Effect of pressure on the transfer functions of premixed methane and propane swirl flames

Francesco Di Sabatino^a, Thibault F. Guiberti^a, Wesley R. Boyette^a,
William L. Roberts^a, Jonas P. Moeck^{b,c}, Deanna A. Lacoste^a

^a*King Abdullah University of Science and Technology, Clean Combustion Research
Center, Thuwal 23955-6900, Saudi Arabia*

^b*Technische Universität Berlin, Institut für Strömungsmechanik und Technische Akustik,
10623 Berlin, Germany*

^c*Norwegian University of Science and Technology, Department of Energy and Process
Engineering, 7491 Trondheim, Norway*

Abstract

This paper 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 from velocity and global OH* chemiluminescence measurements 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.

Keywords: flame dynamics, vortex roll-up, phase-locked imaging, flame transfer function, elevated pressure

---

1. Introduction

When fluctuations of heat release rate in a flame couple with an acoustic mode of a combustion chamber, one refers to thermoacoustic coupling, thermoacoustic oscillations, or thermoacoustic instabilities [1]. Thermoacoustic coupling can lead to high-amplitude oscillations of the pressure, the flow field, and the flame, that can in turn increase noise and pollutant emissions as well as decrease the efficiency of the combustion system and, in severe cases, lead to structural failure. Avoiding the occurrence of thermoacoustic instabilities is a major challenge in the design of stationary gas turbines and aero-engines [2, 3].

A key aspect in understanding and predicting thermoacoustic instabilities is the response of the flame to acoustic perturbations. This response

depends on many parameters, among them the composition of the unburned mixture, the mean flame shape, the flow field, and the operating temperature and pressure. A common approach to quantify the response of the flame to acoustic perturbations uses the flame transfer function (FTF) formalism. The FTF is deduced from the systematic analysis of the heat release rate (HRR) fluctuations of a flame subjected to controlled acoustic forcing, with frequencies typically ranging from a few hertz to a few hundred hertz [1, 4–8]. This approach offers insight into the flame dynamics and provides a valuable tool to predict the flame’s susceptibility to thermoacoustic oscillations. Unfortunately, as the flame dynamics depend on many parameters, the results obtained for a specific configuration at given operating conditions are difficult to extrapolate.

At atmospheric pressure, the dynamics of swirl-stabilized flames is relatively well understood on a qualitative level; however, quantitative predictions are still challenging. For premixed flames, the response to acoustic excitation of the flow is driven by two main mechanisms: the flame vortex roll-up [7–14] and the fluctuations in swirl number [12, 15, 16]. Qualitatively, the effects of burner geometry and forcing frequency [8, 17], equivalence ratio [18], and temperature [18] on the flame dynamics can be predicted reasonably well within certain limits. For technical applications such as stationary gas turbines and aero-engines, equivalence ratio fluctuations play an important role, too [19]. This effect is not considered in the present work, as only premixed swirl flames are studied.

For elevated pressure conditions, only a few studies report on the experimental investigation of flame dynamics through the systematic analysis

of the FTF [20–25]. Cheung *et al.* [20] 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.* [21] 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.* [23] 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 response 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 [25] 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. [22] and [24], 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 the present study 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.

The paper is organized as follows: the experimental apparatus and procedures are presented in Sections 2. In Section 3, the the flame transfer function is introduced, and the results obtained for an atmospheric methane–air swirled flame, which serves as the reference case, are presented. The effects of fuel and pressure on the flame transfer function are reported afterwards. A comprehensive discussion of all the results is reported in Section 4, and the main conclusions are given in Section 5.

2. Experimental setup

The experimental setup presented in Fig. 1 consists of a burner producing a premixed swirl flame, equipped with an acoustic forcing system (a), a high-pressure combustion duct (HPCD) within which the burner is installed (b), and diagnostics for flow and flame characterization.

2.1. Swirled premixed burner

A detailed description of the atmospheric pressure version of the burner used in this study can be found in Lacoste *et al.* [26]. The mixture of gaseous

fuel and air is injected into a plenum of 120 mm length. The flows of methane, propane, and air are controlled by mass flowmeters (Brooks SLA 58 series). From the bottom part of the plenum, the unburned gases flow through a honeycomb and a perforated plate before entering a radial swirler. The swirler features 12 blades with a trailing edge angle of 30° and the associated swirl number S , defined in [27] and determined from measured velocity profiles, is equal to 0.39 [28]. The burner tube has a diameter of 18 mm and is fitted with a central rod of 2.5 mm diameter. The flame is stabilized downstream of the burner tube and confined by a quartz tube of 100 mm length and 70 mm inner diameter.

Compared to the atmospheric pressure version, the acoustic forcing part of the burner has been upgraded in order to allow experiments at elevated pressures. A more powerful loudspeaker with a power rating of 900 W (Beyma 10LW30/N) has been installed at the bottom of the burner, enclosed in a plastic box with 15.4 l volume. Small holes in the sealing between the loudspeaker and the burner allow pressure equalization on both sides of the loudspeaker membrane. The loudspeaker is connected to a high-fidelity amplifier (QSC GX5) driven by a signal generator (NF WF1973). This assembly allows acoustic forcing of the unburned gases at controlled frequency and amplitude.

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 Section 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. 2). This is important because the frequency scaling of the FTF, *i.e.*, the position of the local extrema of the FTF gain, depends on the flame size [29] and should be maintained to allow for a fair comparison between cases. Such scaling also depends on the bulk jet velocity and, for a given fuel, the bulk velocity is kept constant when the operating pressure is increased. Table 1 summarizes, for both fuels and the five pressures investigated, the equivalence ratio of the mixture, ϕ , the thermal power of the flame, P_{th} , the average bulk velocity, $\bar{V}_{\text{bulk}}$, and the Reynolds number based on the injector’s hydraulic diameter, Re .

2.2. High-pressure combustion duct

The high pressure duct HPCD depicted in Fig. 1b 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 pressure, controlled by a back pressure regulator installed on the exhaust line, can be set from 1 to 40 bar. The flame is ignited by a laser spark, generated by focusing a 1064-nm laser beam (first harmonic of a Nd:YAG laser, pulse duration of 7 ns, and energy deposition of 200 mJ/pulse) on the axis of the burner, a few millimeters upstream of the quartz tube confining the flame. Two additional ports of the HPCD are used to feed the burner with fresh gases and water cooling and pass the signals for the hot wire and the loudspeaker.

Table 1: Summary of the experimental conditions and associated laminar burning velocities and flame thicknesses calculated with Cantera [30] for a freely propagating flame with an initial temperature of 300 K using the USC-II mechanism [31] and a mixture-averaged mass diffusion model.

Fuel	P (bar)	ϕ	P_{th} (kW)	$\bar{V}_{\text{bulk}}$ (m/s)	Re	S_L (m/s)	δ_L (mm)
CH ₄	1	0.67	4.0	6.8	7,800	0.176	0.69
	2	0.65	7.9	6.8	15,600	0.122	0.47
	3	0.63	11.5	6.8	23,400	0.087	0.41
	4	0.63	15.1	6.8	31,200	0.074	0.36
	5	0.64	19.4	6.8	39,000	0.069	0.31
C ₃ H ₈	1	0.70	3.9	6.1	7,500	0.233	0.53
	2	0.66	7.4	6.0	15,000	0.167	0.35
	3	0.64	10.7	6.0	22,500	0.130	0.28
	4	0.64	14.3	6.0	30,000	0.114	0.24
	5	0.64	17.9	6.0	37,500	0.104	0.21

2.3. Diagnostics

The determination of the FTF is based on velocity and OH* chemiluminescence measurements. 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. Previous work in a very similar setup [13] has shown that this distance does not introduce any significant changes in the transfer function of the flame for frequencies lower than 1 kHz. The hot wire has been calibrated in air for all pressures investigated.

The spontaneous emission of excited hydroxyl radicals (OH*) is used to determine the HRR fluctuations of the flame. This technique has been validated for perfectly premixed flames [32, 33]. 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 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 does not strictly hold for flames in non-adiabatic combustors, such as the one used in the present study. However, this method was used previously in several other non-adiabatic combustors [34, 29, 12]. In addition, it is shown in Section 4.2 that eventual uncertainties in determining heat release rate fluctuations with OH* chemiluminescence cannot be of 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 $113\text{ }\mu\text{s}$ 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.

2.4. 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 [12].

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. 3 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 was verified that the flame maintains its axisymmetric nature during forcing. This 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.

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 $u' / \bar{u} = 10\%$. When a flame is subjected to velocity perturbations, the heat release rate fluctuates by an amount $\dot{Q}'$, which is associated with fluctuations of OH* chemiluminescence intensity. The FTF is defined as the ratio of the relative heat release rate fluctuation and the relative velocity fluctuation in

the frequency domain:

$$F(f) = \frac{\hat{Q}(f)/\bar{Q}}{\hat{u}(f)/\bar{u}}, \quad (1)$$

where $\hat{(\cdot)}$ denotes the Fourier transform of a variable. The FTF can also be expressed in terms of a gain G and a phase Φ :

$$F(f) = G(f)e^{i\Phi(f)}, \quad (2)$$

where the gain reflects the magnitude of the flame response and the phase defines the lag between global fluctuations of HRR and fluctuations of velocity measured by the hot wire.

In order to facilitate comparisons with FTFs obtained in other studies for different experimental conditions, a Strouhal number [12, 17], 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 1).

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 (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 [7–16, 29].

First, this FTF is consistent with the low-frequency limit for premixed flames [6], *i.e.*, the gain approaches unity and the phase approached 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 [12, 29, 35, 36], 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 [12, 15], and the fluctuation of the top region, driven by vortex roll-up at the tip of the flame following the growth of hydrodynamic waves [9, 10, 7, 11–14]. To highlight these two mechanisms, the flame dynamics have been analyzed at 112 Hz and 176 Hz.

Figure 5 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. 5 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. 6 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 [12, 15, 16]. This mechanism is also evidenced in Fig. 5 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 [7, 9–14]. This mechanism is also visible in Fig. 5. Moreover, Fig. 6 (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 [15], leading to the local minimum in the gain response, which is visible at 112 Hz in Fig. 4.

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).

The strongest temporal fluctuations of the swirl number occur when axial and 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 impinges the swirler and propagate as 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 [12]. 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.

3.2. Fuel effects on the FTF

The FTFs of methane and propane flames measured at atmospheric pressure are compared in Fig. 4. 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, $St = 0.5$). Between 300 and 400 Hz, a third local maximum can be observed for propane while it barely can be noticed for methane. 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 Section 4.1.

3.3. Pressure effects on the FTF

The FTFs measured at five different pressures for the two fuels are compared in Fig. 7. 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 [37]. 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. 2) 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 was 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. For methane, the gain monotonically increases with pressure, allowing identification of a third local maximum, while for propane, the opposite trend can be noticed. However, in this frequency range the gain is significantly smaller than around the first and second local maxima, and therefore, the flame response is 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 Section 4.2.

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 Section 3.1. In agreement with previous studies [7, 9–14], flame dynamics are 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 effects of pressure and fuel on FVR is now described using Figs. 8 and 9. FVR manifests itself by gradually increasing the flame surface area near the outer flame edge in Abel-deconvoluted images of the OH* chemiluminescence between phases 144° and 288°. Regardless of fuel and pressure, the maximum coherent flame surface area, indicative of maximum FVR, is observed at phase 288°. 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°. 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* chemiluminescence intensity (black solid line) near the outer flame edge, as shown in Figs. 8 and 9. 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_{max} in the following.

Figure 10 plots the FTF gain at 176 Hz as a function of the measured FVR_{max} , each data point corresponding to a different pressure/fuel operat-

ing condition. There is an evident proportionality between the FTF gain at 176 Hz and $FVR_{\max}$, indicating that flame vortex roll-up is the main mechanism controlling the temporal fluctuations of flame surface area and controlling, by consequence, the 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 are 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. Discussion

As shown in Figs. 4 and 7, fuel and pressure exhibit their strongest influence on the gain response at the local maximum around 176 Hz. In addition, Figure 10 shows that the gain around 176 Hz is controlled 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 the flame vortex roll-up and discuss 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 control the size and strength of the vortex, more precisely, its tangential vorticity associated with the hydrodynamic wave, and (ii) those that control 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 remains mostly unaltered (Fig. 2). The bulk velocity is maintained for all operating pressures and adapted only slightly (about 10%) when switching between methane and propane (Tab. 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. 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 adapt to sudden changes of 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 [38, 39]. (c) The Lewis number: if the flame curvature or strain take 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 [34], which limits further growth of the flame surface.

According to the Borghi diagram [40–42], the flames of the present study reside in the “reaction sheet” regime of premixed turbulent combustion for all the experimental conditions investigated. The turbulent Karlovitz number needed to position experimental conditions in the Borghi diagram is obtained from the following formulation (Ka_T) [43, 44]:

$$Ka_T = C^{1/2} \times \left(\frac{u'_{\text{turb}}}{S_L} \right)^{3/2} \times \left(\frac{L}{\delta_L} \right)^{-1/2}, \quad (3)$$

where u'_{turb} is the RMS velocity fluctuation, L is the integral length scale, $C = S_L \times \delta_L / \nu$ is a correction factor, and ν 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, Ka_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 assume, 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 δ_L . Table 1 summarizes values of S_L and δ_L calculated with Cantera [30] for a freely propagating flame with an inlet of 300 K and the detailed USC-II mechanism [31] with a mixture-averaged mass diffusion model.

4.1. Effects of fuel on FVR_{max}

At atmospheric pressure, the difference in bulk velocity between both fuels is kept within 10% (see Table 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_{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 [45], FTFs were measured for a larger range of forcing amplitudes and it was shown that the response of both atmospheric methane and propane flames was 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 nonlinear mechanisms. Effects of the Lewis number are now 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 [40]. However, the size of the incoming vortex must be sufficiently small to induce curvature that is large enough to trigger effects of differential-diffusion, that is controlled by the forcing frequency and the flame Markstein length [46]. Based on the model developed by Preetham *et. al* in [46], the cutoff frequency below which differential-diffusion plays no role at atmospheric pressure 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. In fact, the resistance of lean propane flames to strain is typically smaller [43] than that of lean methane flames, and this cannot explain the larger FTF gain observed for propane. Therefore, the difference in gain measured at 176 Hz for propane and methane cannot be attributed to Lewis number and stretch effects. At 5 bar, the cutoff frequency is roughly 2000 Hz, meaning that the Lewis number also plays no significant role at higher pressure.

Properties (a) and (b) are finally examined. Table 1 shows that the laminar burning velocity is larger for propane than for methane at 1 bar. This suggests that propane flames can adapt to sudden changes of the flow faster than methane flames, which would enhance flame vortex roll-up. Table 1 also shows that the ratio δ_L/S_L is smaller for propane than for methane; propane flames are then less likely to be quenched by an incoming vortex (see for example [38, 39, 47]). This may also enhance flame vortex roll-up. In conclusion, the larger gain measured for propane at 176 Hz can most-likely be attributed to intrinsic properties of lean propane flames: 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 δ_L remain respectively larger and smaller for propane than for methane (see Table 1), which explains why the gain is consistently larger for propane than for methane. This analysis suggests that both S_L and δ_L are important parameters that control flame vortex roll-up and the dynamics of these flames forced at 176 Hz. The respective importance of S_L and δ_L/S_L on flame dynamics is currently being investigated and will be reported elsewhere.

4.2. Effects of pressure on FVR_{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.* [14] 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 convects 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 [48], the temperature of the burner walls and of the burnt gases in the outer recirculation zone is increased at thermal steady state [49]. This is evident in Fig. 2 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 [50–52].

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 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 FVR_{max} and on the local gain maximum originates 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. 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. 7. 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 increases with pressure [49] and it is possible that the temperature of the fresh gases entrapped by the forced vortex have a higher temperature than the plenum temperature $T = 300$ K. The temper-

ature at which important laminar flame properties, *i.e.*, S_L and δ_L , should be determined is then unknown. This is particularly problematic because freely propagating flame simulations indicate that S_L increases rapidly with the reactant temperature while δ_L and δ_L/S_L decrease 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) The rate 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 excited OH-radicals in flames and undermine heat release rate measurements from chemiluminescence. Therefore, the accuracy of heat release rate measurements could improve with pressure (closer to adiabatic conditions), and artificially modify trends of measured FTF gain with pressure. (2) The ability of the flame to adapt 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 [53]. 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. 7 and 10 that allow drawing clear and useful information on the 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 means 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 controls flame motion are not the same for methane and propane. Effects of varying turbulence and heat-losses with pressure make the interpretation of the 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.

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 adapt 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, the 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 linked to fuel chemistry should be considered to understand the pressure effect on

the response of premixed swirl flames to acoustic forcing.

Acknowledgements

This work is funded by the Center of Competitive Funding from King Abdullah University of Science and Technology.

References

- [1] S. Candel, Combustion dynamics and control: Progress and challenges, *Proc. Combust. Inst.* 29 (1) (2002) 1–28.
- [2] T. C. Lieuwen, V. Yang (Eds.), *Combustion Instabilities in Gas Turbine Engines*, Vol. 210 of *Progress in Astronautics and Aeronautics*, AIAA, Inc., 2005.
- [3] T. Poinsot, Prediction and control of combustion instabilities in real engines, *Proc. Combust. Inst.* 36 (1) (2017) 1–28.
- [4] L. Crocco, Research on combustion instability in liquid propellant rockets, *Symp. (Int.) Combust.* 12 (1968) 85–99.
- [5] S. Ducruix, T. Schuller, D. Durox, S. Candel, Combustion dynamics and instabilities: Elementary coupling and driving mechanisms, *J. Propul. Power* 19 (5) (2003) 722–734.
- [6] W. Polifke, C. Lawn, On the low-frequency limit of flame transfer functions, *Combust. Flame* 151 (3) (2007) 437–451.

- [7] B. Bellows, M. Bobba, A. Forte, J. Seltzman, T. Lieuwen, Flame transfer function saturation mechanisms in a swirl-stabilized combustor, *Proc. Combust. Inst.* 31 (2) (2007) 3181–3188.
- [8] K. Kim, J. Lee, B. Quay, D. Santavicca, Spatially distributed flame transfer functions for predicting combustion dynamics in lean premixed gas turbine combustors, *Combust. Flame* 157 (9) (2010) 1718–1730.
- [9] C. Külsheimer, H. Büchner, Combustion dynamics of turbulent swirling flames, *Combust. Flame* 131 (2002) 70–84.
- [10] D. Kang, F. Culik, A. Ratner, Combustion dynamics of a low-swirl combustor, *Combust. Flame* 151 (2007) 412–425.
- [11] Y. Huang, V. Yang, Dynamics and stability of lean-premixed swirl-stabilized combustion, *Prog. Energy Combust. Sci.* 35 (4) (2009) 293–364.
- [12] P. Palies, D. Durox, T. Schuller, S. Candel, The combined dynamics of swirler and turbulent premixed swirling flames, *Combust. Flame* 157 (2010) 1698–1717.
- [13] P. Palies, D. Durox, T. Schuller, S. Candel, Experimental study on the effect of swirler geometry and swirl number on flame describing functions, *Combust. Sci. and Tech.* 183 (2011) 704–717.
- [14] K. Oberleithner, S. Schimek, C. Paschereit, Shear flow instabilities in swirl-stabilized combustors and their impact on the amplitude dependent flame response: A linear stability analysis, *Combust. Flame* 162 (2015) 86–99.

- [15] N. Bunce, B. Quay, D. Santavicca, Interaction between swirl number fluctuations and vortex shedding in a single-nozzle turbulent swirling fully-premixed combustor, *J. Eng. Gas Turbines Power* 136 (2) (2014) 021503–1–11.
- [16] S. Candel, D. Durox, T. Schuller, J. Bourgouin, J. Moeck, Dynamics of swirling flames, *Annu. Rev. Fluid Mech.* 46 (2104) 147–173.
- [17] P. Palies, D. Durox, T. Schuller, S. Candel, Nonlinear combustion instability analysis based on the flame describing function applied to turbulent premixed swirling flames, *Combust. Flame* 158 (2011) 1980–1991.
- [18] M. Lohrmann, H. Büchner, Scaling of stability limits in lean-premixed gas turbine combustors, in: *Proc. ASME Turbo Expo.*, 2004, paper no. GT2004-53710.
- [19] T. Lieuwen, H. Torres, C. Johnson, B. Zinn, A mechanism of combustion instability in lean premixed gas turbine combustors, *J. Eng. Gas Turbines Power* 123 (1) (2001) 182–189.
- [20] W. Cheung, G. Sims, R. Copplestone, J. Tilston, C. Wilson, Measurement and analysis of flame transfer function in a sector combustor under high pressure conditions, in: *Proc. ASME Turbo Expo.*, 2003, paper no. GT2003-38219.
- [21] E. Freitag, H. Konle, M. Lauer, C. Hirsch, T. Sattelmayer, Pressure influence on the flame transfer function of a premixed swirling flame, in: *Proc. ASME Turbo Expo.*, 2006, paper no. GT2006-90540.

- [22] B. Schuermans, F. Guethe, D. Pennell, D. Guyot, C. Paschereit, Thermoacoustic modeling of a gas turbine using transfer functions measured under full engine pressure, *J. Eng. Gas Turbines Power* 132 (2010) 111503.
- [23] N. Bunce, J. Lee, B. Quay, D. Santavicca, Mixture-forced flame transfer function measurement and mechanism in a single-nozzle combustor at elevated pressure, in: *Proc. ASME Turbo Expo.*, 2011, paper no. GT2011-46744.
- [24] S. Hochgreb, D. Dennis, I. Ayranci, W. Bainbridge, S. Cant, Forced and self-excited instabilities from lean premixed, liquid-fuelled aeroengine injectors at high pressure and temperatures, in: *Proc. ASME Turbo Expo.*, 2013, paper no. GT2013-95311.
- [25] J. Zhang, A. Ratner, Effect of pressure variation on acoustically perturbed swirling flames, *Proc. Combust. Inst.* 36 (2017) 3881–3888.
- [26] D. Lacoste, J. Moeck, D. Durox, C. Laux, T. Schuller, Effect of nanosecond repetitively pulsed discharges on the dynamics of a swirl-stabilized lean premixed flame, *J. Eng. Gas Turbines Power* 135 (2013) 101501.
- [27] A. Gupta, D. Lilley, N. Syred, *Swirl Flows*, Abacus Press, Tunbridge Wells, England, 1984.
- [28] F. D. Sabatino, D. Lacoste, W. Roberts, A detailed characterization of a high pressure experimental apparatus for flame dynamic studies, in: *Proc. 10th U.S. Nat. Combust. Meeting*, 2017, paper no. 2H03.

- [29] K. Kim, J. Lee, B. Quay, D. Santavicca, The dynamic response of turbulent dihedral V flames: an amplification mechanism of swirling flames, *Combust. Sci. and Tech.* 183 (2) (2010) 163–179.
- [30] D. Goodwin, H. Moffat, R. Speth, *Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes*, Caltech, Pasadena, CA.
- [31] H. Wang, X. You, A. Joshi, S. Davis, A. Laskin, F. Egolfopoulos, C. Law, USC mech version II, High-Temperature Combustion Reaction Model of H₂/CO/C₁-C₄ Compounds.
- [32] I. Hurle, R. Price, T. Sugden, A. Thomas, Sound emission from open turbulent premixed flames, *Proc. R. Soc. London, Ser. A* 303 (1475) (1968) 409–427.
- [33] R. Price, I. Hurle, T. Sugden, Optical studies of the generation of noise in turbulent flames, *Symp. (Int.) Combust.* 12 (1) (1971) 1093–1102.
- [34] R. Balachandran, B. O. Ayoola, C. F. Kaminski, A. P. Dowling, E. Mastorakos, Experimental investigation of the nonlinear response of turbulent premixed flames to imposed inlet velocity oscillations, *Combust. Flame* 143 (2005) 37–55.
- [35] T. Komarek, W. Polifke, Impact of swirl fluctuations on the flame response of a perfectly premixed swirl burner, *J. Eng. Gas Turbines Power* 132 (2010) 061503 (7 pages).
- [36] B. Jones, J. Lee, B. Quay, D. Santavicca, Flame response mechanisms

- flame response mechanisms due to velocity perturbations in a lean premixed gas turbine combustor, *J. Eng. Gas Turbines Power* 133 (2011) 021503–1–9.
- [37] D. Durox, T. Schuller, S. Candel, Combustion dynamics of inverted conical flames, *Proc. Combust. Inst.* 30 (2) (2005) 1717–1724.
- [38] T. Poinso, D. Veynante, S. Candel, Quenching processes and premixed turbulent combustion diagrams, *J. Fluid Mech.* 228 (1991) 561–606.
- [39] W. Roberts, J. Driscoll, M. Drake, L. Goss, Imaging of the quenching of a flame by a vortex – to quantify regimes of turbulent combustion, *Combust. Flame* 94 (1993) 58–69.
- [40] C. Law, *Combustion Physics*, Cambridge University Press, New York, USA, 2006.
- [41] R. Borghi, On the structure and morphology of turbulent premixed flame, *Rec. Adv. in Aerospace Sci.* (1985) 117–138.
- [42] N. Peters, Laminar flamelet concepts in turbulent combustion, *Symp. (Int.) Combust.* (1986) 1231–1250.
- [43] E.-S. Cho, S. Chung, Local Karlovitz numbers at extinction for various fuels in counterflow premixed flames, *Combust. Sci. Technol.* 178 (2006) 1559–1584.
- [44] E. Hawkes, O. Chatakonda, H. Kolla, A. Kerstein, J. Chen, A petascale direct numerical simulation study of the modelling of flame wrinkling

- for large-eddy simulations in intense turbulence, *Combust. Flame* 159 (2012) 2690–2703.
- [45] F. D. Sabatino, T. F. Guiberti, J. P. Moeck, D. A. Lacoste, W. L. Roberts, Experimental analysis of the effect of fuels on the flame describing function of a swirl-stabilized premixed flame, in: 1th Asia-Pacific Conference on Combustion (ASPACC), Sydney, Australia, December 10 - 14, 2017.
- [46] Preetham, S. K. Thumuluru, H. Santosh, T. C. Lieuwen, Linear response of laminar premixed flames to flow oscillations: unsteady stretch effects, *J. Propul. Power* 26 (3) (2010) 524–532.
- [47] M. Stöhr, C. Arndt, W. Meier, Effects of Damköhler number on vortex–flame interaction in a gas turbine model combustor, *Proc. Combust. Inst.* 34 (2013) 3107–3115.
- [48] E. Freitag, On the measurement and modelling of flame transfer functions at elevated pressure, Ph.D. thesis, Technische Universität München (2009).
- [49] T. Guiberti, D. Durox, P. Scoufflaire, T. Schuller, Impact of heat loss and hydrogen enrichment on the shape of confined swirling flames, *Proc. Combust. Inst.* 35 (2015) 1385–1392.
- [50] K. Manoharan, J. O’Connor, S. Hansford, S. Hemchandra, Instability mechanism in a swirl flow combustor: precession of vortex core and influence of density gradient, in: Proceedings of the ASME Turbo Expo 2015, June 15–19, 2015, Montreal, Canada.

- [51] K. Manoharan, S. Hemchandra, Absolute/convective instability transition in a backward facing step combustor: fundamental mechanism and influence of density gradient, *J. Eng. Gas Turbines Power* 137 (2015) 021501–1–11.
- [52] S. Kirthy, S. Hemchandra, S. Hong, S. Shanbhogue, A. Ghoniem, Role of shear layer instability in driving pressure oscillations in a backward facing step combustor, in: *Proceedings of the ASME Turbo Expo 2016*, June 13–17, 2016, Seoul, South Korea.
- [53] N. Peters, The turbulent burning velocity for large-scale and small-scale turbulence, *J. Fluid Mech.* 384 (1999) 107–132.

Figures

Figure 1: Schematic of the experimental setup: (a) swirl burner and (b) high-pressure combustion duct.

Figure 2: 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.

Figure 3: Temporal evolution of the instantaneous (dot) and phase-averaged (line) relative velocity fluctuations (blue) and OH* chemiluminescence intensity (red) over two forcing periods.

Figure 4: Flame transfer functions of methane (red) and propane (blue) flames at atmospheric pressure for a forcing amplitude of 10%.

Figure 5: Phase-locked Abel-deconvoluted images of the OH* chemiluminescence for the reference flame subjected to acoustic forcing at 112 Hz.

Figure 6: 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%.

Figure 7: Flame transfer functions of methane (left) and propane (right) flames for different operating pressures and a forcing amplitude of 10%.

Figure 8: 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 9: 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.

Figure 10: FTF gain measured at 176Hz as a function of FVR_{max} for every operating condition investigated in this study.