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# The impact of equivalence ratio oscillations on combustion dynamics in a backward-facing step combustor

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ABSTRACT

The combustion dynamics of propane–air flames are investigated in an atmospheric pressure, atmospheric inlet temperature, lean, premixed backward-facing step combustor. We modify the location of the fuel injector to examine the impact of equivalence ratio oscillations arriving at the flame on the combustion dynamics. Simultaneous pressure, velocity, heat-release rate and equivalence ratio measurements and high-speed video from the experiments are used to identify and characterize several distinct operating modes. When the fuel is injected far upstream from the step, the equivalence ratio arriving at the flame is steady and the combustion dynamics are controlled only by flame–vortex interactions. In this case, different dynamic regimes are observed depending on the operating parameters. When the fuel is injected close to the step, the equivalence ratio arriving at the flame exhibits oscillations. In the presence of equivalence ratio oscillations, the measured sound pressure level is significant across the entire range of lean mean equivalence ratios even if the equivalence ratio oscillations arriving at the flame are out-of-phase with the pressure oscillations. The combustion dynamics are governed primarily by the flame–vortex interactions, while the equivalence ratio oscillations have secondary effects. The equivalence ratio oscillations could generate variations in the combustion dynamics in each cycle under some operating conditions, destabilize the flame at the entire range of the lean equivalence ratios, and increase the value of the mean equivalence ratio at the lean blowout limit.


## 1. Introduction

Continuous combustion systems common in propulsion and energy applications are susceptible to thermoacoustic instability [1,2]. The instability may occur under lean burn conditions, where most emissions and efficiency benefits are achieved, and near stoichiometry, where high power density is the objective. As a result of the resonant feedback interactions between the driving heat-release rate perturbation mechanisms and the acoustic modes, these combustors are known to exhibit significant pressure and flow oscillations, which may cause flame extinction, structural vibration, flame flashback and even structural damage. Several mechanisms instigate and promote such interactions between acoustic oscillations and the heat release, including: flame–acoustic wave interactions, flame–vortex interactions, equivalence ratio oscillations, flame–wall interactions and the effect of unsteady stretch rate. These may be present individually or simultaneously [3–5].

The two mechanisms that we will explore in this paper which are likely to be the most significant instability mechanisms in large scale gas turbine combustors are the flame–vortex interactions and the equivalence ratio oscillations [6,7]: (i) *Flame–vortex interactions* – the unsteady interaction between the flame surface and the vortex formed in the wake of the recirculation zone generates significant variations in the flame area; hence the heat-release rate. The periodic heat release oscillations may couple positively with the acoustic field, leading to self-sustained acoustic oscillations [8–16]; (ii) *Equivalence ratio oscillations* – the pressure oscillations in the combustor interact with the fuel supply line, leading to noticeable oscillations in the fuel flow rate. Moreover, the velocity oscillations at the location of the fuel supply modulate the air flow rate. The combined oscillations in the fuel and the air flow rates result in equivalence ratio oscillations at the location of the fuel injector. These oscillations are convected to the flame zone, where it directly effects the burning velocity of the flame and the heat of reaction of the mixture, causing heat-release rate oscillations. If the heat-release rate oscillations couple positively with the acoustic field, self-sustained oscillations are established [17–20].

In this paper, we carry out an experimental study in a backward-facing step combustor to identify the contribution of equivalence ratio oscillations on thermoacoustic instability and combustion dynamics. The combustor pressure and the inlet temperature are atmospheric. Extensive instrumentation of the combustor allows monitoring the temporal variations in pressure, heat release, and

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flow velocity; and the temporal and spatial variations of the equivalence ratio.

We fired the combustor at Reynolds numbers of 6500 and 8500, based on the step height and the average flow velocity at the step using propane as the fuel. At each Reynolds number, we varied the equivalence ratio of the fuel–air mixture from near the lean blowout limit to a value approaching the flashback limit. We conducted the experiments with the fuel injector located 28 cm or 93 cm upstream of the step. The fuel injector location affects the combustion dynamics by impacting the spatial and temporal air–fuel premixing, the amplitude of equivalence ratio oscillations, and the convective time scale. By modifying the equivalence ratio reaching the combustion zone, we determine the relative contributions of the flame–vortex interactions and the equivalence ratio oscillations on the combustion dynamics.

## 2. Combustor description

Fig. 1 shows a schematic diagram of the backward-facing step combustor. The combustor consists of a rectangular stainless steel duct with a cross section 40 mm high and 160 mm wide. The air inlet to the combustor is choked. 0.45 m downstream from the choke plate, a 0.15 m long ramp contracts the channel height from 40 mm to 20 mm followed by a 0.4 m long constant-area section that ends with a sudden expansion back to 40 mm. The step height is 20 mm. The overall length of the combustor is around 5.0 m. A circular exhaust pipe comprises the last 3.0 m of the combustor with a cross-sectional area approximately four times that of the rectangular section. The exhaust exits to a trench with a large cross-sectional area. The combustor is equipped with quartz viewing windows. An air compressor supplies air up to 110 g/s at 883 kPa. The propane flow rate is controlled using a Sierra C100M mass flow controller allowing maximum propane flow rate of 2.36 g/s. The uncertainty of the flow rate is ±1% of the full scale. The fuel is injected through several choked spanwise holes in a manifold located 93 cm upstream of the step, or through choked microjets from the top and the bottom walls of the combustor located 28 cm upstream of the step. Images of the flame are captured at 2000 frames per second using a Phantom v7.1 high-speed camera. The pressure measurements are obtained using Kulite MIC-093 high intensity microphones designed for laboratory investigations. The flow velocity is measured 22 cm upstream of the step using TSI IFA300 hot wire anemometer. The sign of the hot wire reading is corrected to account for flow reversal at parts of a cycle under some operating conditions. An optical bandpass filter centered at 430 nm is placed in front of a Hamamatsu H9306-02 photosensor module to measure the CH* chemiluminescence emitted by the flame, which is proportional to the instantaneous heat-release rate [21–23]. More details on CH* chemiluminescence measurement technique can be found in Ref. [24]. Temporal equivalence ratio variations are measured 14 cm upstream of the step using a Hamamatsu P4245 photodiode to detect absorption of a HeNe laser by propane at a wavelength of 3.39 μm. This laser is modulated using a Scitec Instruments 360 OEM optical chopper in order to distinguish between the light emitted by the flame when it flashes back and the laser signal. When the fuel passes through the laser beam, it absorbs some of the laser light, reducing the photodiode signal. The intensity of the light can be related to the fuel concentration using the Beer–Lambert law, as described by Lee et al. in Ref. [18]. Fig. 2 shows the schematic diagram of the temporal equivalence ratio measurement setup. The spatial concentration/equivalence ratio measurements are performed under non-reacting flow conditions by injecting $CO_2$ into the combustor (as a fuel surrogate) together with air and taking point measurements of its concentration using a California Analytical Instruments ZRH $CO/CO_2$ analyzer. The gas probe automatically traverses the combustor cross section 2 cm downstream of the step. The spatial concentration measurement setup is shown schematically in Fig. 3. All data are acquired using a National Instruments PCIe-6259 data acquisition board and the Matlab Data Acquisition Toolbox. A custom Matlab code is used to store the data and control the experiment.

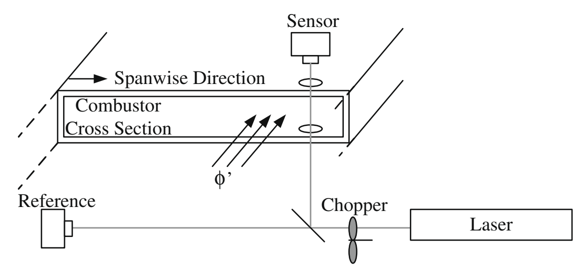


**Fig. 2.** Schematic diagram showing the temporal equivalence ratio measurement setup.

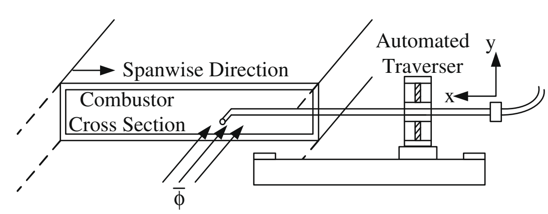


**Fig. 3.** Schematic diagram showing the spatial equivalence ratio measurement setup.

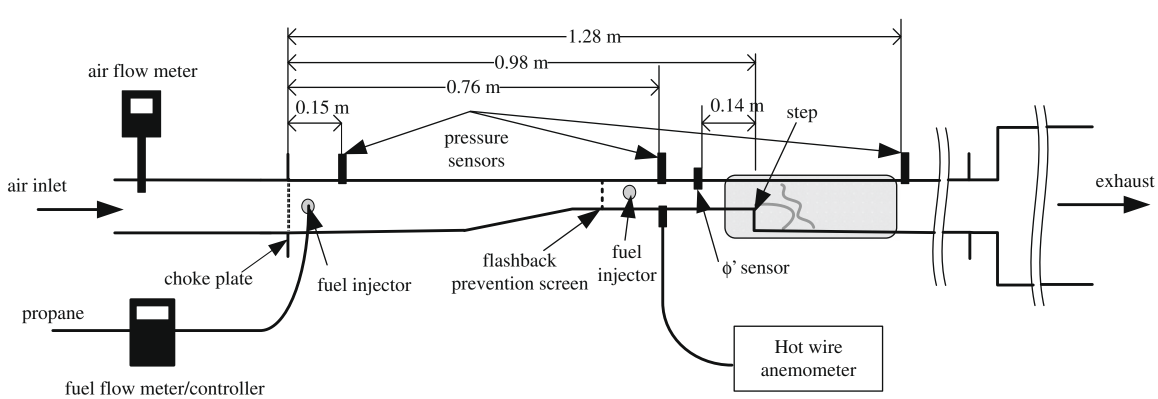


**Fig. 1.** Schematic diagram of the backward-facing step combustor.