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Impact of the flame-holder heat transfer characteristics on the onset of combustion instability

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Abstract

In this paper, we investigate the impact of heat transfer between the flame and the flame-holder on the dynamic stability characteristics of a 50-kW backward facing step combustor. We conducted a series of tests where two backward step blocks were used, made of ceramic and stainless steel whose thermal conductivities are 1.06 and 12 W/m/K, respectively. Stability characteristics of the two flame-holder materials were examined using measurements of the dynamic pressure and flame chemiluminescence over a range of operating conditions. Results show that with the ceramic flame-holder, the onset of instability is significantly delayed in time and, for certain operating conditions, disappears altogether, whereas with the higher conductivity material, the combustor becomes increasingly unstable over a range of operating conditions. We explain these trends using the heat flux through the flame-holder and the change in the burning velocity near the step wall. Results suggest a potential approach of using low thermal conductivity material near the flame-holder as passive dynamics suppression methods.

Keywords: Combustion instability, thermal conductivity, heat transfer, flame-holder, flame speed

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1. Introduction

Combustion systems commonly used in gas-turbine engines are susceptible to thermoacoustic instability, where the combustors are known to exhibit significant pressure and flow oscillations. These instabilities may occur as a result of the resonant feedback interactions between the driving heat release mechanisms and the acoustic environment, which can cause flame extinction and flashback as well as structural vibration and damage. Several mechanisms are known to promote these unsteady coupling processes: e.g., flame-acoustic wave interactions, flame-vortex interactions, equivalence ratio fluctuations, flame-wall interactions and the effect of unsteady stretch rate, which may be present individually or concurrently (Ducruix et al., 2003).

Flame-vortex interactions are among the most significant instability mechanisms in large-scale gas turbine combustors (Venkataraman et al., 1999; Bernier et al., 2004). When the unsteady heat release rate fluctuations associated with large-scale vortical structures couple positively with the acoustic field, self-sustained acoustic oscillations are observed (Poinsot et al., 1987; Ghoniem et al., 2005). The mechanism of flame-vortex interactions has been examined in a number of studies (Poinsot et al., 1987; Ghoniem et al., 2005; Yu et al., 1991; Matveev and Culick, 2003; Altay et al., 2009), where the authors emphasize the role of vortex kinematics (formation, separation and convection) and its interactions with acoustics and the flame in driving the observed instabilities.

This paper presents an experimental investigation into combustion instabilities observed in a laboratory scale backward-facing step combustor, where the dynamics are driven by flame-vortex interactions. In particular, we examine the impact of heat transfer processes near the flame-holder on the dynamic instability characteristics, e.g., the mode transition from a stable operating regime to an unstable operating regime, or the onset of combustion instability. The impact of heat transfer on the flame-vortex driven combustion instabilities has not been extensively studied, while, as will be shown in this paper, it can play an important role in the onset of the instability.

A significant part of the relevant literature discusses the role of heat transfer processes
in the context of the static stability characteristics, i.e., lean blow-off or flame flashback. Bollinger and Edse (1956) reported their experimental study on the effect of geometric parameters on the burner tip temperature at the moment of flashback observed in a bunsen flame. They observed that flashback occurs at a constant burner tip temperature for fuel-lean mixtures, if the thermal conductivity and wall thickness are held constant. Ronney (2003) and Khandelwal et al. (2010) examined the effect of thermal conductivity in a micro-scale combustor. Ronney (2003) demonstrated that the stream-wise conduction through the wall has a significant impact on the operating limit in a micro-scale combustor. Khandelwal et al. (2010) reported that the micro step combustor made of copper (thermal conductivity = 400 W/m/K) was unable to stabilize the flame within the combustor, because of its high thermal conductivity and resultant high heat loss. Kedia and Ghoniem (2011) numerically investigated premixed flame stability characteristics in a perforated plate burner, showing the coupled role of heat loss to the burner and the flame curvature on the static flame stabilization and blow-off mechanism. Kedia et al. (2011) also demonstrated the critical role of the heat transfer in predicting the dynamic response of the flames to acoustic perturbations. Duchaine et al. (2011) reported their numerical study, in which they examined the sensitivity of laminar flame transfer functions to the temperature of the perforated plate walls where conical flames are stabilized. They demonstrated that an increase in the inlet duct temperature can heat up the fresh mixture, inducing a greater local flame speed as well as local flow acceleration, which competitively affect the phase delay of the flame response. These studies suggest that heat transfer between the flame and the flame anchoring plate can play a significant role in determining the flame dynamic response.

In this paper, we discuss the impact of thermal characteristics of the flame-holder on the dynamics of turbulent premixed flames observed in a dump combustor configuration. The flame-holders made of different materials of distinct thermal conductivities, but of the same geometry, are used, which allows us to study the impact of heat transfer characteristics while the flow dynamics or the acoustics in the system are kept the same. The dynamic pressure and flame chemiluminescence measurements are used to examine the combustor’s response
with different flame-holder materials. We report our finding that the distinct heat transfer characteristics near the flame-holder significantly impact the onset of the instability. In the literature, the triggering of combustion instability has been addressed in the context of the nonlinear nature of thermoacoustic oscillations (Lieuwen, 2002) and non-normality of the system (Balasubramaniam and Sujith, 2008; Tulsyan et al., 2009). The former (Lieuwen, 2002) discusses the nonlinear nature of the system, whose stability boundaries are sensitive to the background disturbances under stable operating conditions, whereas the latter studies (Balasubramaniam and Sujith, 2008; Tulsyan et al., 2009) emphasize the role of acoustics in triggering the instability in the context of non-normal nature of the system combined with a nonlinear effect in a ducted diffusion flame or in a vortex-shedding configuration. The role of combustion or other thermal processes, e.g., heat transfer, in mode transitions or triggering of the instability has not been widely reported.

The present study, in which we examine the impact of heat transfer on triggering of the instability, was motivated by our early observation that the onset of the instability is sensitive to the length of time that the combustor operates in the neighborhood of the operating condition corresponding to the mode transition. We find that the onset of the instability can be prevented or significantly delayed by using a material of low thermal conductivity at the flame anchoring region. It is worthwhile noting that the time scale associated with the transition to an unstable operation is very short compared to the characteristic time scale for thermal equilibrium in the flame-holder, as discussed in Section 3.4. Hence, this study is concerned with transient phenomena rather than a steady heat transfer problem. To explain the observed trends, we therefore discuss the transient processes of heat transfer at the flame-holder and their impact on the onset of the dynamics. We demonstrate that heat loss to the combustor wall from the flame, which is then convected to the unburned gas via conduction through the flame-holder is the key mechanism behind our observation.

The paper is structured as follows: Section 2 describes the combustor configuration, instrumentation and diagnostics as well as the experimental procedure and conditions. In Section 3, we start with the overall stability characteristics of the combustor and initial
observations that suggest a possible role of the heat transfer in driving the instabilities. These are presented in Sections 3.1 and 3.2, respectively. We then proceed to the results on our investigation into the effect of using different materials of distinct thermal conductivities at the flame anchoring region. In Section 3.3, we compare the two cases with stainless steel and ceramic flame-holders using the dynamic pressure and flame chemiluminescence measurements. Following the discussion in Section 3.4 on the mechanism underlying the experimental results, the article ends with concluding remarks in Section 4.

2. Experimental Setup

2.1. Combustor and Diagnostics

Figure 1 shows a 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 is choked. At a location 0.45 m downstream from the choke plate, a 0.15 m long ramp reduces 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 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. Quartz viewing windows installed in the vicinity of the step provide optical access.

An Atlas Copco GA 30 FF air compressor supplies air up to 110 g/s at 883 kPa. A Sierra C100M Smart-Trak digital mass flow controller allows a maximum flow rate of 2.36 g/s for propane. The uncertainty of the flow rate is ±1% of the full scale. Fuel is injected through several spanwise holes in a manifold located 0.96 m upstream of the step, which is 0.02 m downstream of the choke plate. Since the fuel is injected near the choke plate where flow velocity oscillations are weak, the amplitude of equivalence ratio oscillations established at the fuel injector is small. In addition, the distance between the fuel manifold and the step creates a substantial convective delay during which equivalence ratio oscillations are damped as a result of turbulent mixing. In our previous study (Altay et al., 2009),
we demonstrated that the equivalence ratio oscillation is negligible by showing spatial and
temporal measurements of equivalence ratio. Air is preheated to a temperature of up to
500 K using an Osram Sylvania 18 kW inline resistive electric heater. The temperature of
the inlet mixture is measured using a type K thermocouple mounted 0.2 m upstream of the
sudden expansion.

Pressure is measured at three locations: 0.20 m upstream of the sudden expansion and
0.25 m downstream from the beginning of the exhaust pipe using Kulite MIC-093 high in-
tensity microphones mounted in semi-infinite line configurations (Englund and Richards,
1984) and 0.15 m downstream of the choke plate using a flush-mounted, water-cooled Kistler
7061B pressure sensor. High-speed, spatially resolved CH$_{\ast}$—chemiluminescence measure-
ments of the flame at speeds up to 2000 Hz are taken using a NAC GX-1 high-speed CMOS
camera with a Nikon 50-mm f/1.8 lens. The camera has a resolution of 1280 × 1024 pixels
and a monochrome bit depth of 12 bits per pixel. A BG-39 optical colored glass filter with
2-mm thickness is placed in front of the camera, to reduce an infrared radiation from the
flame. The temperature of the step block is measured using type K thermocouples at three
locations 3 mm below the step surface: 6, 18 and 30 mm upstream of the sudden expansion
along the centerline of the spanwise direction. All data are acquired using a National In-
struments 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.

2.2. Test Setup and Procedure

To investigate the stability characteristics of the combustor, we conducted two series of
experiments: an equivalence ratio sweep test and a “transient” test. First, we varied the
equivalence ratio of propane/air mixtures either from near stoichiometry toward the lean
blow-off limit or from the lean blow-off limit to near stoichiometry, at the inlet temperature
of 300 K and 500 K. The equivalence ratio was varied in steps of 0.01 (the flow controllers
allow the accuracy of equivalence ratio change within $\Delta \phi \sim 0.002$). Pressure response curves
as a function of the equivalence ratio are presented in Section 3.1, which identify distinct
dynamic regimes of the combustor depending on the operating conditions. As shown in
Section 3.2.1, the combustor exhibits strong hysteresis depending on whether the equivalence ratio is increased or decreased.

Second, to further examine the characteristics of the transient behavior while the combustor switches from the stable regime to the unstable regime, the transient tests were conducted at several equivalence ratios in the neighborhood of the operating point at which mode transition occurs, as identified by the equivalence ratio sweep test. In this series of tests, the equivalence ratio was kept constant either until the combustor exhibits the instability or for 7 minutes if no instability is observed. The rationale behind these tests is based on our observation that the onset of the instability is sensitive to the length of time for which the combustor stays at a constant equivalence ratio, as will be shown in Section 3.2.2. These test results are used to show that the heat transfer at the flame anchoring region plays a role in the onset of the instability, as will be discussed in Sections 3.3 and 3.4.

The two step blocks were manufactured with stainless steel and ceramic, whose thermal conductivities are 12 W/m/K and 1.06 W/m/K, respectively. The two series of tests described above were conducted with each step block installed at the flame anchoring region (see Fig. 2).

Throughout all tests, the combustor was operated at atmospheric pressure and constant Reynolds number of 6500 based on the step height (20 mm). This corresponds to a mean inlet velocity of 5.2 m/s at 300 K, which increases to 12.5 m/s at 500 K. The inlet velocity varies by less than 10% as a function of equivalence ratio.

3. Results

3.1. Stability Characteristics

The combustor exhibits several distinct operating regimes depending on the inlet conditions. Each operating regime can be characterized by the amplitude and frequency of

\footnote{While the cutoff operating time (seven minutes) in the transient tests is large enough compared to the time scale associated with the onset of the instability as discussed in Section 3.4.2, we note that it is arbitrarily chosen based on practical considerations for a large number of repeated tests and thereby has no physical significance.}
pressure oscillations as well as distinct flame dynamics. Altay et al. (2009) and Speth et al. (2007) demonstrated the existence of these operating regimes for propane/hydrogen fuel mixtures and syngas fuel mixtures, respectively, using the pressure measurements and high-speed flame images. In this section, we present the pressure response curve for a propane/air mixture, and highlight the key characteristics of the operating regimes that will be frequently referred to in the subsequent sections.

Figure 3 shows an overall sound pressure level (OASPL) as a function of equivalence ratio for a propane/air mixture. The OASPL in dB is defined as:

\[
\text{OASPL} = 10 \log_{10} \left( \frac{p(t) - \overline{p(t)}}{p_0} \right)^2
\]

where overbars indicate average values, \( p(t) \) is the pressure measured in an interval \( t_1 < t < t_2 \) and \( p_0 = 2 \times 10^{-5} \) Pa. The pressure sensor located at 0.2 m upstream of the sudden expansion (where the flame is nominally anchored) is used for calculating OASPL. Based on the pressure oscillations amplitude, the combustor’s operating regimes can be classified into three categories; we refer to those as **stable, quasi-stable and unstable regimes**. As the equivalence ratio is decreased from stoichiometry toward the lean blow-off limit, the combustor transitions from the unstable regime to the quasi-stable regime, and then to the stable regime, in which the OASPL is \( 150 - 160 \) dB, \( \sim 145 \) dB and below 140 dB, respectively. Each mode transition occurs if the equivalence ratio is varied beyond a certain threshold. Although not shown, the combustor exhibits distinct flame dynamics in each operating regime. The main characteristics of the flame dynamics in each operating regime are briefly summarized here.\(^2\) In the stable regime, small vortices are shed from the step over a range of frequencies which are not coupled with any acoustic mode of the combustor. The flame is stabilized in a typical reacting shear layer, exhibiting a relatively steady motion. In the quasi-stable regime, while the flame remains attached to the step, it experiences periodic

\(^2\)See Altay et al., 2009 for the corresponding flame chemiluminescence images in each operating regime, and Hong et al., 2013b for the corresponding particle image velocimetry data.
fluctuations at $\sim 40$ Hz, interacting with the large wake vortex shed from the step. If the combustor transitions to the unstable regimes, strong oscillations of the flame are observed along with the periodic evolution of the wake vortex throughout the instability cycle. While the flow exhibits strong fluctuations, the flame detaches from the step during the part of each cycle and anchors upstream of the sudden expansion.

In Fig. 3, we observe two distinct unstable regimes in which the combustor oscillates at two different frequencies, e.g., $\sim 40$ Hz and $\sim 70$ Hz, which are referred to as low-frequency unstable regime and high-frequency unstable regime, respectively.\(^3\) According to the one-dimensional acoustic analysis (Hong et al., 2013\(^a\)), the low-frequency unstable regime ($\sim 40$ Hz) corresponds to the quarter-wave acoustic (fundamental) mode, whereas the high-frequency unstable regime ($\sim 70$ Hz) resembles the three quarter-wave (first harmonic) acoustic mode. Within the scope of this study, in which we focus on the onset of dynamic instability, i.e., mode transition between the (quasi-) stable and low-frequency unstable regimes, differentiation between the low-frequency and high-frequency unstable regimes is of no particular importance.

3.2. Observations on the Onset of the Instabilities

For higher inlet temperatures or for fuel mixtures with finite hydrogen concentration, the pressure response curves show similar sets of operating regimes, while the transition points between distinct regimes shift to leaner condition (Altay et al., 2009; Hong et al., 2013\(^b\)). Our prior studies (Altay et al., 2009; Hong et al., 2013\(^b\)) demonstrated that the dependence of the stability characteristics on the operating conditions can be encapsulated in a scaled strained flame consumption speed.\(^4\) Moreover, recent experimental observations suggest that heat transfer processes near the flame anchoring region, which could affect the burning velocity, may also have a significant impact on the stability characteristics, e.g., mode transitions or

\(^3\)The naming of these operating regimes (e.g., “low” and “high”) are based on the relative magnitude of the frequencies, while they both correspond to the longitudinal acoustic modes.

\(^4\)The consumption speed is defined as $S_c = \int_{-\infty}^{\infty} \frac{q''''}{\rho_u(T_b - T_u)} dy$, where $q''''$ is the volumetric heat release rate, $c_p$ is the specific heat of the mixture, $y$ is the coordinate normal to the flame, $\rho_u$ is the unburned mixture density, and $T_u$ and $T_b$ are the unburned and burned gas temperature, respectively.
the onset of combustion instability, as will be discussed in the following sections.

3.2.1. Hysteresis in Mode Transition

In this section, we show the presence of hysteresis in the combustor dynamics. For example, the stability’s boundary at which the mode transition occurs varies depending on whether the combustor load (equivalence ratio) is increased or decreased. This indicates that the operating regimes of the combustor depend not only on the operating conditions, but also on the history of the state, i.e., the combustor tends to persist in its present state. Figure 4 illustrates the observed hysteresis, where the pressure responses recorded while the equivalence ratio is increased or decreased are shown for $T_{in} = 300$ and $500$ K. We observe that although the same sets of operating regimes are observed, the combustor’s selection of the operating regime strongly depends on the previous state as the equivalence ratio is varied. Hysteresis phenomena are attributed to the nonlinear nature of the system dynamics. Similar observations have been reported in a swirl-stabilized combustor for a syngas/air mixture (Speth, 2010) and for a methane/carbon-dioxide/oxygen mixture (Shroll et al., 2012).

In Fig. 4(a), starting at the equivalence ratio near stoichiometry, the combustor operates in the unstable regime at a range of equivalence ratios above a certain threshold ($\phi \approx 0.75$), at which the combustor transitions to the quasi-stable regime. On the other hand, if the equivalence ratio is gradually increased from near the lean blow-off limit, the combustor remains stable even above $\phi \approx 0.75$, until it transitions to the unstable regime at $\phi \approx 0.80$. In the former case (decreasing $\phi$), the unstable mode is triggered immediately after “kicking” the equivalence ratio to high enough value near stoichiometry, while in the latter case (increasing $\phi$), the combustor transitions to the unstable regime if the equivalence ratio exceeds a certain threshold ($\phi \approx 0.80$).

As the inlet flow is preheated to $500$ K, similar hysteresis can be observed (see Fig. 4b). The mode transition between the unstable and stable regimes occurs at $\phi \approx 0.58$ if the equivalence ratio is decreased, or at $\phi \approx 0.60$ if the equivalence ratio is increased. Unlike at $T_{in} = 300$ K, the transition between the low-frequency and high-frequency unstable regimes
also depends on the history of the equivalence ratio. The combustor operates in the high-
frequency unstable regime\(^5\) over a wider range of equivalence ratios \((\phi \geq 0.6)\) as \(\phi\) is decreased
from near stoichiometry. In contrast, if \(\phi\) is increased from near the lean blow-off limit, the
combustor operates in the low-frequency unstable regime until the equivalence ratio reaches
\(\phi \approx 0.78\).

While the mechanism underlying the nonlinear characteristics associated with hysteresis
remains unknown, in this study, we focus on the onset of the instability, i.e., the transition
between the (quasi-) stable regime and the unstable regime. The variation in the critical
values of equivalence ratio at which the combustor switches modes between the stable and the
unstable regimes decreases to 0.02 \((= 0.6 - 0.58)\) at the higher inlet temperature, compared
to 0.05 \((= 0.8 - 0.75)\) at 300 K. One possible interpretation is that for the case where the
equivalence ratio is increased, if the combustor is initially in a hotter state, it transitions
from the stable regime to the unstable regime sooner. In the next section, we start from this
idea and proceed to the results of transient tests.

3.2.2. Impact of Flame-holder Temperature on Time to Instability

While conducting the equivalence ratio sweep tests in an ascending order, we observed
that the onset of combustion dynamics is sensitive to the length of time for which the com-
bustor stays at the equivalence ratios near the mode transition. To confirm this observation,
we conducted a simple test in which we kept the equivalence ratio constant and recorded the
time it takes for the onset of the instability. Based on Fig. 4(a), the equivalence ratio was
chosen to be \(\phi = 0.79\) that is near mode transition.

Figure 5 shows the pressure measurements in time series, where three consecutive tests
are conducted as described below. The combustor was at room temperature of \(\sim 295\) K
(measured using a radiative thermometer) when a propane/air mixture was ignited. The
combustor operated initially in the stable regime. As shown in the figure, after 34 seconds,

\(^5\)The oscillation frequency increases, e.g., from \(\sim 70\) Hz at \(T_{in} = 300\) K to \(\sim 90\) Hz at \(T_{in} = 500\) K. This
is because the acoustic frequency depends on the speed of sound, which varies as the square root of the gas
temperature; \(f \sim c \sim \sqrt{T}\). See Hong et al., 2013a for detailed acoustic analysis.
it transitioned to the unstable regime. Following this test, the combustor was ignited again after it had been switched off for $\sim 90$ seconds. The temperature of the step block was $\sim 317$ K at the moment of ignition. In this case, the combustor operated initially in the stable regime, then transitioned to the unstable regime after 19 seconds. The combustor had been switched off for $\sim 30$ seconds after the second test, before it was ignited again. The temperature of the step block at the third ignition was $\sim 357$ K. Similarly, the combustor transitioned to the unstable regime, after $\sim 11$ seconds. These consecutive tests show that the time it takes until the instability is triggered varies depending on the initial temperature of the flame-holder, all other operating conditions being the same. When the temperature of the flame-holder is initially higher, the transition to the unstable regime occurs sooner. This result motivated us to examine the heat transfer effect on the instability characteristics, as discussed in the following sections.

3.3. Impact of Thermal Conductivity on Stability Characteristics

The heat flux depends on several parameters such as heat transfer coefficient, temperature gradient, flow velocity, geometric characteristics. Among these, the heat transfer coefficient at the wall is determined by the combustor material. Hence, changing that parameter allows us to examine the impact of heat transfer on the combustor dynamics, while the flow and the acoustics in the system are not affected. In this section, we investigate how different materials of distinct thermal conductivities at the step impact the instability characteristics. The step is where the flame is anchored in all the operating regimes, as revealed by the flame images (Altay et al., 2009), and thus the location where the heat transfer between the flame and the combustor wall mainly takes place. The pressure measurements are presented in Sections 3.3.1 and 3.3.3, while the flame images are shown in Section 3.3.2.

3.3.1. Pressure Response

Figure 6 shows the OASPL recorded in the equivalence ratio sweep tests with the stainless steel and ceramic blocks. Starting at $\phi = 0.88$, the equivalence ratio was gradually decreased until the flame blows off. Since, within the scope of this study, we are not particularly
interested in the high-frequency unstable regime as described in Sections 3.1 and 3.2.1, the initial point ($\phi = 0.88$) was chosen as to be high enough to trigger the low-frequency instability. At each equivalence ratio, the combustor was operated for $\sim 4 - 5$ seconds in the stainless steel case and for $\sim 7 - 8$ seconds in the ceramic case, leading to the total running times of $\sim 136$ seconds and $\sim 238$ seconds, respectively. The longer operating time in the ceramic case was intentional, as will be discussed later in this section. Although the duration for which the combustor was operated at each equivalence ratio is not sufficient for thermal equilibrium at the combustor wall as discussed in Section 3.4.2, the equivalence ratio sweep tests were conducted to examine the overall response of the combustor to the equivalence ratio variation. The response for longer operating time at each equivalence ratio is presented in Section 3.3.3.

As seen in Fig. 6, the flame-holder materials have a remarkable impact on the combustion instability, while no significant impact on the static stability characteristics (e.g., lean blow-off limit) is observed. In the ceramic case, the combustor did not exhibit any instability throughout the equivalence ratio range, in which the OASPL remains at 140 dB or lower values, staying in the stable regime, whereas in the stainless steel case, the instability was observed for a range of equivalence ratios ($\phi \geq 0.75$). As the instability was not observed at the beginning ($\phi = 0.88$) in the ceramic case, we operated the combustor for longer time at each $\phi$ (about twice that in the stainless steel case) to confirm that the instability was not triggered, based on our observation that the onset of the instability is sensitive to combustor’s operating time. As will be discussed in Section 3.3.3, if we operate the combustor for much longer time (over several minutes) at relatively high equivalence ratios, the instability may eventually be triggered in the ceramic case as well.

3.3.2. Flame Image

In this section, we examine the flame dynamics using each material as the flame-holder. Figure 7 shows the flame chemiluminescence images for the stainless steel case during one instability cycle, which were recorded at $T_{in} = 300$ K, $Re = 6500$ and $\phi = 0.85$ for a propane/air mixture. The combustor operates in the low-frequency unstable regime, oscillating at $\sim 40$
Hz. The vortex starts to form at the edge of the step when the pressure oscillation is at its maximum (1). This moment corresponds to the peak of flow acceleration as revealed by the PIV measurements (Hong et al., 2013b). As the vortex grows and convects downstream (2−6), the flame convolutes itself around the vortex, showing a significant flame-vortex interaction. In the meantime, the reactant packet is formed between the vortex and the burned gas produced in a previous cycle. When the vortex hits the upper wall of the combustor (6), the flame starts to flash back to upstream of sudden expansion. While the flame flashes back (7−8), the combustor experiences an intense burning of the reactant packet, exhibiting the maximum heat release rate (Altay et al., 2009). The maximum amplitude of pressure fluctuations is ∼2900 Pa.

In Fig. 8, we show the flame images where the ceramic block is used at the step, recorded for the same time period and at the same operating condition as in the stainless steel case (Fig. 7). Similarly, a vortex is formed at the step (1 and 5), and convects downstream (2−4 and 6−8). As the vortex grows and convects downstream, the flame flaps around the vortex. However, the flame does not propagate upstream during the cycle, remaining attached to the step. In addition, the size of wake vortex, while it grows during the cycle, is smaller than that in the stainless steel case. The maximum amplitude of pressure oscillation is lower than that in the stainless steel case, e.g., $p' \sim 470$ Pa, which is also revealed by the pressure response curves shown in Fig. 6. Here, we also observe that the flame chemiluminescence intensity (in terms of the brightness of the flame image) shown in Fig. 8 is remarkably lower than that in Fig. 7. Since the mean heat release should be the same for both cases given the same operating conditions, the observed lower chemiluminescence intensity in Fig. 8 is mainly attributed to weak chemiluminescence oscillations, indicating that the heat release oscillation is significantly weaker in the ceramic case along with the lower pressure fluctuation level.

The flame images presented in Figs. 7 and 8 clearly show that the thermal characteristics near the flame anchoring region significantly impact the flame dynamics. With the ceramic flame-holder, the flame exhibits periodic flapping motion around the vortex shed at the step.
while it remains attached to the step. In contrast, with the stainless steel flame-holder, the flame exhibits strong oscillations where it periodically detaches from the step and propagates upstream during the part of the cycle. Given that we only changed the flame-holder material, the distinct flame dynamics between the two cases should be as a result of the different heat transfer processes near the flame-holder, e.g. heat conduction upstream the expansion plane, all other conditions being the same. The mechanism behind these observations will be discussed in Section 3.4.

3.3.3. Comparison of Transient Responses

As presented in Section 3.3.1, Fig. 6 showed that the use of ceramic block at the flame anchoring region prevents the instability throughout the equivalence ratio sweep test. On the other hand, we also described in Section 3.2.2 that the onset of the instability is sensitive to the length of time for which the combustor operates at a fixed equivalence ratio near mode transition. In this section, we discuss a series of transient tests, where we examine the combustor’s response for much longer operating time than that in the equivalence ratio sweep test.

We define here the “inception time” as the time it takes until the combustor, initially at room temperature before the ignition, transitions from the stable regime to the unstable regime. For example, in Fig. 5, the amplitude of pressure oscillations jumps from $\sim 500$ Pa to $\sim 2500$ Pa after $\sim 34$ seconds, which marks the onset of the instability. Therefore, the inception time in this case is 34 seconds. In what follows, we report a series of tests in which we measure the inception time for several equivalence ratios using the stainless steel or ceramic blocks at the step. If the combustor had remained in the stable regime for 7 minutes, the combustor was switched off. At each equivalence ratio, the test was repeated 3–5 times, as will be reported later in this section.

Figures 9 and 10 show the time series of pressure signals recorded at the equivalence ratios of $\phi = 0.78 – 0.81$ using the stainless steel and ceramic blocks at the step, respectively. The pressure signals are plotted against time ($t_n$) non-dimensionalized by the instability period ($\sim 40$ Hz) such that $t_n = \omega t$, where $t$ is an operating time and $\omega = 2\pi f$ is the instability
frequency \( f = 40 \text{ Hz} \); e.g., 1 second corresponds to \( t_n \approx 250 \). The normalized time allows us to estimate the time necessary for the onset of the instability in terms of the number of instability cycles.

At \( \phi = 0.78 \), the combustor has remained in the stable regime for 7 minutes in both cases with the stainless steel and ceramic blocks (Fig. 9a and Fig. 10a). As we repeat the tests at higher equivalence ratios (\( \phi = 0.79 - 0.81 \)), we observe the difference between the two flame-holder cases. In the stainless steel cases (see Figs. 9b–d), the combustor becomes unstable after a certain amount of time at each equivalence ratio. The inception time decreases from \( \sim 90 \) seconds to less than \( \sim 1 \) second as the equivalence ratio is raised from \( \phi = 0.79 \) to \( \phi = 0.81 \), indicating that the combustor tends to exhibit the instability sooner at higher equivalence ratio. In particular, at \( \phi = 0.81 \), the combustor becomes unstable almost immediately after the ignition. We note here that the mode transition to the unstable regime was also observed at \( \phi = 0.80 \) in the equivalence ratio sweep test (ascending order; see Fig. 4a), indicating that the combustor is intrinsically unstable above \( \phi \approx 0.80 - 0.81 \).

In contrast, for the case using the ceramic block at the step, the combustor remains in the stable regime for 7 minutes even at \( \phi = 0.79 - 0.80 \), as shown in Figs. 10(b–c). At \( \phi = 0.81 \), the combustor exhibits an instability after \( \sim 80 \) seconds. A comparison between the stainless steel and ceramic cases at \( \phi = 0.79 - 0.81 \) demonstrates that the use of lower thermal conductivity material at the flame anchoring region can successfully prevent the instability (at \( \phi = 0.79 - 0.80 \)) or significantly delay its onset in time (at \( \phi = 0.81 \)). Similar effect of low thermal conductivity was also shown in the equivalence ratio sweep test (Fig. 6) and in the flame images recorded at \( \phi = 0.85 \) (Figs. 7 and 8), where the instability was not observed in the ceramic case.

To construct a comprehensive set of data to support the observation described above, we repeated the transient tests at a range of equivalence ratios. Figure 11 shows two different pressure signals plotted against the non-dimensional time, both recorded at \( \phi = 0.81 \) using the ceramic block. As shown in the figure, the combustor’s response shows a large variance between the two tests. In the repeated case shown in Fig. 11(b), the combustor became
unstable after ∼46 seconds, which occurred earlier than the first test shown in Fig. 11(a). However, it transitioned back to the stable regime after ∼4 seconds, remaining there for the next ∼30 seconds. The combustor transitioned back and forth between the stable and unstable regimes until it remained consistently in the unstable regime, after ∼390 seconds ($t_n \approx 9.75 \times 10^4$). Although not shown here, the combustor exhibited this intermittent instability at several equivalence ratios in the repeated tests using the ceramic block, whereas this behavior of being intermittently unstable had never been observed in the stainless steel cases in which the combustor was always robustly unstable once it transitioned to the unstable regime. This again confirms that the heat transfer through the combustor wall near the flame anchoring region has a critical impact on the combustion instability. In what follows, if the combustor is intermittently unstable for certain time, we measure the inception time as the time after which the instability is consistently observed.

In Fig. 12, we show the inception times measured over a range of equivalence ratios using the two materials. The error bars are plotted to show the variance of inception times measured in the repeated tests. With the ceramic flame-holder, the average inception time is larger than ∼40 seconds ($t_n \sim 10,000$) over a range of equivalence ratio, whereas with the stainless steel flame-holder, the average inception time is smaller than 4 seconds ($t_n \sim 1000$) except a few cases at relatively low equivalence ratios ($\phi \leq 0.81$). This trend of larger inception times for the ceramic cases, observed from the large amount of data set, confirms that the onset of the instability can be significantly delayed in time over a range of equivalence ratio with the use of ceramic block at the flame anchoring region. The error bars indicate that the cases with the ceramic block show larger variance among the repeated tests, mainly attributed to being intermittently stable or unstable, as described above (note that y-axis of Fig. 12 is in log scale). We note that a number of error bars are biased to shorter inception times, i.e., the lower ends of the error bars show larger variance from average values, which is attributed to few exceptional cases where the combustor exhibited the instability earlier than other cases at given operating conditions.6 At $\phi = 0.79 - 0.80$, the combustor with the

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6The bias of the error bars in turn indicates that the inception times in most cases are close to their
ceramic block did not exhibit any instability for the test running time (7 minutes) in the repeated tests, whereas with the stainless steel block, the combustor transitioned from the stable to the unstable regime within $\sim1$ minute ($t_n \sim 1.5 \times 10^4$). Given that the combustor was operated in each test for 7 minutes at most, these results indicate that the use of ceramic block at the flame anchoring region can potentially expand the stability margin to higher equivalence ratio. In the next section, we suggest a possible mechanism underlying our observations on the effect of lower thermal conductivity on preventing or delaying the onset of the instability.

3.4. Mechanism

3.4.1. Hypothesis

Here, we qualitatively discuss the experimental observations described in the preceding sections, while a more quantitative analysis is presented in Sections 3.4.2 and 3.4.3. We propose a mechanism for the impact of the thermal conductivity on the onset of the instability in the context of the dependence of the instability on the flame speed, which varies as a function of the local reactants temperature.

To consider the effect of the heat transfer near the flame-holder, we first refer to the prior studies by our research group (Altay et al., 2009; Speth and Ghoniem, 2009), where we demonstrated that the operating regimes and the mode transitions can be correlated with the strained flame consumption speed, which is computed as a function of fuel composition, inlet temperature and equivalence ratio. The mode-transitions shift to lower equivalence ratio at higher inlet temperatures or higher concentrations of hydrogen in the fuel mixture (Altay et al., 2009; Hong et al., 2013b), indicating that higher flame speed leads the combustor to be more readily unstable at leaner conditions. The consumption speed was used to collapse the pressure response data for different inlet temperatures and fuel compositions onto a single characteristic curve. This was shown to work well for both the step (Altay et al., 2009; Hong et al., 2013b) and the swirl-stabilized (Speth and Ghoniem, 2009) combustors using average values, showing the consistency in the repeated tests.
propane/hydrogen fuel mixtures and syngas fuel mixtures. These results indicate that the mode transition from the stable to the unstable regimes occurs as the strained flame speed exceeds the critical values.

To illustrate, we use the data shown in Fig. 4a (the case for increasing \( \phi \)) and compute the consumption speed at each data point using the strained flame code (Marzouk et al., 2003; Speth et al., 2005). In Fig. 13, we plot the OASPL as a function of the flame consumption speed. The figure shows that the mode transition to the unstable regime occurs at \( S_c \approx 26 - 27 \) cm/s. Stated differently, in order for the combustor to become unstable, the flame speed must be higher than this value.

Now, consider the setup shown in Fig. 2. The flame is anchored at (2) in the stable and quasi-stable regimes, and moves between (1) and (2) during the unstable regime. Naturally, heat is transferred by convection from the burned gas to the step block along the surface (3), and conducted through the step block to the surface (1)–(2). Therefore, as the heat from the burned gas side is convected to the incoming fresh mixture through the top surface of the step block, the unburned gas temperature is raised in the low velocity region near the wall. This raises the speed of the flame in that region, which, if raised beyond a critical value, can promote its propagation upstream, leading to the onset of the instability. The mechanism proposed herein is illustrated in Fig. 14.

For example, consider the two cases shown in Figs. 7 and 8, which were recorded at the same condition (\( T_{in} = 300 \) K, \( Re = 6500 \) and \( \phi = 0.85 \)) with the stainless steel and the ceramic blocks, respectively. Given that the combustor is initially at room temperature in both cases (and all other operating conditions are the same), different thermal conductivities should play a role in differentiating the two cases. In the stainless steel case (Fig. 7), we observe that while the vortex grows in size, the burned gas trapped in the wake region consistently exists immediately downstream of the step, i.e., at (3) in Fig. 2. This, along with the strong flow fluctuation, enhances the heat convection to the step block. In contrast, in the less conducting ceramic case (Fig. 8), the flame convoluted around the vortex stays further downstream of the step, which suggests that there is less contribution to heating the step
wall. Furthermore, due to its lower thermal conductivity, less heat is conducted through the ceramic block, resulting in lower temperature of the reactants and thus, delaying the onset of the instability. In the next section, we examine the temperature fields at the flame-holder and the relevant heat fluxes to support the hypothesis proposed above.

3.4.2. Temperature Distribution at the Flame-holder

To quantify the heat flux through the flame-holder, we model the heat transfer problem within the step block, and compare the simulation results with experimental measurements. We note that a time scale associated with the transition to the unstable operation, i.e., the onset of the instability, is much smaller than the characteristic time scale for thermal equilibrium in the step block. Consider, for example, the temperature of the step block heated by the convection from the burned gas (see Fig. 2). For a rough estimate of the time scale, the cooling of the step block to ambient air or to the reactants are neglected, and the temperature of the step block is assumed to be spatially uniform. The temperature variation in the step block can be estimated using the following heat equation:

\[ \rho c_p V \frac{dT}{dt} = h(T_{\text{ext}} - T)A \]  

where \( \rho, c_p, V \) denote the density, specific heat and volume of the solid block. \( h \) is the heat convection coefficient, and \( A \) is the area for the heat convection. \( T_{\text{ext}} \) is the burned gas temperature. From Eq. (2), the characteristic time constant \( t_c \) of this thermal process can be obtained:

\[ t_c = \frac{\rho c_p V}{hA} \]  

For the stainless steel block, the time constant is estimated to be \( \sim 18,900 \) seconds (\( \sim 5 \) hours). According to this value, for example, it takes \( \sim 4 - 5 \) minutes for the temperature of the step block to increase from 300 K to 325 K, assuming \( T_{\text{ext}} = 2042 \) K (assumed here.

\(^{7}\)The Biot number defined as \( hL_c/k_s \) is estimated to be \( \sim 0.158 \) (\( < 1 \)), where \( h, L_c \) and \( k_s \) denote the heat convection coefficient, characteristic length scale of a solid block and thermal conductivity of a solid block, respectively. The temperature inside the step block is regarded as uniform in this example as an approximation, while spatial distribution of the temperature field are presented later in this section.
to be the adiabatic flame temperature at $\phi = 0.8$ for a propane/air mixture), which is not far from our simulation result presented later in this section, where the average temperature of the block reaches approximately $\sim 325$ K after 7 minutes. Given that the inception times in the stainless steel cases (see Fig. 12) are within $\sim 1$ minute, it is apparent that the characteristic time scale associated with the combustor’s selection of the operating regime or the transition between distinct regimes is a transient phenomenon before the step block (or combustor wall) reaches thermal equilibrium. This is also revealed by the comparison between the equivalence ratio sweep test and the transient test (presented in Sections 3.3.1 and 3.3.3, respectively), where both tests are consistent in that the stability boundary turns out to be $\phi \approx 0.79 - 0.8$ with the stainless steel flame-holder. Therefore, we consider the transient process rather than a steady heat transfer problem, as discussed next.

The two-dimensional computational domain used in the simulation is shown in Fig. 15(a), which illustrates the span-wise cross section of the step block; a rectangle of 35 mm wide and 54 mm high. The initial temperature of the step block is assumed to be 300 K. On the top surface, a propane/air mixture flows at 5 m/s and 300 K. In the surrounding regions, stationary air at 300 K exists at the left and bottom surfaces and part of the right surface, as shown in Fig. 15(a). The channel wall thickness is neglected. The burned gas is located immediately downstream of the step block in the combustor channel. Since the burned gas is trapped in the recirculation zone where the flow velocity is relatively low, it is assumed to be stationary.

In this simulation, while the radiative heat fluxes can be important, especially in the burned gas side where the temperature is high, only convective heat flux is considered based on the order of magnitude estimation (see Section 3.4.4 for further details). We solve the following equations that describe heat conduction in the step block and convection at the boundary surfaces.

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T)$$  \hspace{1cm} (4)

$$k \nabla T = h(T_{\text{ext}} - T)$$  \hspace{1cm} (5)
where \( T = T(x, y, t) \) is the temperature distribution in the step block as a function of time and space, \( T_{\text{ext}} \) is the temperature of ambient air or burned gas. \( k \) and \( h \) denote the thermal conductivity of the step block and the convection coefficient at the boundaries, respectively. The burned gas temperature is assumed to be 2012–2043 K, which correspond to the adiabatic flame temperature at \( \phi = 0.78–0.8 \). The thermophysical properties of the reactants and products are provided by Cantera (Goodwin, 2005), using the GRI-Mech 3.0 kinetic model. Following these assumptions, the coefficients of natural convection and forced convection at the boundaries are computed for the side and bottom surfaces and for the top surface of the step block, respectively, using the Nusselt number correlations (Incropera and DeWitt, 2007). The densities of the ceramic and stainless steel blocks are 673 and 8000 kg/m\(^3\), and the specific heats are 840 and 503 J/kg/K, respectively. A transient temperature variation in the step block was computed using a finite difference scheme in COMSOL 4.1 for 7 minutes, which corresponds to the operating time in the experiments as described in Section 3.3.

Figures 16(a) and 16(b) show the computed temperature distribution after 7 minutes in the stainless steel and the ceramic blocks, respectively, both corresponding to the case for a propane/air mixture at \( \phi = 0.8 \). In both cases, finite temperature gradients are observed over the step block.\(^8\) The temperature is the highest near the surface where the burned gas exists, while it is lower upstream as well as near the bottom surface where heat loss to an ambient air or the fresh mixture occurs. The temperature of the step block is higher in the ceramic case, where the maximum temperature is approximately twice that in the stainless steel case, resulting in larger temperature gradients over the space. This is because of the lower heat capacity of the ceramic block. In addition, the heat conduction in the stainless steel case is enhanced due to its higher conductivity, which leads to higher heat loss to the surrounding air or the incoming reactants.

In Fig. 16(c), we compare the simulation result with the temperature measurements

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\(^8\)This is expected based on the estimated Biot numbers, \( \sim 0.16 \) and \( \sim 1.79 \) for the stainless steel and the ceramic blocks, respectively. See also footnote 7.
in the stainless steel block at $\phi = 0.78$, at the three locations marked as (1)–(3) in Fig. 16(a): 6, 18 and 30 mm upstream from the edge of the step along the centerline of the spanwise direction, all 3 mm below the top surface. The simulations agree well with the measurements, except that the computation overestimates the temperature downstream at (3), the closest location to the flame. This may be because we assumed the adiabatic flame temperature for the burned gas temperature without accounting for the wall cooling. We note that the temperature was measured only in the stainless steel block, as the ceramic block is too brittle to machine the hole for installation of the thermocouples. Nonetheless, the result for the stainless steel block confirms that the simulation and the experiments are in good agreement.

Next, we use the computed temperature field to calculate the integrated heat flux out of the top surface of the step block, as illustrated in Fig. 15(b). The line integral is performed along the top surface:

$$\dot{q} = \int_{L} h(T - T_0) dL \quad (6)$$

where $\dot{q}$ is the integrated heat flux per unit depth (W/m), $T$ and $T_0$ are the temperature at the top surface of the step block and of the incoming unburned gas, respectively. $L$ is the width of the step block (35 mm) as indicated in Fig. 15. Figure 17 shows the estimated heat flux as a function of time for the two materials. As shown in the figure, the heat flux increases with time until it reaches nearly steady state after $\sim$3 minutes. The heat flux in the stainless steel case is higher by $\sim 50\%$ than that in the ceramic case, confirming that more heat is convected to the reactants in the stainless steel case.

In the following section, we use the result shown in Fig. 17 to discuss the observation presented in Section 3.3 in the context of the burning velocity of the flame near the flame-holder, as proposed in Section 3.4.1.

3.4.3. Flame Speed Variation and Dynamic Instability Characteristics

Here, we first examine the dependence of the strained flame consumption speed on the reactants temperature ($T_u$) and the equivalence ratio ($\phi$) using the strained flame code
(Marzouk et al., 2003; Speth et al., 2005). Figure 18 shows the variation in the consumption speed as a function of $T_u$, at selected values of $\phi$ near the transition point ($\phi \approx 0.8$). The consumption speed increases with the reactants temperature as well as the equivalence ratio.

Next, we use Figs. 17 and 18 to estimate the rise in the local unburned gas temperature near the top surface of the step block, i.e., thermal boundary layer, as well as the variation of the flame speed in that region. If the thermal boundary layer thickness is $\delta_t$, then the rise in the local reactants temperature can be estimated using the control volume shown in Fig. 15(b), such that $\dot{q} = \rho_u c_p U_u \delta_t \Delta T$, where $\rho_u$ and $c_p$ denote the density and specific heat under constant pressure of the unburned gas, respectively. $U_u$ and $\Delta T$ denote the average flow velocity and the temperature rise within the thermal boundary layer, respectively. $\delta_t$ is estimated to be $\sim 3$ mm using the relation $\delta_t = \delta/Pr$, where $\delta = 0.382L/(Re)^{1/5}$ is the momentum boundary layer thickness in turbulent flow (Munson et al., 2002), $L$ is the streamwise width of the step block (35 mm) and $Re = 6500$. $Pr$ is the Prandtl number of the unburned gas ($\approx 0.725$ at $\phi = 0.8$), defined as $Pr = \nu/\alpha$ where $\nu$ is the kinematic viscosity and $\alpha$ is the thermal diffusivity.

Figure 19 shows the estimated time-variation in local reactants temperature near the step wall. For both materials, the temperature steeply increases for the first $\sim 100$ seconds, which then gradually becomes steady state, reaching 330 K in the stainless steel case and 322 K in the ceramic case. The results confirm that local temperature of the unburned mixture near the step surface, i.e., within the thermal boundary layer, is higher than the average temperature of the bulk flow (which remains close to the inlet temperature of 300 K), due to the heat convected from the flame-holder.

The impact of the local temperature rise of the reactants on the local flame speed as well as on the onset of the instability is quantified next. According to Figs. 18 and 19, the flame speed increases by $\sim 13\%$ and $\sim 23\%$ after 7 minutes in the ceramic and stainless steel cases, respectively (i.e., from $\sim 22$ cm/s to $\sim 25$ cm/s and $\sim 27$ cm/s at $\phi = 0.8$). We recall from Fig. 13 that the critical value of the consumption speed at the onset of the instability is $\sim 26 - 27$ cm/s. Therefore, according to Fig. 18, the reactants temperature must be
raised beyond \( \sim 325 \text{ K} \) at \( \phi = 0.80 \) for the flame speed to exceed this critical value. Figure 19 indicates that in the stainless steel case, it takes \( \sim 130 \text{ seconds} \) to reach this temperature, whereas in the ceramic case, the reactants temperature is below \( \sim 325 \text{ K} \) for 7 minutes. If one compares these estimated values with the transient test results shown in Fig. 12, it is consistent that the combustor never exhibited the instability (nor the flame speed exceed the critical value) in the ceramic case. In the stainless steel case, the measured inception time is \( \sim 40 \text{ seconds} \) \( (t_n \sim 10,000) \) at \( \phi = 0.8 \), which is smaller but in the same order of magnitude as the estimated inception time above. Thus, the results show the validity of the proposed mechanism for the effectiveness of using low thermal conductivity material as the flame-holder, which prevents or delays the onset of the instability.

3.4.4. Additional Comments

Here, we comment on neglecting the heat radiation in our simulation presented in Section 3.4.2. We compare the radiative heat flux with the convective heat flux, in the reactant side and the product side. In the former case, the heat can be radiated from the step block surface to the incoming unburned gas, whereas in the latter case, the heat radiation from the burned gas to the step block surface can matter due to the high temperature of the burned gas. The radiative heat flux can be estimated as \( \dot{q} \approx \varepsilon \sigma (T_{fs}^4 - T_0^4) \), where \( \sigma \) is the Stefan-Boltzmann constant, \( 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^{-4} \) and \( \varepsilon \) is the emissivity. In the reactant side, \( T_{fs} \) and \( T_0 \) are the temperatures of the step block and the unburned gas, respectively, whereas in the product side, they denote the burned gas temperature and the temperature of the step block, respectively. The value of \( T_0 \) is assumed here to be 300 K in both cases. The value of \( T_{fs} \) is taken to be the maximum temperature of the block after 7 minutes operation \( (T_s \approx 370 \text{ K} \) as shown in Fig. 16a) in the reactants side or the adiabatic flame temperature \( (T_f \approx 2043 \text{ K} \) at \( \phi = 0.8 \) in the products side. The emissivities of the stainless steel and the burned gas (where dominant emitters are H\(_2\)O and CO\(_2\)) are \( \sim 0.5 \) and in the order of \( \sim 0.01 \) at 1 atm, respectively (Siegel and Howell, 2002). For a one-to-one comparison, the radiative heat fluxes should be integrated along the same line as the convective heat flux (Fig. 17); 0.02 m in the burned gas region and 0.035 m in the unburned gas region. Hence,
the estimated radiation fluxes are $\sim 6$ W/m and $\sim 197$ W/m in the reactant and product sides, respectively. The former, compared with the result shown in Fig. 17, is two orders of magnitude smaller than the convective heat flux, hence negligible. The latter is lower than the convective heat flux, which is estimated to be $\sim 750$ W/m in the simulation (not shown here), while being in the same order of magnitude. However, we should consider only the heat radiated from the burned gas directly to the step block, since the heat flux is radiated to 360 degrees. Accounting for this, the radiation to the step block is estimated to be only $4.8\%$ of total, which is $\sim 9.85$ W/m. Therefore, the radiative heat flux to the step block in the burned gas side, which is also smaller than the convective heat flux by two orders of magnitude, can be neglected as well. The validity of our model is also shown in Fig. 6(c), where the comparison between the simulation and the temperature measurements in the stainless steel block shows good agreement.

4. Concluding Remarks

In this study, we examined the impact of the flame-holder thermal characteristics on the dynamic instabilities observed for lean premixed propane/air flames in a backward-facing step combustor. We report our observation that the instability in the step combustor is sensitive to an initial temperature of the combustor wall near the flame stabilization region. Starting from this observation, we examined the role of heat transfer in the onset of the instability, using the two materials of distinct thermal conductivities — stainless steel and ceramic — at the flame anchoring region. The experimental results show that the use of a low thermal conductivity material can prevent or delay the onset of the instability. In addition, the combustor exhibits a robust instability in the stainless steel case for a range of operating conditions, whereas in the ceramic case, the instability, even after it is triggered, is not robust and the combustor tends to operate in the stable regime, exhibiting intermittent transitions between the stable and the unstable regimes.

We suggest a possible mechanism underlying these observations in the context of heat transfer processes and resultant variations in the flame speed. To support this hypothesis, we present the computed and measured temperatures at the flame-holder and the heat flux
to the reactants near the surface for both materials. We quantified the local temperature rises of the unburned gas and the associated flame speed variations, and compared those with the critical flame speed at the onset of the instability. We show that low heat-conducting material can indeed prevent or delay the onset of the instability, by lowering the heat flux to the reactants and the corresponding flame burning speed near the flame-holder.

The results presented in this paper have several implications. The dynamic instability characteristics of turbulent premixed flames depend not only on the operating conditions and geometry but also on the heat transfer characteristics near the flame anchoring region. This suggests that using blocks of ceramic, low heat conducting materials of certain geometry and if strategically located in the flame anchoring region, can potentially be a passive dynamics suppression approach over a wide range of operating conditions. Alternatively, cooling the flame-holder may be effective for mitigating combustion instabilities.

The physics behind the intermittent transitions between the stable and unstable regimes observed in the ceramic cases is unknown yet, as well as the mechanism underlying the hysteresis phenomenon presented in Section 3.2.1, which will be pursued in a future publication.

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References


Figure 1: Schematic of the backward-facing step combustor with instrumentation.

Figure 2: Schematic diagram showing the step block installation into the combustor. As shown in the flame chemiluminescence images (Figs. 7 and 8), the flame is nominally anchored at the edge of the step (2), or moves along the wall between (1) and (2) if it flashes back during the unstable regime. The temperature of the step block is measured at three locations, as indicated in the figure, 6, 12, and 18 mm upstream from the edge of the step, all being 3 mm below the top surface of the step block. (3) is the region where the burned gas heats up the wall, as discussed in Section 3.4.
Figure 3: Overall sound pressure level as a function of equivalence ratio for a propane/air mixture at $T_{in} = 300$ K and $Re = 6500$. The pressure is measured at 0.2 m upstream of the sudden expansion. The typical operating regimes are referred to as stable, quasi-stable (QS), low-frequency unstable (LU, ◦) and high-frequency unstable (HU, △) regimes. The peak frequency at each equivalence ratio is represented by a color shown in the side bar: $\sim 40$ Hz (LU) and $\sim 70$ Hz (HU).

Figure 4: Overall sound pressure level for a propane/air mixture as a function of equivalence ratio, demonstrating a strong hysteresis depending on the history of the equivalence ratio ($\phi$). Pressure signals were recorded while decreasing or increasing the equivalence ratio in the range between near stoichiometry and lean blow-off limit. $Re = 6500$ for all the cases and $T_{in} = (a)$ 300 K and (b) 500 K.
**Figure 5:** A time series of pressure signals recorded at $\phi = 0.79$ for a propane/air mixture, demonstrating the impact of initial wall temperature on the onset of the instability. The combustor was initially at room temperature in the case (1), whereas in the cases (2) and (3), the wall temperature was higher as a result of consecutive operations after the case (1).

**Figure 6:** Overall sound pressure level for a propane/air mixture as a function of equivalence ratio. The two different materials were used at the flame anchoring region: stainless steel and ceramic. $T_{in} = 300$ K and $Re = 6500$ for both cases. The combustor’s total operating time is $\sim 136$ seconds in the stainless steel case and $\sim 238$ seconds in the ceramic case, respectively.
Figure 7: A sequence of flame chemiluminescence images for one instability cycle, where the stainless steel block is installed at the step. The combustor operates in the unstable regime, oscillating at \( \sim 40 \) Hz. The operating conditions are: \( \phi = 0.85 \), \( T_{in} = 300 \) K and \( Re = 6500 \).
Figure 8: A sequence of flame chemiluminescence images for the same time period as in Fig. 7, where the ceramic block is installed at the step. The combustor is relatively stable compared to the stainless steel case. The operating conditions are: $\phi = 0.85$, $T_{in} = 300$ K and $Re = 6500$. 
Figure 9: A set of pressure signals shown in time series, recorded at \( \phi = 0.78 - 0.81 \), where the stainless steel block is used at the flame anchoring region. At each equivalence ratio, the pressure measurements are performed at 0.2 m upstream of the step, while \( \phi \) is kept constant.
Figure 10: A set of pressure signals shown in time series, recorded at $\phi = 0.78 - 0.81$, where the ceramic block is used at the flame anchoring region. At each equivalence ratio, the pressure measurements are performed at 0.2 m upstream of the step, while $\phi$ is kept constant.

Figure 11: Pressure signals are shown in time series for repeated tests at $\phi = 0.81$ using the ceramic block at the flame anchoring region. The case (a) is the same data as shown in Fig. 10(d); the case (b) shows the repeated case, which illustrates the intermittent existence of the instability.
Figure 12: Normalized inception times at a range of equivalence ratios, tested with the two materials as a flame-holder: stainless steel (⊙) and ceramic (△). The markers in a green circle indicate the cases in which the combustor did not exhibit the instability for 7 minutes. The operating time is normalized (y-axis) such that 1 second corresponds to \( t_n = \omega t \approx 250 \), where \( \omega = 2\pi f \) is the instability frequency (\( f = 40 \) Hz).

Figure 13: Overall sound pressure level recorded for the stainless steel case while increasing the equivalence ratio (the same pressure data shown in Fig. 4a), plotted against the strained flame consumption speed.
Figure 14: Schematic diagram illustrating the hypothesis discussed in Section 3.4.1 as a proposed mechanism underlying the impact of heat transfer near the flame-holder on promoting the unstable operation of the combustor. $S_L$ denotes the burning velocity of the flame.

Figure 15: (a) The 2-D model of the step block used for calculating the time-varying temperature field; (b) Schematic diagram showing the flow within the thermal boundary layer with heat flux entering from the burner wall.
Figure 16: The computed temperature distributions in the step block after 7 minutes at $\phi = 0.8$ for the (a) stainless steel and (b) ceramic cases. The temperature variation as a function of time at $\phi = 0.78$ is plotted in (c), which compares the numerical result with the measured temperature at the locations (1)–(3) shown in (a).

Figure 17: The estimated heat flux convected to the unburned gas through the top surface of the step block for the stainless steel and ceramic cases.
Figure 18: Dependence of the strained flame consumption speed on the unburned gas temperature and the equivalence ratio. The consumption speed is computed using the strained flame code (Marzouk et al., 2003; Speth et al., 2005) for propane/air flames.

Figure 19: Temperature rise of the reactants near the top surface of the step block due to the heat convected from the step block (shown in Fig. 17).