mJ per pulse at 532 nm, and a 1200 × 1600 pixels dual
frame CCD camera (LaVision Imager Pro X). The camera is equipped with a lens
(60 mm AF Micro Nikkor) and a 10 nm bandpass filter centered a 532 nm (LaVision
VZ17-0117). The laser beam is converted into a laser sheet of about 1 mm thickness
and 60 mm height through a combination of spherical and cylindrical lenses. The
laser sheet is focused along the central axis of the burner, allowing the measurement
of the axial and radial components of the velocity field. The flow of reactants is seeded
with titanium dioxide (TiO$_2$) particles featuring an average diameter of around 3 µm.
The images are processed with a multi-pass technique (LaVision DaVis 8.4.0) with
a 16 × 16 pixels final interrogation area and 50% overlap, yielding a vector spacing
of 0.4 mm. The PIV system is synchronized with the signal generator controlling
acoustic forcing to measure phase-locked velocity fields during the forcing period.

Finally, OH planar laser-induced fluorescence (OH-PLIF) imaging of the flames
has been conducted to infer the flame front position and curvature as a function of
fuel, equivalence ratio, and phase of the modulation period. The 10-Hz OH-PLIF
system used is fairly standard, and the interested reader is referred to [11] for more
details. The laser sheet for the OH-PLIF overlaps that of the PIV but has a thickness
of around 200 µm.

### 3.3 Experimental Procedure

For each experimental condition, the flame is first ignited and run for at least 15
minutes to ensure that thermal steady state is reached. The acoustic forcing of the
flow of reactants is then started, and the amplitude of the forcing signal is adjusted
to obtain a velocity fluctuation amplitude equal to 10% of the mean flow velocity.
A 10% amplitude has been chosen to ensure the linear response of the flames to the
acoustic forcing while overcoming the natural level of turbulent fluctuations, which
is about 5%. The frequency of the forcing signal is increased from 32 Hz to 400 Hz by steps of 16 Hz. The forcing signal, the velocity signal measured with the hot wire, and the OH∗chemiluminescence signal collected with the PMT are simultaneously recorded for 10 s with a sampling frequency of 20 kHz and are used to compute the FTF.

The flame dynamics is collected and analyzed at the forcing frequencies of 176 Hz and 336 Hz. These frequencies are chosen because they correspond to the local maxima of the gain of the FTF. This is also where the influence of the fuel and φ will be investigated in detail. To collect phase-locked images of OH∗ chemiluminescence, OH-PLIF, and velocity fields, the forcing period is divided into 10 phases, θ, with an interval of 36° each. The phase θ = 0° is selected when \( u' = 0 \) and \( \frac{\partial u}{\partial t} > 0 \) at the position of the hot wire. The phase-locked OH and velocity fields are collected at the forcing frequency of 176 Hz only.

To investigate the flame dynamics, 1000 images of OH∗ chemiluminescence are collected for each of the ten phases of the forcing period and are then averaged to ensure statistical convergence. After checking that the flame is axisymmetric on average, an Abel-deconvolution is applied to evaluate the distribution of the OH∗ chemiluminescence intensity in the central longitudinal plane. A similar procedure is followed with the measured velocity fields. To ensure statistical convergence, 800 instantaneous velocity fields are averaged for each of the ten phases of the forcing period. The phase-averaged velocity fields are smoothed using a 5×5 pixel Gaussian filter. The coherent flow structures, i.e., the outer recirculation zone (ORZ) and the vortex generated by acoustic forcing (AGV), are identified in the phase-averaged velocity fields using the Q-criterion \[38, 112\]. The quantity Q is defined as \( Q = 0.5(||Ω||^2 - ||S||^2) \), where Ω and S are vorticity tensor and strain rate tensor, respectively. The Q fields of each experimental condition are then normalized with respect to the overall maximum value, which is obtained for the unforced propane flame with \( \phi = 0.70 \). Furthermore,
a total of 750 OH-PLIF images are recorded for each condition examined. Raw images are first corrected for background noise, and a binarized flame front is then extracted using a Canny edge-detection algorithm. The signed curvature is finally computed at each flame front position and for each available OH-PLIF image. Due to the limited optical resolution of the OH-PLIF arrangement (roughly 0.4 mm), the maximum curvature measurable is estimated to be $|\kappa| = 2500 \text{ m}^{-1}$.

### 3.4 Results

In this section, the results obtained in this study are presented. First, the transfer functions of both fuels are displayed, then the images of the OH* chemiluminescence from the flames during the forcing cycle at 176 Hz and 336 Hz are presented. Therefore, the unforced velocity fields and the evolution of the acoustically generated vortex at 176 Hz are shown. Moreover, the phase-locked flame front curvature measurements are presented at 176 Hz. The results are analyzed in terms of equivalence ratio at 176 Hz and laminar burning velocity at 336 Hz to be consistent with publications [1, 2]. The two parameters can be related using Table 3.1.

#### 3.4.1 Flame Transfer Functions

The transfer functions of the flames considered in this chapter (see Table 3.1) are presented in Fig. 3.2. Both gain and phase show the trend that is typical for swirl flames. At low frequency, the gain approaches one and the phase approaches zero [44]. Focusing on the gain, a local minimum is found at 112 Hz followed by a local maximum at 176 Hz [3, 10, 42, 113, 114]. The competition between the fluctuations of the bottom region of the flame, generated by the oscillations of the flame base angle driven by the fluctuations of the swirl number [10, 37], and the oscillations of the top region due to flame vortex roll-up [10, 27, 34, 38, 39, 40, 41], generates this distinctive trend of the gain. The phase shows a linear trend for frequencies ranging from 32 Hz
Figure 3.2: Flame transfer functions of methane (left) and propane (right) premixed swirl flames at 10% of forcing amplitude. Arrows indicate trends with increasing equivalence ratio.

to 112 Hz. Around 112 Hz, the phase decreases suddenly but then resumes its linear increase for frequencies above 128 Hz. This sudden decrease of the phase is observed at around the same frequency of the first local minimum of the gain. Since the flame transfer function is a smooth complex-valued function, a zero in the gain is thus naturally accompanied by a phase jump.

Having presented the general trend of the gain and phase of the FTF, the effect of equivalence ratio can now be detailed. As shown in Fig. 3.3 (right), for all the equivalence ratios investigated, the extrema of the gain do not show any significant shift in frequency. Note that the bulk velocity has been slightly adjusted for the highest values of $\phi$ for both fuels to maintain similar values of frequency for the extrema of the gain. At its first maximum (64 Hz), the gain magnitude first increases
with the equivalence ratio up to $\phi = 0.73$ for methane, and $\phi = 0.79$ for propane, but then decreases. Similar behavior can be observed at the frequency of the second gain maximum (176 Hz), but with more pronounced effects. Finally, around 336 Hz, the gain monotonically increases with the equivalence ratio. No clear trend can be revealed at the local minimum of gain near 112 Hz. These trends are highlighted in Fig. 3.3 (left). Similar behavior is observed for both fuels although propane flames show globally higher gain responses, especially for frequencies around 176 Hz and 336 Hz. For both fuels, at frequencies lower than 112 Hz, the phase is not affected by the change in equivalence ratio, while for higher frequencies, it decreases with equivalence ratio, as highlighted by the black arrows in Fig. 3.2. In the interest of conciseness, only the effects of fuel and equivalence ratio at 176 Hz and 336 Hz, where the gain magnitude is large, are analyzed and discussed.

Figure 3.3: FTF gain (left) and frequency (right) of the local maxima as a function of equivalence ratio.

The effect of the laminar burning velocity on the gain response at 336 Hz is also presented in Fig. 3.4. It is shown that by increasing $\phi$, and consequently $S_L$, the gain at 336 Hz increases linearly for both fuels.
Figure 3.4: Gain response at 336 Hz as a function of the equivalence ratio (left) and laminar burning velocity (right). The error bars represent the discrepancy in the value of \( S_L \).

3.4.2 Flame Dynamics

176 Hz

The phase-locked Abel-deconvoluted images of OH\(^*\) chemiluminescence are shown in Figs. 3.5 (methane) and 3.6 (propane). For clarity, only one phase each 72° is presented. The phases that are not shown in these figures do not provide any additional information to the motion of the AGV and to the analysis of the results. These images are normalized with respect to the global maximum value of OH\(^*\) chemiluminescence intensity at the same equivalence ratio and for the same fuel. An iso-contour of 0.4 is highlighted in black to assist visualization of the flame motion. The iso-contour is calculated to delimit the surface area of the flame that accounts for 60% of the total intensity of the OH\(^*\) chemiluminescence/heat release of the flame. It is used to highlight the flame boundaries in order to help in visualizing the flame dynamics and the flame vortex roll-up mechanism. As shown in a previous study [3], choosing a different value for the iso-contour has no influence on the analysis and conclusions. The acoustically generated vortex (AGV) and the outer recirculation zone (ORZ) are also
Figure 3.5: Phase-locked 0.5 iso-contours of normalized $Q$-criterion superimposed to the normalized phase-averaged Abel-deconvoluted OH$^*$ chemiluminescence intensity of methane flames at 10% forcing amplitude at 176 Hz.

highlighted in these figures. The way they are determined is detailed in Sec. 3.4.4.

As presented in the introduction, the FVR is an important mechanism that controls the flame response to the acoustic excitation at 176 Hz. In order to characterize the FVR for all the conditions investigated, an ellipse is fitted in the 0.4 iso-contour near the flame tip. The choice of an ellipse is dictated by the fact that it is the sim-
plest geometrical shape that fits the best in the flame shape. Only the phase during the forcing period for which the perimeter of the ellipse is the largest is considered. For example, it is \( \theta = 332^\circ \) for methane flames at \( \phi = 0.65 \) and \( \theta = 260^\circ \) for propane flames at \( \phi = 0.83 \).
Figure 3.7: Temporal fluctuation of the normalized OH\(^*\) chemiluminescence integrated over the top (blue) and bottom (red) regions, and over the entire flame (black) for methane (left) and propane (right) flames at 176 Hz.

Figures 3.5 and 3.6 show that modifying the equivalence ratio or the fuel has a
large influence on the perimeter of these ellipses. Trends are examined in more detail in Sec. 3.5. Each image has been divided into two regions by a solid black line: a top region above the line, that is positioned to include all the contributions of the flame vortex roll-up to the flame motion, and a bottom region below this line. This line can be slightly moved, up or down, without substantially changing the normalized integrated OH* chemiluminescence intensity signals. The OH* chemiluminescence intensity can be integrated over each of the top and bottom regions, and over the entire flame, for each forcing phase, fuel, and equivalence ratio in order to analyze flame dynamics in more detail. Results are shown in Fig. 3.7.

Note that the results presented in this figure are obtained from the images without Abel deconvolution. These integrated OH* chemiluminescence intensities are normalized by the value obtained by averaging over the same region and over the whole forcing period. This normalization procedure is used only to ease the comparison of amplitude of fluctuations and phase differences by having the mean value equal to one. The relative amplitude and phase are not modified by the normalization procedure. The error bars represent the range of amplitudes that the signals can exhibit, while slightly modifying the position of the solid black line. For both fuels, the amplitude of the temporal fluctuations of the OH* chemiluminescence intensity of the top region (blue squares) is two to six times larger than that of the bottom region (red circles), depending on fuel and equivalence ratio. This suggests that the dynamics of the top region is predominant. However, for the largest equivalence ratio (lowest row), and regardless of fuel, the relative contribution of the bottom region increases. An explanation for this behavior is provided in Sec. 3.5. On the other hand, the maximum difference between the amplitude of the temporal fluctuations of the OH* chemiluminescence intensity of the top region (blue squares) and those of the entire flame (black triangles) ranges from 0.1 % to 5 %. This very small difference underlines that the dynamics of the bottom region is negligible compared to the one
of the top region, even for cases where their fluctuations are out-of-phase (largest equivalence ratio).

3.4.3 336 Hz

To better understand the response of the flame to acoustic perturbation of the flow at 336 Hz, the phase-locked Abel-deconvoluted OH\(^*\) chemiluminescence images are reported in Fig. 3.8 for propane and in Fig. 3.9 for methane. The same post-processing technique of Figs. 3.5 and 3.6 described in Sec. 3.4.2 is applied to these figures.

Also at 336 Hz, changing fuel and equivalence ratio, the maximum size of the ellipse changes. Trends are examined in more detail in Sec. 3.5. The OH\(^*\) chemiluminescence intensity integrated over each region during the forcing period is reported in Fig. 3.10. These signals are normalized with their average value in the same region of the flame over the whole forcing cycle.

For both fuels, the relative amplitude of the fluctuations of the bottom region with respect to the top region changes with \(\phi\) and \(S_L\). More precisely, the amplitude of the fluctuations of both regions increases with increasing the laminar burning velocity. Moreover, the phase difference between the two regions changes with \(S_L\). The fluctuations of the two regions are almost out-of-phase for the lower values of \(S_L\), while they are almost in-phase for the higher values of laminar burning velocity.

3.4.4 Velocity fields

Examples of velocity fields measured without acoustic forcing are presented in Fig. 3.11 (left), for cold flows, and in Fig. 3.11 (right), for reactive cases. Typical features of cold and reactive swirl flows are observed, including: an inner recirculation zone (IRZ) enclosed by an annular jet (AJ) surrounded by an outer recirculation zone (ORZ). The ORZ is highlighted by a 0.5 iso-contour of the normalized \(Q\)-criterion. Figure 3.11 (left) shows that changing the equivalence ratio, fuel, and/or bulk veloc-
Figure 3.8: Phase-locked abel-deconvoluted OH* chemiluminescence images of propane flames at 10% of the forcing amplitude at 336 Hz.
Figure 3.9: Phase-locked abel-deconvoluted OH* chemiluminescence images of methane flames at 10% of the forcing amplitude at 336 Hz.
Figure 3.10: Temporal fluctuation of the normalized OH* chemiluminescence integrated over the top (blue) and bottom (red) regions for methane (left) and propane (right) flames at 336 Hz.
ity (see Table. 3.1) has no noticeable influence on the cold flow fields. On the other hand (see Fig. 3.11 (right)), the presence of the flame substantially modifies the flow field by yielding higher velocities in the AJ, as well as modifying the IRZ and ORZ. In the presence of a flame, when $\phi$ is increased, the position of the ORZ shifts upstream while its size reduces. A similar trend is observed for both fuels. Comparing Figs. 3.11 (left) and 3.11 (right), it is obvious that the presence of the flame plays a major role in defining the velocity field and outweighs the small differences in bulk velocity between the different cases (see Table. 3.1).

To analyze the interactions between the flame, the AGV, and the ORZ at 176 Hz, the phase-locked 0.5 iso-contours of the normalized $Q$-criterion are superimposed to the phase-locked normalized $OH^*$ chemiluminescence intensity in Figs. 3.5 (methane) and 3.6 (propane). These figures highlight the evolution of the vortex generated by acoustic forcing. The vortex is shed from the outer shear layer at the nozzle tip (around $\theta = 44^\circ$). It then travels downstream, interacts with the flame and finally merges with the ORZ ($\theta = 260^\circ$). Unfortunately, the $Q$-criterion is not able to track the AGV inside the ORZ. The size of the AGV increases with time during the forcing cycle and it reaches its maximum measurable value at $\theta = 188^\circ$. Regardless of fuel, the maximum size of the AGV seems to decrease as the equivalence ratio is increased. The evolution of the AGV is analyzed in Sec. 3.5 for a forcing frequency equal to 176 Hz only.

### 3.4.5 Flame Front Curvature at 176 Hz

Lean premixed propane flames have a non-unity Lewis number ($Le = 1.88$). Consequently, it is important to assess whether or not differential-diffusion effects can play a role in the response of the flame to acoustic forcing. To investigate this potential effect, the probability density function (PDF), of flame front curvature ($\kappa$), should be determined. For this purpose, the forced-flame front curvature is measured by
Figure 3.11: Unforced mean velocity fields for methane (top) and propane (bottom) measured without (left) and with (right) flame.

using OH-PLIF images. Figure 3.12(a) shows an example of instantaneous OH-PLIF image and flame front (color-coded to the signed curvature $\kappa$), for a propane flame with $\phi = 0.7$, at the phase $\theta = 332^\circ$.

The OH-PLIF snapshots are assembled in the 10 phase bins. The signed curvature of the flame front is measured for all snapshots with a certain phase and
Figure 3.12: (a) Snapshot of OH-PLIF and extracted flame front for propane with $\phi = 0.70$ and $\theta = 332^\circ$. PDFs of curvature $\kappa$ for propane (b) and methane (c).

equivalence ratio, and the corresponding PDF is computed. This is shown, for example, in Figs. 3.12(a) and (b) for propane and $\phi = 0.70$ at $\theta = 332^\circ$. Figure 3.12(c) shows the PDF of signed curvature for methane at $\phi = 0.67$ at $\theta = 332^\circ$. The phase considered in Figs. 3.12(a)-(c) corresponds to the time of most intense flame vortex roll-up during the forcing period at 176 Hz. Both distributions of signed curvature $\kappa$ are unimodal and very similar. Values of $\kappa$ are biased towards negative values. Therefore, concave flame sheets that are curved towards reactants are most probable, and this could be due to the flame topology. In addition, the curvature probability gradually decreases and reaches a zero value near $|\kappa| = 2000 \text{ m}^{-1}$, which is below the detection limit of $|\kappa| = 2500 \text{ m}^{-1}$, suggesting that the entire meaningful curvature dynamics is captured with the available OH-PLIF arrangement. Similar results are obtained for all the operating conditions considered in this study. These results are used in the next section to assess the impact of differential-diffusion on the dynamics.
of the lean propane flames that feature non-unity Lewis numbers.

3.5 Discussion of the Results

The results presented in the previous sections are analyzed in more depth here. First, the dependency between the gain of the FTF at 176 Hz and 336 Hz, and the maximum size of the FVR is discussed. Then, parameters controlling the maximum size of the FVR are identified. Next, an explanation for the behavior of the FTF gain at 176 Hz and 336 Hz, when the equivalence ratio or $S_L$ is increased is proposed. Finally, effects of fuel and equivalence ratio on the FTF phase are discussed.

3.5.1 Relation between FVR and FTF Gain

As shown in Fig. 3.7, the dynamics of the flame at 176 Hz is mainly controlled by the motion of its top region which is driven by FVR. However, the contribution of the bottom region to the flame dynamics increases with the equivalence ratio for both fuels. This trend could be attributed to the decrease in bulk velocity that is needed to maintain the local gain maximum at 176 Hz when the equivalence ratio is increased (see Tab. 3.1). Indeed, decreasing the bulk velocity usually results in the reduction of the frequency at which the temporal fluctuations of the swirl number are negligible [10, 31, 41, 115]. Since swirl number fluctuations are known to influence mainly the dynamics of the bottom region, it is possible that reducing the bulk velocity augments the dynamics of the bottom region due to the introduction of swirl number fluctuations at 176 Hz.

From the phase-locked OH$^*$ chemiluminescence images, the maximum perimeter of the flame vortex roll-up, referred to as FVR$_{\text{max}}$ and defined by the white ellipses in Figs. 3.5 and 3.6 can be evaluated for all the conditions examined. This maximum perimeter is used as a measure of the maximum size of the flame vortex roll-up during the forcing cycle. The rolling up of the flame around the toroidal vortex shed at the
nozzle tip due to the incoming acoustic wave modulates the flame surface area, and consequently the heat release from the flame. Therefore, the maximum size of the FVR during the forcing cycle, the FVR\textsubscript{max}, can be used as a metric of the impact of the FVR on the flame surface area, heat release, and flame dynamics. The magnitude of the FTF gain measured at 176 Hz is plotted as a function of FVR\textsubscript{max} in Fig. 3.13 (top). Figure 3.13 shows that the magnitude of the FTF gain at 176 Hz is proportional to FVR\textsubscript{max}. The error bars in Fig. 3.13 represent the uncertainty in the fitting
process of the ellipse into the 0.4 iso-contour of normalized OH* chemiluminescence intensity. Figure 3.13 (bottom) plots the magnitude of the FTF gain measured at 176 Hz as a function of FVR$_{\text{max}}$ if only the contribution of the top region to the OH* signal is accounted for. This can be achieved by using the top region of the phase-locked OH* chemiluminescence images (without Abel deconvolution), instead of the photomultiplier tube signal to compute the FTF gain. The magnitude of the FTF gain at 176 Hz remains proportional to FVR$_{\text{max}}$, which confirms that flame vortex roll-up in the top region of the flame controls the flame dynamics. Therefore, in order to quantify the effects of fuel and equivalence ratio on the FTF gain at 176 Hz, it is important to understand the effects of fuel and equivalence ratio on FVR.

From Fig. 3.10 it is possible to observe that both regions of the flame are oscillating during the forcing cycle, highlighting that both regions are contributing to the response of the flame to acoustic forcing at 336 Hz. From Figs. 3.8 and 3.9, FVR$_{\text{max}}$ can be estimated. The value of the gain of the FTF at 336 Hz as a function of the FVR$_{\text{max}}$ is reported in Fig. 3.14.

![Graph](image)

Figure 3.14: Gain of the FTF at 336 Hz as a function of FVR$_{\text{max}}$ for all the conditions analyzed in this chapter. The error bars represent the uncertainty in the fitting process of the white ellipse into the iso-contour of the normalized OH* chemiluminescence.
A linear behavior can be observed, highlighting that the FVR is an important parameter determining the flame response to acoustic forcing at 336 Hz. On the other hand, it is important to note that a non-zero value of FVR$_{\text{max}}$ results in a zero value of the gain. If the motion of the bottom region was negligible compared to the top region, a gain equal to zero should result from a zero value of the FVR$_{\text{max}}$. In other words, the gain is zero when the FVR$_{\text{max}}$ is not zero because the motion of the bottom region of the flame is destructively interfering with the fluctuation of the top region reducing the global response of the flame to acoustic forcing. An additional explanation for this non-zero offset could be that an ellipse of finite perimeter could fit in the thickness of the turbulent flame brush even if the FVR is not present (see Fig. 3.1). This is because the thickness of the turbulent flame brush is of the same order as the size of the ellipse (see Figs. 3.8 and 3.9).

### 3.5.2 Effects of Differential-diffusion

For a non-unity Lewis number mixture, such as the lean propane–air mixtures examined here, the burning velocity and the heat release rate can be affected by the local flame curvature, which may, in turn, affect flame dynamics and FTF gain. However, such differential-diffusion effects can only occur if the local flame radius of curvature is comparable to the Markstein length [116]. In their investigations of the dynamics of laminar premixed lean propane conical flames, Gaudron et al. [103] observed that differential-diffusion starts to play a role for a small circular injector with a diameter of 1.5 mm and that this was due to significant curvature near the conical flame tip. Careful examination of their flame images suggests that the radius of curvature of the flame tip is close to $R = 0.24 \text{ mm}$ while the Markstein length for the $\phi = 0.88$ propane–air mixture examined is roughly $\mathcal{L} = 0.15 \text{ mm}$ [117]. Therefore, the ratio of the radius of curvature to the Markstein length below which differential-diffusion is found to play a role in [103] is $R/\mathcal{L} = 1.6$. To remain conservative, much larger
radii of curvature of up to three times the Markstein length may be considered as potentially yielding differential-diffusion effects. In this study, using the methodology of [118], the Markstein lengths are evaluated to \( \mathcal{L} = 0.209 \text{ mm} \) for propane flames at \( \phi = 0.7 \) and \( \mathcal{L} = 0.146 \text{ mm} \) for methane flames at \( \phi = 0.67 \), leading to critical radii of curvature of \( R = 0.627 \text{ mm} \) and \( R = 0.438 \text{ mm} \) and critical curvatures of \( \kappa = 1595 \text{ m}^{-1} \) and \( \kappa = 2283 \text{ m}^{-1} \), respectively. It is evident from Figs. 3.12(b) and (c) that such large magnitudes of curvature are not encountered with high probabilities in the flames examined here. Similar results are obtained for the other flames of this study (not shown here for conciseness). Therefore, differential-diffusion effects that are able to locally enhance or impair the burning velocity and heat release rate in the flames examined here are not statistically probable at a forcing frequency of 176 Hz.

This can be confirmed by using the model developed by Preetham et al. [119], which suggests that the cutoff forcing frequency below which differential-diffusion plays no role in the dynamics of the present flames is \( f = 1000 \text{ Hz} \), which is much larger than the maximum forcing frequency considered here, \( f = 400 \text{ Hz} \). This model also shows that the hydrodynamic strain starts to play a role only for frequencies much higher than 1000 Hz. Therefore, differential-diffusion effects are ignored for the remaining analysis and the local burning velocity will be considered equal to the unstretched laminar burning velocity \( S_L \).

### 3.5.3 Effects of the Laminar Burning Velocity

All the flames considered in this study reside in the “reaction sheet” regime of the Borghi diagram [120, 121, 122, 123]. Therefore, the flames locally behave as laminar when interacting with turbulent eddies. In addition, from Figs. 3.5 and 3.6, the characteristic size of the AGV, obtained at phase \( \theta = 188^\circ \), can be estimated to be 6–10 mm, which is much larger than the flame thickness. For these reasons, the laminar burning velocity remains the controlling burning velocity on a microscopic
level and it is expected to play a role on the FVR. As previously stated, the flame vortex roll-up mechanism is generated from the interaction of the toroidal vortex shed from the shear layer at the nozzle tip and the flame itself. The vortex propagates along the top region of the flame, modifying the flow field locally. At the same time, due to the modified flow field, the flame is pulled along with the vortex increasing its perimeter, and consequently, its surface area. The increase in flame surface area is then followed by a decrease that could be due to local quenching induced by the interaction with the vortex. This fluctuation of the flame surface area results in the fluctuation of the global heat release from the flame. Higher values of laminar burning velocity could delay the local quenching, resulting in a greater increase of the surface area, and consequently, in a higher amplitude of global heat release fluctuation, i.e., higher FTF gain, during the forcing cycle. For this reason, the laminar burning velocity can be an important parameter controlling the FVR mechanism.

For all the conditions investigated, FVR$_{\text{max}}$ is plotted in Fig. 3.15 as a function of $S_L$ for a forcing frequency of 176 Hz. The vertical error bars represent the uncertainty in the fitting process of the ellipse into the 0.4 iso-contour of normalized OH$^*$ chemiluminescence intensity. The horizontal error bars represent the discrepancy in the value of $S_L$ taken from the literature. The corresponding equivalence ratios are also reported in the graph.

For both fuels, FVR$_{\text{max}}$ first increases with $S_L$ and then decreases. For the three smallest equivalence ratios of each fuel, FVR$_{\text{max}}$ is almost proportional to $S_L$. This can be explained by the fact that increasing the laminar burning velocity allows the flame to more readily conform to any change in the flow field, without being quenched, promoting flame vortex roll-up. However, the largest values of equivalence ratio for each fuel correspond to the lowest values of FVR$_{\text{max}}$ even though $S_L$ is large. This behavior suggests that other mechanisms are involved and that additional parameters
Figure 3.15: The FVR$_{\text{max}}$ at 176 Hz as a function of $S_L$ for all the flames considered in this study.

play a role in controlling the maximum size of the FVR at 176 Hz.

The maximum perimeter of the flame vortex roll-up at 336 Hz is plotted as a function of $S_L$ in Fig. 3.16.

Figure 3.16: The FVR$_{\text{max}}$ at 336 Hz as a function of the laminar burning velocity for all the experimental conditions analyzed in this study. The vertical error bars represent the uncertainty in determining the dimensions of the FVR$_{\text{max}}$. The horizontal error bars represent the discrepancy in the value of $S_L$. The dashed blue line is interpolated considering only the three lowest $S_L$ of each fuel.
It is possible to observe a linear trend between the laminar burning velocity and the FVR$_{\text{max}}$ for $S_L < 0.23\text{ m/s}$. Similar to 176 Hz, below this threshold value, a higher value of $S_L$ increases the ability of the flame to adapt to sudden changes in the flow field generated by the impinging vortex producing a bigger flame vortex roll-up. For $S_L > 0.23\text{ m/s}$ and for each fuel, the trend between $S_L$ and the FVR$_{\text{max}}$ diverges from the linearity, suggesting that other parameters are also affecting the maximum perimeter of the FVR at 336 Hz.

### 3.5.4 Effects of the Stabilization Distance on the AGV Circulation

As proposed by [126, 129], another parameter that needs to be considered in the FVR process is the circulation of the impinging acoustically generated vortex. According to [130], the circulation of a vortex, $\Gamma$, can be defined as the line integral over a closed contour, $C$, of the tangential component of the velocity, or as the integral over the cross-section area enclosed by $C$, $A$, of the vorticity component perpendicular to the cross-section area:

$$\Gamma = \oint_C \mathbf{u} \cdot d\mathbf{s} = \int_A \mathbf{\omega} \cdot dA \quad (3.1)$$

Here, $d\mathbf{s}$ is a line element of the contour and $dA$ is an element of the cross-section area. In this chapter, the circulation of the AGV at 176 Hz is evaluated by integrating the vorticity over the cross-section area of the vortex delimited by the 0.5 iso-contour of the normalized $Q$-criterion. The temporal evolution of $\Gamma$ over a forcing period is plotted in Fig. 3.17 for the experimental conditions investigated at 176 Hz. The error bar represents the uncertainty in the definition of the cross-section area of the vortex. The error bar is shown only for phase $\theta = 224^\circ$ of the propane flame with $\phi = 0.69$. This is done to keep the graph readable. All the other data in the graph have similar uncertainties. From the planar velocity data, only the azimuthal vorticity can be determined. However, as the acoustic forcing is axisymmetric, the coherent structure
that is generated is an azimuthal vortex that evolves in the measurement plane. Therefore, considering the circulation evaluated only from the azimuthal vorticity is a reasonable simplification.

Figure 3.17: Temporal evolution of the circulation of the AGV during the forcing cycle at 176 Hz for all the experimental conditions investigated in this study.

Regardless of fuel and equivalence ratio, the AGV circulation increases with time, after the AGV is being shed from the injector nozzle and while it is convected further downstream. The maximum value of the circulation, \( \Gamma_{\text{max}} \) is measured at phase \( \theta = 188^\circ \) for all the flames because for this value the AGV merges with the ORZ and its circulation cannot be determined anymore. Figure 3.17 shows that all the curves describing the temporal evolution of the AGV collapse within the experimental uncertainties, except for the two largest \( \phi \) of each fuel. For both fuels, the two largest \( \phi \) yield significantly smaller values of \( \Gamma_{\text{max}} \) over the whole forcing cycle. This suggests that the AGV is much weaker for the two largest \( \phi \) of each fuel. This is corroborated by Figs. 3.5 and 3.6 where the largest \( \phi \) exhibits the smallest AGV at \( \theta = 188^\circ \). It is important to note that the AGV circulation does not decrease continuously with \( \phi \). For each fuel, there exists a critical equivalence ratio below which the AGV circulation is not a function of \( \phi \). Above this threshold, the AGV circulation decreases suddenly.
and rapidly when $\phi$ is increased. The critical equivalence ratios are $\phi = 0.70$ and $\phi = 0.74$ for methane and propane, respectively. Additional values of equivalence ratio will be needed to understand this sudden decrease in the value of the circulation with increasing the equivalence ratio. The sudden decrease in the value of $\text{FVR}_{\text{max}}$ for the highest values of laminar burning velocity (see Fig. 3.15) could be due to the decrease in the maximum circulation of the AGV. When $\Gamma_{\text{max}}$ decreases, the value of $S_L$ is not high enough to keep increasing the $\text{FVR}_{\text{max}}$. This would result in an overall lower value of $\text{FVR}_{\text{max}}$ for the largest laminar burning velocities.

It has been shown in previous studies [35, 37, 38, 99] that the interaction between the flame and the shear layers near the nozzle tip, where the AGV is shed, controls the properties of the AGV. In particular, Bunce et al. [37] suggested that the closer the flame is to the shear layer near the nozzle tip, the weaker is the AGV. This could be attributed to the increase of the temperature in the shear layer due to its closer proximity to the flame, which could affect gas expansion, baroclinic generation of vorticity, and viscous diffusion, and thereby reduce the circulation of the AGV [35, 37, 126, 131, 132, 133, 134, 135, 136].

![Figure 3.18: Position of the flame front near the nozzle tip obtained from time averaged images of OH$^*$ chemiluminescence of unforced flames.](image-url)
In order to verify if the distance from the flame to the shear layer may be responsible for the decrease of $\Gamma_{max}$ observed for the largest $\phi$, the position of the flame front near the nozzle tip is presented in Fig. [3.18]. It is obtained from the time-averaged OH$^*$ chemiluminescence images of the unforced flames, without Abel deconvolution. After normalizing each image, a 0.4 iso-contour is considered. The square dots correspond to this iso-contour for each experimental condition. The dashed and solid lines are linear extrapolations of the flame fronts. Even though the value of the iso-contour (0.4) is somewhat arbitrary, choosing another value does not change the trend of the results. In the absence of acoustic forcing, the angle of the flame base is constant. It is not a function of fuel and equivalence ratio. More importantly, all the flames stabilize at different heights above the nozzle tip. For each fuel, flames featuring the largest $\phi$ are stabilized closer to the nozzle. In addition, for the same $\phi$, methane flames sit closer to the nozzle than propane flames, even though their laminar burning velocities are smaller. The effect of fuel on the stabilization distance of premixed swirl flames will be the topic of further investigations.

Figure 3.19: The $\Gamma_{max}$ as a function of $d$ for the cases examined at 176 Hz.

For each flame, it is possible to define a stabilization distance, $d$, as the length of a vertical line starting from the nozzle outer rim and ending as it intersects the linearly
extrapolated flame front (colored lines in Fig. 3.18). The maximum circulation, $\Gamma_{\text{max}}$, is plotted as a function of the stabilization distance, $d$, in Fig. 3.19. For both fuels, $\Gamma_{\text{max}}$ varies almost linearly with $d$. When the flame stabilizes close to the nozzle tip, the size of the AGV and its circulation are small. Note that there is a small difference between the two fuels. For a given stabilization distance, the strength of the AGV is consistently smaller for propane flames in comparison to methane flames. This could be explained by the fact that propane flames have higher thermal power than methane flames for a similar bulk velocity (see Table 3.1), potentially resulting in a higher temperature in the shear layer near the nozzle tip.

### 3.5.5 Combined Effects of $S_L$ and the AGV Circulation

In the previous subsections, it has been shown that increasing the equivalence ratio, and, in turn, the laminar burning velocity has two competing effects on flame vortex roll-up. It promotes flame propagation but it also brings the flame closer to the nozzle, which weakens the AGV responsible for FVR. In this section, these combined and competing effects are discussed at a forcing frequency of 176 Hz. In Fig. 3.20, the FVR$_{\text{max}}$ is plotted as a function of the product of the laminar burning velocity and the maximum circulation of the AGV: $S_L \times \Gamma_{\text{max}}$. The FVR$_{\text{max}}$ is almost proportional to this product. It could be argued that discrepancies lie within the rather large experimental uncertainties. Figure 3.20 confirms that both the laminar burning velocity and the circulation of the acoustically generated vortex are important parameters that control the flame vortex roll-up and, in turn, the dynamics of these premixed swirl flames at 176 Hz. These results also suggest that, for AGVs of equal circulation, the maximum size of the flame vortex roll-up, as well as the FTF gain, increases linearly with the laminar burning velocity. This is an important result that promotes the development of low-order models for the prediction of flame transfer functions. A corollary is that low-order models have no chance in predicting
accurately the FTF gain if they do not account for all the parameters controlling the generation and growth of the acoustically generated vortex during a forcing cycle.

![Graph showing FVR max at 176 Hz as a function of the product SL × Γ max.](image)

Figure 3.20: The FVR max at 176 Hz as a function of the product \( S_L \times \Gamma_{\text{max}} \).

Even though no phase-locked velocity fields were measured, it is reasonable to assume the decrease of the stabilization distance weakens the AVG also at 336 Hz. This would result in a less efficient FVR, and consequently in a deviation from linearity of the relation between FVR max and \( S_L \), as shown in Fig. 3.16.

### 3.6 Effect of Flame Temperature on the AGV

In addition to the increase in \( S_L \), an increase in \( \phi \) induces an increase in flame temperature. This temperature increase could, in turn, increase the temperature in the shear layer and weaken the AGV. The laminar burning velocity as a function of the ratio of the adiabatic flame temperature, \( T_{\text{ad}} \), over the temperature of the unburnt gases, \( T_u \), is presented in Fig. 3.21. Since no temperature measurements are carried out, \( T_u \) is imposed equal to 300 K for all the experimental conditions. Figure 3.21 shows that \( S_L \) and \( T_{\text{ad}}/T_u \) are closely related and they might both weaken the AGV. On the other hand, the laminar burning velocity shows a broader range of variation.
(about a factor of 2) than $T_{ad}/T_u$ (about 25%). From this, one can infer that the effect of the increase of the laminar burning velocity is perhaps dominant compared to the increase in flame temperature. Further study will be necessary to decouple these two effects and to investigate their relative importance.

Figure 3.21: Laminar burning velocity as a function of $T_{ad}/T_u$. The error bars represent the discrepancy in the values of $S_L$.

3.7 Effect of Equivalence Ratio and Fuel on the FTF Phase

As shown earlier in the results section, the phase of the FTF at 176 Hz and 336 Hz is also affected by the fuel and the equivalence ratio. For both fuels, increasing $S_L$ decreases the stabilization distance, $d$, (see Fig. 3.18) as well as the distance between the tip of the flame and the nozzle (see Fig. 3.1). Since the bulk velocity $\bar{u}_{\text{bulk}}$ is similar in all the cases, the time lag between the oscillations of the velocity measured at the hot wire position and the fluctuations of the heat release rate, that mainly occur near the flame tip, is also reduced when $S_L$ increases [6, 15, 137, 138]. This explains why the FTF phase consistently decreases with equivalence ratio for both fuels for forcing frequencies $f > 128$ Hz (see Fig. 3.2), where the FVR controls the
3.8 Conclusions

For both methane and propane lean premixed swirl flames, changing the equivalence ratio modifies the phase and the gain of the flame transfer functions in a similar fashion. The phase is affected only at frequencies higher than 112 Hz, which corresponds to the local minimum of the gain. The phase decreases when $\phi$ is increased. The gain is mainly a function of equivalence ratio at the forcing frequencies near 64 Hz, 176 Hz, and 336 Hz, that correspond to the three local maxima of the FTF gain. At 64 Hz and 176 Hz, a non-monotonic behavior of the FTF gain is observed as the equivalence ratio is increased. The magnitude of the FTF gain first increases with equivalence ratio but then decreases. At 336 Hz, the magnitude of the FTF gain increases monotonically with equivalence ratio. While focusing primarily on the forcing frequencies corresponding to the second and third local maximum of the FTF gain, 176 Hz and 336 Hz, an analysis based on phase-locked images of OH$^*$ chemiluminescence, OH-PLIF, and velocity fields is proposed.

3.8.1 Analysis at 176 Hz

- The FTF gain and the maximum size of the flame vortex roll-up are proportional for all the flames considered. This underlines that the flame vortex roll-up is an important mechanism controlling the response of these flames to acoustic forcing.

- Based on the statistical analysis of the local curvature of the flame front, differential-diffusion effects have been ruled out and cannot explain the observed effects of fuel and equivalence ratio on the FTF gain and phase.

- The two main parameters controlling the flame vortex roll-up and the magni-
tude of the FTF gain at 176 Hz, are the laminar burning velocity $S_L$ and the circulation of the vortex $\Gamma$. A proportionality relationship between the flame vortex roll-up maximum size and the product of $S_L$ and $\Gamma_{\text{max}}$ has been established.

- The laminar burning velocity influences the FTF gain in two competing ways. Increasing the laminar burning velocity enhances the ability of the flame to conform to sudden flow changes and wrap around a vortex. On the other hand, increasing the laminar burning velocity reduces the distance between the flame base and the nozzle, which weakens the vortex generated by the acoustic forcing.

- For acoustically generated vortices of equal circulation, the maximum size of the flame vortex roll-up as well as the FTF gain increase linearly with the laminar burning velocity. This finding is useful for the development of low-order models dedicated to flame transfer function predictions. However, these experiments also show that low-order models cannot accurately predict the FTF gain unless all the parameters controlling the generation and growth of an acoustically generated vortex during a forcing cycle are taken into account.

- An empirical relationship between the magnitude of the FTF gain and the product $S_L \times \Gamma_{\text{max}}$ is proposed. This relationship could help engines designers to anticipate how different fuels or mixture compositions affect the response of the flame to acoustic perturbations. This could be a valuable tool for the development of new engines since it could be used to assess these effects without carrying out expensive experiments or simulations.

### 3.8.2 Analysis at 336 Hz

- For each fuel, modifying $S_L$ affects mainly the gain at its local maxima. Increasing $\phi$, i.e., increasing $S_L$, the gain response at 336 Hz increases approximately...
linearly.

- The flame vortex roll-up has a strong impact on the gain at 336 Hz. However, the fluctuations of the bottom region of the flame are still active at this frequency and cannot be neglected.

- The maximum size of the FVR scales linearly with the laminar burning velocity, for values of $S_L$ lower than a specific value (0.23 m/s in this study). On the other hand, the trend of the $FVR_{\text{max}}$ diverges from linearity, for values of $S_L$ higher than this threshold. This could be due to the decrease in the distance between the flame front and the shear layer region that weakens the acoustically generated vortex.

Finally, to conclude on a more practical note, the results presented in this chapter show that for frequencies at which the flame is the most responsive to acoustic perturbations, i.e., at the maximums of the gain, for a given fuel, an increase in $S_L$ generally increases the magnitude of the response, but not always. If the stabilization distance from the injection nozzle is not changed by $S_L$, then the magnitude of the gain increases. However, if the increase in $S_L$ and $T_{\text{ad}}$ is strong enough to decrease the stabilization distance, the properties of the AGV are changed. In this case, depending on the frequency and the mechanisms controlling the flame dynamics, the gain can increase (as at 336 Hz), or decrease (as at 64 and 176 Hz). This information is valuable for engine designers as it allows them to anticipate changes in the flame response to acoustic perturbations and, thus, thermoacoustic interactions, when the fuel (composition) is varied.
Chapter 4

Effect of Pressure on the Transfer Functions of Premixed Methane and Propane Swirl Flames [3]

Abstract

This chapter reports on the effect of pressure on the response of methane–air and propane–air swirl flames to acoustic excitation of the flow. These effects are analyzed on the basis of the flame transfer function (FTF) formalism, experimentally determined at pressures up to 5 bar. In parallel, phase-locked images of OH$^*$ chemiluminescence are collected and analyzed in order to determine the associated flame dynamics. Flame transfer functions and visual flame dynamics at atmospheric pressure are found to be similar to previous studies with comparable experimental conditions. Regardless of pressure, propane flames exhibit a much larger FTF gain than methane flames. For both fuels, the effect of pressure primarily is to modify the gain response at the local maximum of the FTF, at a Strouhal number around 0.5 (176 Hz). For methane flames, this gain maximum increases monotonically with pressure, while for propane flames it increases from 1 to 3 bar and decreases from 3 to 5 bar. At this frequency and regardless of pressure, the flame motion is driven by flame/vortex roll-up, suggesting that pressure affects the FTF by modifying the interaction of the flame with the vortex detached from the injector rim during a forcing period. The complex heat transfer, fluid dynamics, and combustion coupling in this configuration does not allow keeping the vortex properties constant when pressure is increased. However, the different trends of the FTF gain observed for methane and propane fuels with
increasing pressure imply that intrinsic flame properties and fuel chemistry, and their variation with pressure, play an important role in controlling the response of these flames to acoustic forcing. This entire chapter has been published in \[3\].

### 4.1 Introduction

At elevated pressure conditions, only a few studies report on the experimental investigation of flame dynamics through the systematic analysis of the FTF \[139\] \[140\] \[141\] \[142\] \[143\] \[144\]. Cheung et al. \[139\] presented a study on the effects of pressure on the FTF of a lean premixed, pre-vaporized aero-engine injector. The FTFs at atmospheric pressure and at 15 bar were compared, but no explanation for the observed differences was provided: at 15 bar, for low frequencies, the gains were lower than at atmospheric pressure, while for high forcing frequencies, the opposite trend was observed. Freitag et al. \[140\] investigated the effect of pressure on the FTF of a premixed swirl flame burning natural gas. Five different pressures, from 1 to 5 bar, were examined. At higher frequencies, a phase shift was observed with increasing pressure. This effect was attributed to changes in the location of the intense combustion regions. A decrease in the gain response was observed for lower frequencies with increased pressure, while the reverse trend was found for higher frequencies. These complex variations of the gain response could not be explained or correlated to flame characteristics. Bunce et al. \[142\] investigated the effects of pressure on the FTF up to 4 bar in a lean fully premixed swirl-stabilized industrial-scale gas turbine combustor. Gain and phase of the FTF were found to be qualitatively similar to previous studies but no trend regarding the pressure effect was highlighted. More recently, Zhang and Ratner \[144\] investigated the effect of pressure on the flame dynamics of a lean premixed low-swirl burner. Four different pressures, from 1 to 4 bar, were considered but only three forcing frequencies were analyzed. Because the velocity fluctuations were not measured, the interpretation of the flame response in terms of
the FTF was not possible. The flame response of industrial burners was measured at intermediate and full engine pressure in Refs. [141] and [143], respectively; however, as data for only one pressure level was presented, the effect of pressure on the FTF remains unknown in these cases.

The objective of this chapter is to investigate the effects of pressure on the transfer function of a turbulent swirl-stabilized premixed flame and to correlate the results with the flame dynamics. Two different fuels, methane and propane, are investigated in order to understand how fuel affects the pressure-dependence of the flame dynamics. Five different pressures, from 1 to 5 bar, are considered for each fuel. The flame dynamics are analyzed using phase-locked images of OH* chemiluminescence.

4.2 Experimental Conditions and Diagnostics

The experimental setup utilized in this chapter consists of the swirl stabilized burner presented in Sec. 2.1.1, the HPCD, detailed in Sec. 2.1.2, within which the burner is installed, and diagnostics for flow and flame characterization described in Sec. 2.2.

4.2.1 Experimental Conditions

For the methane–air flame at atmospheric pressure, the mass flow controllers are set such that the equivalence ratio is 0.67 and the thermal power of the flame is 4 kW. This flame is the reference flame of the present study and its dynamics are detailed in Sec. 4.3.1. At elevated pressure conditions and for propane flames, the equivalence ratio was slightly modified such that the mean flame shape and size remain as similar as possible to the reference case (see Fig. 4.1). This is important because the frequency scaling of the FTF, i.e., the position of the local extrema of FTF gain, depends on the flame size [145] and should be conserved to allow fair comparison between cases. Such scaling also depended on the bulk jet velocity, and for a given fuel, the bulk velocity is kept constant when pressure is increased.
Figure 4.1: Photographs of the methane–air and propane–air flames at pressures from 1 to 5 bar. The exposure time is 5 s for all images. The red dot shows the position of each flame’s center of mass.

Table 4.1 summarizes, for both fuels and the five pressures investigated, the equivalence ratio of the mixture, $\phi$, the thermal power of the flame, $P_{th}$, the average bulk velocity, $V_{\text{bulk}}$, and the Reynolds number based on the injector’s hydraulic diameter, $Re$.

### 4.2.2 Diagnostics

The determination of the FTF is based on velocity and OH* chemiluminescence measurements. Similarly to chapter 3, the velocity fluctuations induced by acoustic forcing are measured by a hot wire (Dantec miniCTA) located inside the burner 1 cm upstream of the swirler, i.e., about 7 cm upstream of the injector outlet. The hot wire has been calibrated in air for all pressures investigated (see Appendix A).

The global OH* chemiluminescence emission intensity is measured through one of the quartz windows with a photomultiplier (Hamamatsu H10721) located outside of the HPCD and equipped with a 40-nm bandpass filter (Lavision 1108760) centered at 310 nm. The OH* chemiluminescence emission from the whole flame is focused on the
Table 4.1: Summary of the experimental conditions and associated laminar burning velocities and flame thicknesses calculated with Cantera [17] for a freely propagating flame with an initial temperature of 300 K using the USC-II mechanism [18] and a mixture-averaged mass diffusion model.

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<th>( P ) (bar)</th>
<th>( \phi )</th>
<th>( P_{th} ) (kW)</th>
<th>( \bar{V}_{bulk} ) (m/s)</th>
<th>Re</th>
<th>( S_L ) (m/s)</th>
<th>( \delta_L ) (mm)</th>
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<td>37,500</td>
<td>0.104</td>
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<tr>
<td>C(_3)H(_8)</td>
<td>1</td>
<td>0.70</td>
<td>3.9</td>
<td>6.1</td>
<td>7,500</td>
<td>0.233</td>
<td>0.53</td>
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<td></td>
<td>2</td>
<td>0.66</td>
<td>7.4</td>
<td>6.0</td>
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<td>3</td>
<td>0.64</td>
<td>10.7</td>
<td>6.0</td>
<td>22,500</td>
<td>0.130</td>
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<td>4</td>
<td>0.64</td>
<td>14.3</td>
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<td>0.114</td>
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<td>5</td>
<td>0.64</td>
<td>17.9</td>
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<td>0.104</td>
<td>0.21</td>
</tr>
</tbody>
</table>

photomultiplier detector using a converging lens with 0.2 m focal length. It should be noted that the proportionality relationship between heat release rate and OH* chemiluminescence intensity is not strictly verified for flames in non-adiabatic combustors such as those studied here. However, this method was used previously in several other non-adiabatic combustors [10, 110, 145]. In addition, it is shown later that eventual uncertainties in measuring heat release rate with OH* chemiluminescence cannot be of the first order.

All data, i.e., acoustic forcing signal, hot wire signal, and photomultiplier signal, are recorded simultaneously with an oscilloscope (Agilent Technologies Infiniium 2.5 Ghz) during 10 s and with a sampling rate of 100 kHz.

The flame dynamics are investigated with a high-speed CMOS camera (Lavision HSS8) equipped with an intensifier (Lavision IRO), a UV lens (105 mm F/5.6 Coastal Optics), and a 40-nm bandpass filter (Lavision 1108760) for selection of the OH* chemiluminescence signal. The exposure time of each image is kept fixed at 113 \( \mu s \) and the acquisition rate is set equal to the forcing frequency investigated. A delay generator (Berkeley Nucleonics BNC Model 575) synchronizes the acoustic forcing
and the camera and allows examining different phases of the forcing period.

4.2.3 Experimental Procedure

The flame response to acoustic forcing of the flow is investigated following the experimental procedure detailed here. First, for each experimental condition (fuel, equivalence ratio, pressure), the rig is run for about 15 minutes to ensure that the burner has reached thermal equilibrium. Second, the acoustic modulation of the incoming flow is started, and the forcing signal is adjusted such that the corresponding velocity fluctuation amplitude $u'$ reaches 10% of the mean flow velocity $\bar{u}$. This fluctuation amplitude has been chosen because it provides a good compromise between significant changes in the flame surface area and the linearity of the flame response [10].

For the determination of the FTF, the forcing signals, the velocity measured by the hot wire, and the OH* chemiluminescence signal measured by the photomultiplier are recorded simultaneously. An example of instantaneous (dot) and phase-averaged signal (line) of the velocity $u$ (blue) and OH* chemiluminescence intensity $I$ (red) is shown in Fig. 4.2 for the reference flame. The instantaneous signals can differ significantly from the phase-averaged signals because of the turbulent nature of the flow.

Flame dynamics are analyzed at two forcing frequencies, 112 Hz and 176 Hz, through phase-locked visualization of the spatial distribution of the OH* chemiluminescence intensity. These frequencies have been chosen because they correspond to extrema of the flame transfer function gain as will be shown later. For each frequency investigated, the period is split into 10 phase intervals of 36°. For each phase interval, 1000 snapshots are recorded and then averaged. Since the mean flame is axisymmetric, an Abel deconvolution is applied after averaging to infer the spatial distribution of the OH* chemiluminescence intensity in the central longitudinal plane. By processing phase-averaged images recorded for forcing at 112 Hz and 176 Hz, it
Figure 4.2: Temporal evolution of the instantaneous (dot) and phase-averaged (line) relative velocity fluctuations (blue) and OH* chemiluminescence intensity (red) over two forcing periods.

was verified that the flame maintains its axisymmetric nature during forcing, which allows applying Abel deconvolution at each phase of the forcing period. Phase 0° corresponds to \( u = \bar{u} \) and \( \partial u/\partial t > 0 \) at the location of the hot wire.

4.3 Results

The response of the flames to incoming velocity perturbations has been investigated for forcing frequencies ranging from \( f = 32 \) to \( f = 512 \) Hz, with incremental steps of 16 Hz and a constant forcing amplitude of \( u'/\bar{u} = 10\% \). In order to facilitate comparisons with FTFs obtained in other studies for different experimental conditions, a Strouhal number \([10, 31]\), defined here as \( St = fD/\bar{V}_{\text{bulk}} \) is introduced, where \( f \) is the forcing frequency and \( D \) is the diameter of the burner tube. The bulk velocity, \( \bar{V}_{\text{bulk}} \), is taken equal to 6.4 m/s. This value corresponds to the average bulk velocity for the two fuels examined (see Table [4.1]).
4.3.1 Methane Flame at Atmospheric Pressure

The reference flame of this study is the atmospheric methane–air flame with an equivalence ratio of 0.67 and a thermal power of 4.0 kW. Its transfer function is presented in Fig. 4.3 (red). This FTF is typical of swirl-stabilized flames and it can be explained based on the current knowledge of flame dynamics from previous studies [8, 10, 27, 34, 36, 37, 38, 39, 40, 141, 145].

![Figure 4.3: Flame transfer functions of methane (red) and propane (blue) flames at atmospheric pressure for a forcing amplitude of 10%.

First, this FTF is consistent with the low-frequency limit for premixed flames [44],
i.e., the gain approaches unity and the phase approaches zero at very low frequencies. At higher frequencies, the gain converges towards zero exhibiting the low-pass nature of the flame. Second, in agreement with previous studies \cite{10, 113, 114, 145}, a local gain maximum follows a local gain minimum. In the present case, these are found at 176 Hz (St = 0.5) and 112 Hz (St = 0.27), respectively. This shape originates from two competing mechanisms: the oscillation of the bottom region of the flame, driven by the fluctuations of the flame base angle due to swirl number variations \cite{10, 37}, and the fluctuation of the top region, driven by vortex roll-up at the tip of the flame following the growth of hydrodynamic waves \cite{10, 27, 34, 38, 39, 40, 41}. To highlight these two mechanisms, the flame dynamics have been analyzed at 112 Hz and 176 Hz.

Figure 4.4: Phase-locked Abel-deconvoluted images of the OH* chemiluminescence for the reference flame subjected to acoustic forcing at 112 Hz.

Figure 4.4 shows phase-locked, Abel-deconvoluted OH* chemiluminescence images for 10 phases of a forcing period at 112 Hz. Two different regions of the flame can
be defined: the top region above the dashed horizontal line shown in Fig. 4.4 and the bottom region below this line. The position of the line separating bottom and top regions is chosen to ensure that contributions of flame vortex roll-up to the flame motion appear only in the top region. This is done by examining phase-locked images of the OH* chemiluminescence and positioning the line immediately below the most upstream flame-rolling feature, which is visible for phase 144° at 112 Hz. The position of the line separating bottom and top regions is a function of the forcing frequency. The temporal evolution of the normalized OH* chemiluminescence intensity integrated over each of these two regions is plotted in the top frame of Fig. 4.5 for the reference flame forced at 112 Hz. Normalization is realized by dividing each signal by its averaged value over a full period in the same region.

At 112 Hz, the integrated OH* chemiluminescence intensity fluctuates with time in a sinusoidal manner in both regions. HRR fluctuations in the bottom region are attributed to fluctuations of flame surface area due to swirl number fluctuations [8, 10, 37]. This mechanism is also evidenced in Fig. 4.4 where temporal fluctuations of the flame angle are visible in the bottom region. HRR fluctuations in the top region are attributed to flame vortex roll-up [10, 27, 34, 38, 39, 40, 41]. This mechanism is also visible in Fig. 4.4. Moreover, Fig. 4.5 (top) shows that top and bottom fluctuations of the OH* chemiluminescence intensity are out of phase for a forcing frequency of 112 Hz. Both mechanisms destructively interfere [37], leading to the local minimum in the gain response, which is visible at 112 Hz in Fig. 4.3.

At 176 Hz, fluctuations of OH* chemiluminescence intensity are minimal in the bottom region while they are large in the top region. Hence, at this frequency, swirl number fluctuations do not significantly contribute to fluctuations in the heat release rate, which is fully controlled by flame vortex roll-up. This leads to the local maximum in the gain response at 176 Hz (top frame in Fig. 4.3).

The strongest temporal fluctuations of the swirl number occur when axial and
Figure 4.5: Temporal evolution of the normalized OH* chemiluminescence intensity integrated over the top (red) and bottom (blue) regions for the reference flame forced at a frequency of 112 Hz (top) and 176 Hz (bottom) and an amplitude of 10%.
azimuthal perturbations of the inlet flow are out of phase at the burner tube outlet, \( i.e. \), the axial velocity reaches its maximum value while the azimuthal velocity reaches its minimum value, and vice versa. Azimuthal velocity perturbations are generated when an acoustic wave impinged the swirler and propagates as a vorticity wave at convective speeds. In contrast, the axial velocity fluctuations associated with the acoustic wave propagate at the speed of sound. The phase difference between the two at the burner tube outlet, therefore, depends on the swirler to outlet distance and on the forcing frequency \([10]\). With this burner, axial and azimuthal perturbations are out of phase at the burner tube outlet for a forcing of 112 Hz but are nearly in-phase for a forcing of 176 Hz. Consequently, at 176 Hz, the bottom part of the flame does not contribute to the flame dynamics.

### 4.3.2 Fuel Effects on the FTF

The FTFs of methane and propane flames measured at atmospheric pressure are compared in Fig. 4.3. Both FTFs exhibit the same trends in terms of gain and phase but differ on a quantitative level. The gain is generally larger for propane compared to methane over the entire range of frequencies considered. The largest difference, approximately 60\%, occurs at the frequency of the local maximum (176 Hz, \( \text{St} = 0.5 \)). Differences in the phase response can be noticed for frequencies around 112 Hz, corresponding to the gain minimum, as well as for frequencies larger than 250 Hz. A possible explanation for the differences observed when the fuel is changed is proposed in Sec. 4.4.1.

### 4.3.3 Pressure Effects on the FTF

The FTFs measured at five different pressures for the two fuels are compared in Fig. 4.6. All FTFs exhibit similar trends. For the phase, only small differences can be observed for frequencies close to 112 Hz and larger than 250 Hz. Differences for
frequencies larger than 250 Hz are not attributed to a direct pressure effect but to small variations of flame length with pressure. Indeed, it is known that the FTF phase increases approximately linearly with the flame length \[^{[15]}\]. Although efforts were made to maintain the flame length when the operating pressure was increased, the positions of the flames’ center of mass (red dot in Fig. \[^{[4.1]}\]) suggest that the flame length is not strictly constant. For methane, the longest flame is found at 1 bar while the shortest is found at 2 bar. This is consistent with the largest (smallest) phase difference measured at 1 bar (2 bar). Flames at 3, 4, and 5 bar lie in between because of their intermediate length. A constant flame length is better maintained for propane conditions, and discrepancies of phase with pressure are smaller.

It is also important to note that increasing pressure does not modify the frequencies at which the gain extrema are encountered. However, the magnitude of the gain around the local maximum at 176 Hz changes significantly with pressure, while it is fairly independent of this parameter around and below 112 Hz. A pressure effect can also be observed between 300 Hz and 400 Hz. However, the gain is smaller in this frequency range, and therefore, less likely to cause self-excited feedback in conjunction with acoustic modes. More interestingly, the operating pressure has a different effect on the gain response around 176 Hz depending on the fuel. For methane, the gain at 176 Hz increases monotonically with pressure from \( G = 1.12 \) at 1 bar to \( G = 1.56 \) at 5 bar. Conversely, for propane, the gain increases from \( G = 1.79 \) at 1 bar to \( G = 1.94 \) at 3 bar but then decreases to \( G = 1.57 \) at 5 bar. Possible reasons for this behavior are presented in Sec. \[^{[4.4.2]}\].

### 4.3.4 Flame Vortex Roll-up

The physical mechanisms responsible for the trends of FTF gain with frequency at atmospheric pressure have been described in Sec. \[^{[4.3.1]}\]. In agreement with previous studies \[^{[10] [27] [34] [38] [39] [40] [41]}\], and as shown in Sec. \[^{[4.3.1]}\] flame dynamics are
Figure 4.6: Flame transfer functions of methane (left) and propane (right) flames for different operating pressures and a forcing amplitude of 10%.
entirely governed by flame vortex roll-up (FVR) in the flame’s top region and this explains the large gain measured at 176 Hz.

Because FVR has a significant impact on the gain response near 176 Hz at atmospheric pressure, it is interesting to examine whether increasing pressure affects FVR or not. The method chosen to assess the effects of pressure and fuel on FVR is described using Figs. 4.7 and 4.8. FVR manifests itself by gradually increasing the

Figure 4.7: Phase-locked Abel-deconvoluted images of the OH* chemiluminescence for the methane flames at 1 (top row), 3 (middle row), and 5 bar (bottom row), subjected to acoustic forcing at a frequency of 176 Hz and an amplitude of 10%. Only half of the forcing period is shown.
Figure 4.8: Phase-locked Abel-deconvoluted images of the OH∗ chemiluminescence for the propane flames at 1 (top row), 3 (middle row), and 5 bar (bottom row), subjected to acoustic forcing at a frequency of 176 Hz and an amplitude of 10%. Only half of the forcing period is shown.
flame surface area near the outer flame edge in Abel-deconvoluted images of the OH\(^\ast\) chemiluminescence between phases 144\(^\circ\) and 288\(^\circ\). Regardless of fuel and pressure, the maximum coherent flame surface area, indicative of maximum FVR, is observed at phase 288\(^\circ\). Therefore, it is possible to quantify the extent of FVR for each pressure and fuel by measuring the flame surface area near the outer flame edge at phase 288\(^\circ\). This is done here by extracting the perimeter of the ellipse (white dashed line) providing the best fit of the 0.4 iso-contour of the normalized OH\(^\ast\) chemiluminescence intensity (black solid line) near the outer flame edge, as shown in Figs. 4.7 and 4.8. Although the isovalue 0.4 is somewhat arbitrary and is not more sensible than, for example 0.3 or 0.5, this value is kept for all cases investigated, and relative comparisons remain meaningful. The perimeter of this ellipse is given in mm and is referred to as FVR\(_{\text{max}}\) in the following.

![Graph](image)

Figure 4.9: FTF gain measured at 176 Hz as a function of FVR\(_{\text{max}}\) for every operating condition investigated in this study.

Figure 4.9 plots the FTF gain at 176 Hz as a function of the measured FVR\(_{\text{max}}\), each data point corresponding to a different pressure/fuel operating condition. There is an evident proportionality between the FTF gain at 176 Hz and FVR\(_{\text{max}}\), indicating that flame vortex roll-up is the main mechanism controlling temporal fluctuations of flame surface area and controlling, by consequence, temporal fluctuations of heat
release rate for a forcing frequency of 176 Hz, regardless of fuel and pressure. This finding suggests that understanding how much the outer flame edge wraps around an incoming vortex is sufficient to predict the FTF gain, for frequencies where swirl number fluctuations were negligible, for any given fuel and pressure. Therefore, parameters controlling flame-vortex interaction are discussed in the next section and the potential to predict the FTF gain accurately in various cases is assessed.

4.4 Discussion

As shown in Figs. 4.3 and 4.6, fuel and pressure exhibit their strongest influence on the gain response at the local maximum around 176 Hz. In addition, Figure 4.9 shows that the gain around 176 Hz is controlled only by flame vortex roll-up, i.e., the ability of the flame to yield surface area by wrapping around an incoming vortex. Therefore, the purpose of this section is to identify which parameters affect flame vortex roll-up and discussed how fuel and pressure influence, directly or indirectly, such parameters.

Parameters controlling flame vortex roll-up can be classified in two categories: (i) those that controlled the size and strength of the vortex, more precisely, its tangential vorticity associated with the hydrodynamic wave, and (ii) those that controlled the ability of the flame sheet to sustain and expand in a vortex environment.

In the present study, changes in fuel and operating pressure are accommodated in such a way that the mean flame shape remained mostly unaltered (Fig. 4.1). The bulk velocity is maintained for all operating pressures and adapted only slightly (about 10%) when switching between methane and propane (Tab. 4.1). It can, therefore, be assumed that the streamwise evolution of hydrodynamic waves triggered by the acoustic forcing, hence, the tangential vorticity responsible for flame vortex roll-up, is only weakly affected. Therefore, for any given pressure, effects of fuel on the FTF gain can only be attributed to parameters belonging to category (ii). Since the kinematic viscosity is inversely proportional to pressure, the Reynolds number increases linearly
with pressure when fixing the bulk velocity (see Tab. 4.1). This may affect the flow field and the growth of hydrodynamic waves and modify the vortex tangential velocity. For any given fuel, parameters controlling effects of pressure may belong to both categories (i) and (ii).

We consider four properties relevant for controlling the ability of a flame to sustain and expand in a vortex environment (category (ii)). (a) The flame speed: to increase its surface area, the flame must conform to sudden changes in the flow field and this is promoted by a larger flame speed. (b) The ratio of the flame thickness to the flame speed: when it interacts with a vortex, the flame sheet is curved. If the vortex strength is too large, the flame sheet might be quenched, preventing further increase of its surface area. Resistance of a flame sheet to an incoming vortex is controlled by the ratio of the flame thickness to the flame speed \([146, 147]\). (c) the Lewis number: if the flame curvature or strain takes large values - these are controlled by the size of flow features - Lewis number effects can play a role by modifying locally the flame speed and resistance to quenching. (d) Excitation amplitude: if the velocity fluctuation amplitude is large, saturation of the FTF gain is typically observed, for example, through mutual annihilation of adjacent flame sheets \([110]\), which limits further growth of the flame surface.

According to the Borghi diagram \([120, 121, 122]\), the flames reside in the “reaction sheet” regime of premixed turbulent combustion for all the experimental conditions investigated in this study. The turbulent Karlovitz number needed to position experimental conditions in the Borghi diagram is obtained from the following formulation \((\text{Ka}_T)\) \([123, 148]\):

\[
\text{Ka}_T = C^{1/2} \times \left( \frac{u'_{\text{turb}}}{S_L} \right)^{3/2} \times \left( \frac{L}{\delta_L} \right)^{-1/2}, \tag{4.1}
\]

where \(u'_{\text{turb}}\) is the RMS velocity fluctuation, \(L\) is the integral length scale, \(C = S_L \times \delta_L/\nu\) is a correction factor, and \(\nu\) is the kinematic viscosity. The RMS velocity fluctuation measured at atmospheric pressure has an average value of 10% of the bulk
velocity. For all experimental conditions of this study, $K_{a_T}$ is approximately equal to 3. Therefore, flames behave locally as laminar in their interactions with large vortices. The size of the vortex impinging the flame is on the order of the integral length scale, which is taken here as the diameter of the burner tube (18 mm). It is then reasonable to consider, as a first approximation, that the flame-vortex roll-up is mainly affected by the laminar burning velocity $S_L$ and the laminar thermal flame thickness $\delta_L$. Table 4.1 summarizes values of $S_L$ and $\delta_L$ calculated with Cantera [17] for a freely propagating flame with an inlet of 300 K and the detailed USC-II mechanism [18] with a mixture-average mass diffusion model.

4.4.1 Effects of Fuel on $FVR_{\text{max}}$

At atmospheric pressure, the difference in bulk velocity between both fuels is kept within 10% (see Table 4.1). Consequently, only a minor effect on the development of hydrodynamic waves and the associated tangential vorticity is to be expected, which cannot explain the large gain variation (59%) and $FVR_{\text{max}}$ difference observed at 176 Hz when both fuels are compared. Therefore, such differences must be attributed to properties (a), (b), (c), or (d), controlling the response of a flame sheet to an incoming vortex. Property (d) is considered first. In another study using the same burner [89], FTFs are measured for a larger range of forcing amplitudes and it is shown that the response of both atmospheric methane and propane flames is linear for a forcing amplitude of 10%. Therefore, saturation does not occur and the much smaller gain measured at 176 Hz for methane cannot be explained by flame sheet annihilation. Effects of the Lewis number are considered (property (c)). The Lewis number of the lean propane flames investigated here is 1.9 while it is 0.97 for the methane flames. Taking into account the negative curvature of the flame sheet induced by the incoming vortex (flame sheet is concave towards reactants) the flame speed may be locally increased for propane flames [120]. However, the size of the incoming vortex must be
sufficiently small to induce magnitudes of curvature that are large enough to trigger effects of differential-diffusion and this is controlled by the forcing frequency and the flame Markstein length \cite{119}. Based on the theory of \cite{119}, the cutoff frequency below which differential-diffusion plays no role with this burner at 1 bar is close to 1000 Hz, which is much larger than the forcing frequencies considered in this study. It is also unlikely that strain controls the dynamics of the flames investigated here. Indeed, the resistance of lean propane flames to strain is typically smaller \cite{148} than that of lean methane flames and this cannot explain the larger FTF gain observed for propane. Therefore, the difference of gain measured at 176 Hz for propane and methane is not attributed to Lewis number and stretch effects. The cutoff frequency is roughly 2000 Hz at 5 bar, meaning that the Lewis number also plays no role at higher pressure.

Properties (a) and (b) are finally examined. Table 4.1 showed that the laminar burning velocity is larger for propane than for methane for the 1 bar condition. This suggested that propane flames can conform to sudden change of flow faster than methane flames, which would enhance flame vortex roll-up. Table 4.1 also shows that the ratio $\delta_L/S_L$ is smaller for propane than for methane meaning that propane flames are less likely to be quenched by an incoming vortex (see for example \cite{146, 147, 149}). This may also enhance flame vortex roll-up. In conclusion, the larger gain measured for propane at 176 Hz is most-likely attributed to intrinsic properties of a lean propane flame: the laminar burning velocity and laminar flame thickness. The same conclusion can be drawn for the larger operating pressures considered here. From 1 bar to 5 bar, $S_L$ and $\delta_L$ remain respectively larger and smaller for propane than for methane (see Table 4.1), which explains why the gain is consistently larger for propane than for methane. This analysis suggests that both $S_L$ and $\delta_L$ are important parameters that control flame vortex roll-up and the dynamics of these flames forced at 176 Hz. The importance of $S_L$ on flame dynamics is investigated in chapter 3.
4.4.2 Effects of Pressure on \( \text{FVR}_{\text{max}} \)

The Reynolds number increases linearly with pressure when the bulk velocity is kept constant. As pointed out above, this may generally affect the evolution of acoustically excited hydrodynamic waves, hence, the flame vortex roll-up. Oberleithner et al. [38] have shown that increasing turbulence in the shear layer between fresh and burnt gases reduces its sensitivity, which results in a lower growth rate of the hydrodynamic waves and, thus, weaker tangential vorticity when it convected downstream.

On the other hand, since the density increases linearly with pressure, so does the thermal power of the flame. Because the heat loss at the chamber wall scales sublinearly with pressure [150], the temperature of the burner walls and of the burnt gases in the outer recirculation zone is increased at thermal steady state [9]. This is evident in Fig. 4.1 where the quartz tube confining the flame is glowing red at the highest pressure but does not radiate at atmospheric pressure. When temperature increases, the kinematic viscosity increases, which counteracts to some extent the effect of pressure to increase the Reynolds number. Similarly, a higher temperature of the burnt gases increases the density gradient produced by the flame across the inner shear layer, which is known to affect flow stability. Depending on the experimental conditions, this increased density gradient could increase or attenuate the growth rate of large structures [151, 152, 153].

For all these reasons, it is difficult to control the evolution of acoustically excited hydrodynamic waves, in other words, size and strength of vortices impinging the flame when the operating pressure is increased. Measuring vortex properties with particle imaging velocimetry, as it is done in chapter 3, was not possible in the HPCD at the time of the experiments. Therefore, it is currently not possible to determine without doubt whether the effect of pressure on \( \text{FVR}_{\text{max}} \) and on the local gain maximum originated from either changes in the hydrodynamic response (i.e., vortex formation) or modification of intrinsic flame properties (i.e., flame speed and thickness).
As mentioned in Sec. 4.3.3, for methane, the gain at 176 Hz increases monotonically with pressure from $G = 1.12$ at 1 bar to $G = 1.56$ at 5 bar. Conversely, it increases from $G = 1.79$ at 1 bar to $G = 1.94$ at 3 bar but then decreases to $G = 1.57$ at 5 bar for propane. Increasing the operating pressure evidently has a qualitatively different effect depending on whether methane or propane is used as fuel. This finding is worth noting. At any given pressure, thermal power and Reynolds number are very close for both methane and propane flames. Therefore, possible effects of the operating pressure on the hydrodynamic response would apply to both fuels, which contradicts the results shown in Fig. 4.6. Consequently, changes of vortex properties with pressure alone cannot be responsible for the experimental observations, and changes of intrinsic flame properties that are relevant to flame vortex roll-up at pressure must play a role, too.

In the range of pressures investigated, both propane and methane flames remain in the reaction sheet regime (see above). Therefore, it is relevant to consider laminar properties to analyze effects of pressure on flame vortex roll-up. However, as explained earlier, the temperature of the burnt gas in the outer recirculation zone increased with pressure \cite{9} and it is possible that the temperature of the fresh gases entrapped by the forced vortex is higher than the plenum temperature, $T = 300$ K. The temperature at which important laminar flame properties, \textit{i.e.}, $S_L$ and $\delta_L$, should be calculated was then unknown. This is particularly problematic because freely propagating flame simulations indicate that $S_L$ increases rapidly with the reactant temperature while $\delta_L$ and $\delta_L/S_L$ decreases rapidly. While these trends are compatible with the overall increase of FTF gain with pressure, the lack of data available at pressure precludes further analysis.

There are other mechanisms through which pressure may indirectly influence the measured FTF gain. Two of them are described here. (1) It is noted earlier that the amount of heat lost to the burner walls relative to the thermal power of the flame
decreases with pressure. Heat-losses may influence the production of OH* excited radicals in flames and undermine heat-release rate measurements from chemiluminescence. Therefore, the accuracy of heat release rate measurements could improve at elevated pressure and artificially modify trends of measured FTF gain with pressure. (2) The ability of the flame to conform to sudden flow changes depends on the laminar burning velocity (see above). However, if these transient flow features are large enough to affect macroscopic flame sheets, a turbulent burning velocity should be considered instead. Because the Reynolds number increases linearly with pressure here, increasing pressure increases the turbulent burning velocity for a fixed laminar burning velocity [154]. This may also affect trends of measured FTF gain with pressure.

Based on the above, it is not possible in this study to provide a fully detailed picture of the effects of pressure on the FTF gain. However, there are two important features of Figs. 4.6 and 4.9 that allow drawing clear and useful information on effects of pressure on flame dynamics. First, it is shown that the mechanisms controlling flame motion are the same regardless of pressure, albeit they are a function of the forcing frequency. This meant that most of the previous body of knowledge obtained at atmospheric pressure applies to elevated pressure. Second, trends of FTF gain with pressure when flame vortex roll-up controlled flame motion are not the same for methane and propane. Effects of varying turbulence and heat-losses with pressure make interpretation of results more difficult but these effects must apply to both fuels equally. Therefore, they cannot account for all our experimental observations. This implies that fuel chemistry must be considered to understand effects of pressure on the dynamics of premixed swirl flames.
4.5 Conclusions

Effects of pressure on the response of swirl-stabilized lean premixed methane and propane flames to acoustic excitation have been reported and analyzed. Flame transfer functions have been measured for pressures up to 5 bar, along with the characterization of the flame motion using phase-locked OH*-chemiluminescence images. The main findings are:

- The main effect of pressure on the flame transfer function is to modify the gain around 176 Hz (St = 0.5), where a local maximum associated with flame vortex roll-up is observed. For lower forcing frequencies, the pressure has a minimal impact on both the phase and the gain of the flame transfer function.

- For methane flames, the magnitude of the gain around 176 Hz (St = 0.5) increases monotonically with pressure. For propane flames, the magnitude of the gain around 176 Hz increases from 1 to 3 bar but then decreases from 3 to 5 bar.

- Regardless of fuel and pressure, the flame motion around 176 Hz (St = 0.5) originates from flame vortex roll-up, and this mechanism fully controls the transfer function gain. A proportionality relationship is found between the gain of flame transfer function measured at 176 Hz and a parameter quantifying the degree of flame vortex roll-up using phase-locked OH* chemiluminescence images, $FVR_{max}$.

- At any given pressure, the gain of the flame transfer function is larger for propane flames than for methane flames. Lean propane flames feature a larger laminar burning velocity and a smaller laminar flame thickness than lean methane flames. Therefore, lean propane flames conform more readily to sudden flow changes and are more resistant to being quenched by an incoming vortex than...
lean methane flames, leading to more efficient flame vortex roll-up.

- Increasing the operating pressure influences intrinsic flame properties, turbulence, and heat losses. It was not possible to determine the relative influence of these parameters on the observed trends and infer, without ambiguity, effects of pressure on flame dynamics. However, effects of turbulence and heat-losses must apply to both fuels equally, which is not compatible with the observation that trends of the flame transfer function gain with pressure are different for methane and propane fuels. Therefore, intrinsic flame properties \textit{i.e.}, fuel chemistry, should be considered to understand effects of pressure on the response of premixed swirl flames to acoustic forcing.

- A patent, WO2019086986, has been filed from the results presented in this chapter. The patent describes a fuel tester for characterization of the susceptibility to thermoacoustic instabilities of lean premixed swirl flames.
Chapter 5

Enhancement of the Lean Stability and Blow-off Limits of Methane-Air Swirl Flames at Elevated Pressures by Nanosecond Repetitively Pulsed Discharges

Abstract

Stabilizing premixed flames can be a challenge, especially in conditions relevant for industrial applications like lean mixtures, high flow rates, and elevated pressures. While the use of non-thermal plasma discharges for stabilizing lean premixed flames at atmospheric pressure has been widely investigated, few studies have addressed their ability to stabilize flames at elevated pressures. This chapter examines the effect of nanosecond repetitively pulsed (NRP) plasma discharges to improve stabilization and extend the blow-off limit of lean methane-air premixed swirl flames at pressures up to 5 bar. The effect of two discharge regimes, NRP glows and NRP sparks, is investigated. The electrical characterization of the discharges is performed and direct images at 60 Hz of the flames, with and without NRP discharges, are collected to assess the effect of the discharges on flame stabilization. Results show that NRP discharges efficiently stabilize and extend the lean blow-off limit of premixed methane-air swirl flames, at pressures up to 5 bar. These results are obtained for a ratio of NRP discharge power to flame thermal power of less than 0.7%. Moreover, the peak voltage necessary to maintain this power ratio does not increase linearly with increased pressure, even though the reduced electric field should linearly decrease with the pressure. It is also observed that the relative effectiveness of improving
the stabilization and extending the blow-off limit of the NRP glows and NRP sparks, changes by increasing the pressure. Based on discharge physics and current knowledge of the effect of pressure on the electrical properties of flames, explanations for these results are proposed. This entire chapter has been submitted to [4].

5.1 Introduction

Non-thermal plasma, produced by nanosecond repetitively pulsed (NRP) discharges, has been successfully tested to stabilize flames and extend the blow-off limit to higher bulk flow velocities or lower equivalence ratios [64, 65, 66, 67, 68, 69, 70, 71, 72]. However, all these studies were carried out at atmospheric pressure or below, while many types of combustors operate at elevated pressures, to increase power density and efficiency. Recently, Kim and Cohen [155] showed that NRP discharges could decrease the lean blow-off limit of methane-air jet flames at pressures up to 5 bar. They reported that the extension of the lean blow-off limit at 5 bar was twice smaller than at 2 bar, suggesting that the plasma actuation was decreasingly effective with increasing pressure. As they did not provide any characterization of the discharges (optical or electrical), it was difficult to draw any conclusion on the plasma efficiency as well as on the stabilization mechanism. Therefore, their conclusions could not be extended to other types of combustion configurations, such as for example swirl stabilized flames [71], or other plasma actuation strategies, such as for example plasma actuation in the recirculation zone [68].

On the other hand, NRP plasma discharges have shown promising results in enhancing the ignition of combustible mixtures [79, 80, 81, 82, 83, 84, 85, 86, 87, 88]. These studies showed that NRP discharges could be an effective way to decrease the lean flammability limit, minimum ignition energy, and ignition delay time. They investigated a wide range of pressures, from sub-atmospheric to elevated pressures that mimic the operating conditions of commercial devices. The results obtained were
usually attributed to a combined thermal and chemical effect of the discharges or a hydrodynamic enhancement of the mixing \cite{13}; these effects could also be relevant for lean combustion stabilization. Therefore, it might be expected that non-thermal plasma produced by NRP discharges could have a positive impact on combustion stabilization at elevated pressures.

The objectives of this study are, first, to assess whether NRP discharges can be used to enhance the lean stability and blow-off limits of premixed swirl flames at elevated pressures and, second, to determine which regime of the NRP discharges is more effective in the range of the pressures studied.

5.2 Experimental Setup and Methodology

5.2.1 Experimental Setup

A schematic of the experimental setup is presented in Fig. 5.1 and its detailed description can be found in chapter \cite{2} Sec. 2.1.3. The flows of air and methane are controlled by thermal mass flow meters (Brooks SLA 58 Series). They are mixed five meters upstream of the combustion chamber to ensure a homogeneous mixture in the combustion area. A radial swirler with a geometrical swirl number of 0.45 \cite{156} is installed 5 cm upstream of the combustion chamber. The injection tube has an inner diameter of 18 mm and the flame is stabilized above a stainless-steel rod 3-mm in diameter with an inverted cone profile of 6.5-mm diameter at its tip. The combustion chamber is rectangular, with a square section of $85 \times 85$ mm$^2$ and a length of 150 mm. Four perpendicular quartz windows permit visualization of the flame. This burner is installed in a high-pressure vessel, equipped with four thick quartz windows, aligned with those of the combustion chamber. A DSLR camera (Nikon D810) installed outside of the high-pressure vessel is used to investigate the stability of the flame. Images, as well as videos at 60 Hz, are recorded for each of the operating conditions.

The NRP discharges are generated between the tip of the rod and a stainless
Figure 5.1: Schematic of experimental setup. All dimensions are in millimeters.

steel ring at the top of the injection tube. The rod is connected to the positive high-voltage output of a pulser (FID GmbH, Model FPG 10-30NM10), while the ring is grounded. Energy deposited by the plasma is determined from the measured voltage and current, following the procedure detailed in [77] and in chapter 2, Sec. 2.2.6. Voltage is measured with a voltage probe (Tektronix P6015A), and the current is measured on the ground cable with a current probe (Pearson Current Monitor, Model 6585). The repetition rate is maintained at 30 kHz for the entire study. The characteristics of the NRP discharges are adjusted by varying the applied voltage.

5.2.2 Methodology

Characterization of the burner stability is performed up to 5 bar, following the procedures detailed here. After ignition of the flame at atmospheric pressure, the pressure is adjusted, with the help of a back pressure valve, until the desired value is achieved. Bulk flow velocity at the outlet of the injection tube is maintained constant for all conditions at 7.5 m/s. When the desired pressure is reached, starting from a stable flame and after waiting ten minutes to reach thermalization, the equivalence ratio, $\phi$, 
is decreased by steps of 0.005, until blow-off occurs. Between each change in equivalence ratio, a delay of one minute is observed. For each experimental condition, the DSLR camera records a ten-second video to assess the stability of the flame. Flame extinction and re-ignition events are observed while the equivalence ratio is reduced; these are counted during the videos. When ten or more extinction events are detected, the flame is considered unstable. A different definition of the flame instability may be chosen, but the general trend of the pressure’s effect will not be altered.

Figure 5.2: Flames at pressures from 1 to 5 bar, for stable conditions (first row), unstable conditions (second row), with NRP glows (third row), and with NRP sparks (fourth row).

The effect of NRP discharges on flame stability and blow-off is investigated for each pressure. Two regimes of NRP discharges are tested, the NRP glow regime, and the NRP spark regime, as defined in [73, 74]. For the NRP glows, the thermal and hydrodynamic effect of the discharges can be considered negligible (see [78]), consequently promoting the chemical impact of the plasma. On the other hand, the NRP sparks have a strong thermal and hydrodynamic effect (see [76, 77]). For all
conditions investigated, the ratio between the average power of the discharges, $P_{Glow}$ for the NRP glows, or $P_{Spark}$ for the NRP sparks, and the thermal power of the flame, $P_{Thermal}$, is kept constant. First, the equivalence ratio corresponding to the transition stable-unstable flame without plasma actuation is set. Then, the NRP plasma discharges are applied continuously and the equivalence ratio is decreased slowly, following the procedure detailed in the previous paragraph. This procedure is followed for both NRP discharge regimes (i.e., for two different applied voltages).

Examples of single-shot pictures, extracted from the collected videos, are presented in Fig. 5.2. Each column corresponds to an operating pressure. The first row presents stable flames; the second row is unstable flames. Third and fourth rows correspond to flames burning at the same equivalence ratio as the unstable flames but with NRP glows and NRP sparks actuation, respectively. Photos of the flame with NRP sparks at 5 bar are not taken due to strong camera saturation and pulser limitations.

5.3 Results and Discussion

5.3.1 Effect of Pressure on Flame Stability and Blow-off

Figure 5.3 presents the characterization of the burner stability, at pressures up to 5 bar. Recall that the bulk velocity is kept constant, and consequently, the Reynolds number, Re, as well as the thermal power, $P_{Thermal}$, scales with the pressure. At atmospheric pressure, Re is about 8,300 and $P_{Thermal} \approx 4.5$ kW, while at 5 bar, Re is about 42,000 and $P_{Thermal} \approx 20$ kW. At atmospheric pressure, the flame is stable down to $\phi = 0.765$, and the blow-off occurs at $\phi = 0.73$. When the pressure is increased, the equivalence ratio of unstable flames and blow-off decreases continuously. At 5 bar, the unstable flame and the blow-off occurs at $\phi = 0.655$ and $\phi = 0.63$, respectively.

This effect of pressure could be explained by the increase of $P_{Thermal}$ with pressure, inducing an increase in the temperature of the combustion chamber. Even though the metallic parts of the burner are water-cooled and the quartz windows are cooled by
outer jets of nitrogen, an increase of the burner temperature with pressure is observed (the windows glowing red). However, this decrease in the equivalence ratio at blow-off with the pressure could also be induced by a decrease in the local flame thickness with pressure \[148\], resulting in a more compact and stable flame. Further investigation will be necessary to quantify the relative impact of these two effects.

### 5.3.2 Electrical Characterization of the NRP Discharges

Voltage and current measurements are performed for each experimental condition, once the steady-state is reached (after 10 s of plasma actuation). Each measurement is repeated 100 times. The uncertainty in the results corresponds to the standard deviation from the average value. After synchronization of the voltage and current waveforms, the energy deposited by the discharges is determined by integrating the product of the voltage and current. Examples of voltage, current, and associated energy for an NRP glow and an NRP spark are presented in Fig. [5.4](a) and (b), respectively. These measurements are performed at 3 bar, with an unstable flame ($\phi = 0.67$).
Figure 5.4: Example of voltage and current waveforms with corresponding energy for (a) an NRP glow discharge, and (b) an NRP spark discharge, at 3 bar.

The voltage, current, and deposited energy differ for the two discharge regimes. For the NRP glows (Fig. 5.4 (a)), both the voltage and the current fluctuate strongly, due to multiple reflections between the electrode gap and the pulser. The energy is about 1.8 mJ per pulse, corresponding to a $P_{Glow}$ of 54 W. To keep the ratio $P_{Glow}/P_{Thermal}$ constant for all pressure, the applied voltage is adjusted for each pressure. The value of $P_{Glow}/P_{Thermal}$ is fixed at 0.32%.

For the NRP sparks (Fig. 5.4 (b)), the voltage and current waveforms display three main peaks, spaced by about 600 ns. This is a property of the pulser and can not be adjusted. The corresponding energy is about 5 mJ per pulse. To keep the
ratio $P_{\text{Spark}}/P_{\text{Thermal}}$ constant for all pressures, the applied voltage is adjusted for each pressure. Note that for an applied voltage corresponding to the NRP sparks, the occurrence of a spark regime is not 100%. Some of the discharges are in the glow regime. This is taken into account in the evaluation of the average power of the NRP spark actuation. The value of $P_{\text{Spark}}/P_{\text{Thermal}}$ is fixed at 0.7%.

### 5.3.3 Effect of Pressure on the Plasma Actuation

Because the thermal power of the flame increases almost linearly with pressure, to maintain a constant ratio of plasma power over flame thermal power, it is necessary to adjust the electrical actuation (i.e., the applied voltage), for each operating pressure. Figure 5.5 presents peak voltages and average energy per pulse measured for both the NRP glows and the NRP sparks, as a function of the pressure. As the pulse repetition frequency of the NRP discharges is kept constant at 30 kHz, a linear increase in the plasma power corresponds to a linear increase in the energy per pulse. Figure 5.5 shows that this adjustment is reasonably achieved. Note that this increase of the energy per pulse with pressure corresponds to visually similar NRP discharges for each pressure (see Fig. 5.2). The actuation with NRP sparks could not be investigated at 5 bar due to the limitation of the maximal output voltage of the pulser (14.5 kV).

For both plasma actuation, the necessary applied voltage increases with the pressure, but less than expected. Indeed, when the pressure increases, the density of the gas increases. Therefore, to maintain a similar discharge behavior, for a fixed electrode geometry, it is expected that the applied voltage linearly increases with increased pressure.

For example, at atmospheric pressure, the actuation by NRP glows is obtained for a peak voltage of 7 kV. At 5 bar, the peak voltage barely reaches 13.7 kV, while about 35 kV would have been expected. Several mechanisms could be responsible for this result. First (as mentioned in Sec. 5.3.1), due to scaling of $P_{\text{Thermal}}$ with the pressure,
the temperature in the combustion chamber increases with the pressure. This thermal change lowers the gas density and partly compensates for the effect of pressure on the reduced electric field. Second, the level of pre-ionization of the inter-electrode gap could increase with the pressure, due to an increase in the electron density of the flame. In fact, the NRP discharges are generated in a complex media that included methane-air mixture, flame front, and burnt gases. Studies of the electron density in flames at elevated pressure would be necessary to quantify this effect. Finally, as the energy deposited in the NRP glows increases with pressure, an increase in the electron density (as well as a potential change in the time of recombination) could also contribute to this non-linear effect of pressure. A more detailed analysis will be necessary to identify the main mechanisms responsible for this non-linear effect of the pressure on the peak voltage.

From a practical point of view, this result is promising for the implementation of plasma actuators at elevated pressure. For applied voltages higher than 20–30 kV, the electromagnetic interference (EMI) has the potential to become an important issue, one that should be treated with extreme care. An extrapolation of the results
presented in Fig. 5.5 suggests that standard devices could be used in the combustion chamber for up to 15–20 bar.

5.3.4 Effect of the NRP Plasma Discharges on the Flame

The effect of NRP glows and NRP sparks on stability and lean blow-off limits, as a function of the pressure, are presented in Fig. 5.6. To aid in comparison, the results presented in Fig. 5.3 for the flame without plasma actuation are also recalled. Over the entire pressure range, the stability, as well as the blow-off limits, are extended to lower $\phi$ by both NRP glows and NRP sparks actuation. At any pressure, $\phi$ is decreased by 5 to 7% for both the stability and the blow-off limits, compared to the flame without discharges. At pressures up to 2 bar, the NRP sparks are more effective than the NRP glows, while at higher pressures, the NRP glows have a stronger effect on the flame stability, and produce results similar to the NRP sparks for blow-off. This change in the relative efficiency of both NRP discharge strategies, with the pressure, could be explained by a change in the main mechanisms of plasma action.

Figure 5.6: Stability and lean blow-off limits with and without NRP discharges as a function of pressure. Error bars represent standard deviation in reproducibility of results.
Depending on their regime, NRP discharges can affect flames through thermal, kinetic, and/or transport mechanisms [13]. For the NRP sparks, the three energy pathways are active and can be considered as a local source of ignition [13, 157]. On the other hand, NRP glows are known to have a negligible thermal and transport impact [78], and their kinetic effect is predominant. At low pressure, the local ignitions at the outlet of the injection tube, caused by the NRP sparks, seem to stabilize the flame better than a purely kinetic actuation. This result is expected because (i) a combined thermal-kinetic impact is usually more efficient on combustion processes than a purely kinetic actuation (see for example [158]), and (ii) $P_{Spark}$ is twice larger than $P_{Glow}$, so for a similar flame, the impact on the flame should be stronger. As the pressure is increased, the applied voltage, as well as the energy per pulse, is increased. For the NRP glows, this should have resulted in a stronger chemical effect, and possibly a small thermal impact. For the NRP sparks, a higher energy deposition could increase the ultra-fast heating of the gas (described at atmospheric pressure in [77, 159]). In this case, the expansion and shock waves following the discharge could carry enough energy to destabilize the combustion front, therefore counterbalancing the local ignition.

In summary, with increased pressure, the NRP sparks become less efficient than NRP glows, probably due to the generation of pressure and shock waves disturbing the flame stabilization. This proposed explanation is supported by visual observations in which a stable flame is blown-off if the plasma actuation by NRP sparks becomes too strong, even at atmospheric pressure. Further investigation is necessary to demonstrate this destabilization process of swirl flames by strong NRP sparks.

### 5.3.5 Comparison of the Stabilization Strategies

To further evaluate plasma actuation strategies, it is interesting to compare the power required to avoid flame blow-off by NRP sparks, NRP glows, and fuel addition. For a
given pressure, consider the thermal power of the flame, corresponding to the lowest equivalence ratio at blow-off, which can be obtained with NRP discharges. The additional power necessary to avoid blow-off, ΔPower, is equal to P_{Spark}, for the actuation by NRP sparks. In the case of fuel addition, ΔPower is equal to P_{ΔFuel}, which is the thermal power carried by the additional fuel rate (considering optimal combustion), which should be added to the mixture to avoid blow-off. Finally, in the case of NRP glow actuation, ΔPower is equal to P_{Glow} for elevated pressures, and to P_{Glow} + P_{ΔFuel}, at pressures up to 2 bar. The three different additional powers and their impact on the equivalence ratio at blow-off are illustrated in Fig. 5.6 for atmospheric pressure. Figure 5.7 summarizes the results obtained for 1, 2, 3 and 4 bar.

![Figure 5.7: Comparison of different additional powers needed to extend blow-off limit.](image)

For all pressures, to obtain the same extension of the blow-off limit, it is energetically more efficient to add power by plasma actuation than by increasing the flow rate of fuel. This trend increases with pressure. At 1 bar, it is necessary to add 6 times more power by fuel addition, compared to plasma power by NRP sparks, while at 4 bar, 12 times more power by fuel addition is necessary to obtain the same result as
for plasma power by NRP glows. It is worth noting that, at elevated pressure, a lower value of $P_{\text{Glow}}$ than $P_{\text{Spark}}$ would have the same impact on the lean blow-off limit, whereas at pressure lower than 2 bar, additional fuel must be added to NRP glows to achieve the same impact than NRP sparks. Fig. 5.7 shows that for pressures in the 1–4 bar range, NRP discharges are always more energetically efficient in extending the blow-off limit than increasing the flow rate of fuel. Note that this comparison does not include the efficiency of the pulser, which could mitigate this result.

5.4 Conclusions

The ability of NRP plasma discharges to enhance the lean stability and blow-off limits of methane-air swirl flames, at pressures up to 5 bar, has been investigated. The effects of two discharge regimes, NRP glows and NRP sparks, with two corresponding values of the ratio of plasma power to flame thermal power, have been analyzed. Main findings are:

- The peak voltage necessary for a comparable plasma actuation of the flame, at constant bulk velocity, does not scale linearly with pressure. For both NRP glows and NRP sparks, at 4 bar, peak voltages are less than twice of those corresponding to atmospheric pressure conditions.

- The NRP discharges effectively extend stability and blow-off limits for all the pressures considered. At pressures higher than 2 bar, the NRP glows discharges appear to be more efficient than the NRP sparks. This result is opposite to that obtained at atmospheric pressure, in this study as well as in the literature.

- In terms of stabilization strategy, it is more energy efficient to avoid the blow-off of a flame by adding NRP discharges, rather than increasing the flow rate of the fuel.
These results are promising for the control of flame stability by non-thermal plasma at elevated pressure. However, they also emphasize that investigations of plasma-assisted combustion at pressures relevant to industrial applications are necessary. Indeed, a simple extrapolation of the results obtained at atmospheric pressure would produce erroneous results.
Chapter 6

Concluding Remarks

In this work, the dynamics of lean premixed swirl flames have been investigated at atmospheric and elevated pressures. In particular, the flame response to acoustic perturbations and the lean blow-off (LBO) and instabilities (LI) have been analyzed. Moreover, the use of NRP plasma discharges to extend the LBO and LI limits has been analyzed at elevated pressures. A high-pressure swirl combustor for the study of the interactions between lean premixed swirl flames, acoustic waves, and non-thermal plasma discharges have been designed, fabricated, and commissioned at KAUST. The present work shows the capability of the test rig to investigate the interactions between lean premixed swirl flames and non-thermal plasma discharges at elevated pressures.

In chapter 3, the effects of fuel and equivalence ratio on the transfer function of premixed swirl flames have been analyzed. A suite of measurements such as heat release rate and velocity fluctuations using PMT and HWA has been used. Whereas, the flow and flame dynamics have been analyzed using phase-locked OH* chemiluminescence images, phase-locked PIV, and phase-locked OH-PLIF. The main findings are:

- The change in fuel and equivalence ratio mainly affects the gain of the flame transfer function at the frequency of its local maxima, 64 Hz, 176 Hz, and 336 Hz. The gain increases and then decreases at 176 Hz with increasing $\phi$. While, it monotonically increases, with increasing the equivalence ratio at 336 Hz;

- The flame vortex roll-up is the main phenomenon controlling the response of the
flame to acoustic fluctuations at the frequency of the local maxima, 176 Hz and 336 Hz. A proportionality relation between the FTF gain and the maximum size of the FVR can be established;

- Differential-diffusion effects have been ruled out as parameters controlling the FTF gain and phase changing fuel and equivalence ratio;

- The laminar burning velocity, $S_L$, and the maximum circulation of the acoustically generated vortex, $\Gamma_{max}$, controls the FVR, and consequently the FTF gain, at the frequency of the local maximum, 176 Hz. An empirical relation between the product, $S_L \times \Gamma_{max}$, and the maximum size of the flame vortex roll-up has been established;

- The $S_L$ affects the FTF gain in two competing ways. The increase in laminar burning velocity enhances the flame vortex roll-up. On the other hand, it also reduces the distance between the flame and the nozzle, which weakens the acoustically generated vortex;

- The flame temperature, which increases with increasing the equivalence ratio, can also weaken the AGV. Further investigations are needed to assess the relative impact of the flame temperature and laminar burning velocity on the AGV.

The response of lean premixed swirl flames to acoustic perturbations has been investigated in chapter at elevated pressures, measuring the flame transfer function, and analyzing the flame dynamics using phase-locked images of the OH* chemiluminescence from the flame. The main conclusions are:

- The change in pressure mainly affects the gain of the FTF at around 176 Hz where the flame vortex roll-up is the main phenomena controlling the response of the flame to acoustic fluctuations;
• The increase in pressure affects the magnitude of the gain around 176 Hz in different ways depending on the fuel. For methane flames, the gain increases monotonically with pressure, while it first increases and then decreases for propane;

• As in chapter 3 a proportionality relation between FTF gain at 176 Hz and a parameter defining the size of the flame vortex roll-up, \( FVR_{\text{max}} \), has been established;

• Propane flames feature higher values of the FTF gain than methane flames at any given pressure. This is associated with the larger values of laminar burning velocity and smaller values of laminar flame thickness that lead to a more efficient FVR;

• Parameters related to fuel chemistry should be considered to understand the effect of pressure on the response of premixed swirl flames to acoustic oscillations.

In chapter 5 the ability of NRP plasma discharges to extend the stability limits of lean premixed swirl flames has been investigated, collecting natural luminosity of the flames, and measuring voltage and current of the discharge. The main conclusions are:

• At constant bulk flow velocity, the peak voltage applied to generate the NRP plasma discharges shows a non-linear dependence on pressure. For example, at 4 bar, the peak voltage is less than twice of that corresponding to atmospheric pressure;

• The stability limits, i.e., LBO and LI limits, are effectively extended by NRP plasma discharges at all the pressures considered. These are very interesting and promising results for the control of flame dynamics by plasma discharges at elevated pressures;
• NRP glow discharges appear to be more efficient than NRP sparks at elevated pressures. This is in contrast with what it has been observed at atmospheric pressure in this study as well as in the literature;

• It is more efficient to extend the blow-off limit by applying NRP plasma discharges than increasing the flow rate of fuel.

6.1 Future Research Work

The results presented in this work are interesting and promising, but investigations are still needed to assess the effects of pressure on the dynamics of lean premixed swirl flames and its control by non-thermal plasma discharge. Therefore, the work presented in this thesis can be extended in the following directions:

• The flame response to acoustic perturbations should be further investigated at even higher pressures, 10 to 20 bar, close to the operating conditions of gas turbines. Moreover, additional diagnostics should be implemented to assess the effect of pressure on the flame vortex roll-up, and consequently on to the FTF gain;

• Similarly, the use of NRP plasma discharges to control the dynamics of the flame should also be investigated at even higher pressures. The pollutant emissions should be measured to assess the impact of the NRP plasma discharges on them. Furthermore, additional laser-based diagnostics should be implemented to investigate the interactions between NRP plasma discharges and flames.

• Additionally, the effect of plasma discharges on the flame response to acoustic fluctuations should be analyzed at elevated pressures.
REFERENCES


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APPENDICES

A Calibration of the Hot Wire Anemometer

To convert the voltage signal produced by the power supply of the hot wire anemometer (HWA) to a velocity signal, a calibration procedure needs to be implemented (see Sec. 2.2.5). This procedure is detailed in the following appendix. The HWA probe is positioned in a tube with a known cross-sectional area, then a laminar and one-dimensional flow of air is generated inside the tube, adjusted by a well-calibrated mass flow controller (Brooks SLA 58 Series). Therefore, a flat velocity profile should be obtained in the tube. Note that the thin wire must be placed in the center of the tube to avoid wrong measurements due to the presence of the boundary layer. The flow of air is incremented from zero to the maximum value relevant for the experiment where the HWA is utilized. For each value of the flow rate, a value of voltage from the HWA is recorded. Therefore, the value of the mass flow rate of air can be easily converted to a velocity value since the cross-sectional area of the tube and the density of air know. A third-order polynomial fitting is used to generate the calibration curve. An example of a calibration curve is reported in Fig. A.1.

Since the properties of air ($\rho, \nu$) change with pressure, the calibration of the HWA should be done at each pressure investigated. An example of calibration curves at different pressures is reported in Fig. A.2.
Figure A.1: Example of calibration curve for hot wire anemometer.

Figure A.2: Examples of calibration curve for hot wire anemometer at different pressures.
B Measurement of the Swirl Number

An important parameter that should always be considered when a swirl flame is analyzed is the swirl number. It is defined as the ratio of the axial flux of the tangential momentum over the axial flux of the axial momentum of the flow, as reported in Eq. B.1 [91].

\[
S = \frac{\int_{0}^{R} \rho U_z U_\theta r^2 dr}{R \int_{0}^{R} \rho U_z^2 r dr}
\]  

(B.1)

Where \( R \) is the radius of the nozzle, \( U_z \) is the axial velocity, \( U_\theta \) is the tangential velocity, and \( \rho \) is the density of the fluid. Even though many relations have been derived to evaluate \( S \), based on geometrical parameters [160], the proper way of obtaining this number is to measure it. Different diagnostic techniques can be utilized to derive \( S \), such as laser-Doppler velocimetry, PIV, and hot wire anemometry. In this work, PIV is employed for this purpose. The \( S \) of the swirl stabilized burner utilized in chapter 3 and 4 has been determined with the following procedure, that it is also reported in [16]. To obtain the swirl number, the axial and tangential velocity fields should be determined. For doing so, two PIV measurement orientations, vertical and horizontal, are considered as shown in Fig. B.1.

Since swirling flows are strongly three-dimensional, the \( \Delta t \) between the two laser pulses of the PIV system should be selected in such a way that most of the seeding particles remain in the measurement plane between the two pulses. The \( \Delta t \) depends on the bulk velocity and on the dimensions of the laser sheet in the measurement section. The axial and tangential velocity fields, obtained with the two PIV arrangements, are reported in Fig. B.2 (a) and (b), respectively.
Figure B.1: The two PIV arrangements, vertical and horizontal, for the measurement of the swirl number. A schematic of the swirl burner presented in Sec. 2.1.1 is also reported. Figure adapted from [16].

Figure B.2: The axial (a) and tangential (b) velocity fields obtained with the two PIV arrangements. Figure adapted from [16].

From this velocity fields, the velocity profiles can be extracted (see Fig. B.3).

Note that the two velocity profiles must be extracted at the same position, 4
Figure B.3: The axial and tangential velocity profiles obtained with the two PIV arrangements. Figure adapted from [16].

millimeters above the nozzle in this study, to have meaningful results. Therefore, the swirl number is calculated by integrating these two profiles based on Eq. B.1.
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**Patents**

- WO2019086986, Fuel Tester for Characterization of the Susceptibility to Thermoacoustic Instabilities and Method, May 9, 2019