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

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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.

## 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

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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 Section 2. In Section 3, the flame transfer function is introduced, and the results obtained for an atmospheric methane–air swirl 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. Swirl 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, $\phi$, the thermal power of the flame, $P_{\mathrm{th}}$, the average bulk velocity, $\bar{V}_{\mathrm{bulk}}$, and the Reynolds number based on the injector's hydraulic diameter, Re.

### 2.2. High-pressure combustion duct

The high pressure combustion duct HPCD depicted in Fig. 1b is a 0.67 $\mathrm{m}^3$ 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 downstream 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.

### 2.3. Diagnostics

The determination of the FTF is based on velocity and OH* chemiluminescence measurements. The velocity fluctuations in-