

Laser diode-based phosphor thermometry applied to high pressure hydrogen combustion

Eugène Laporte^{1,*}, Sylvain Petit¹, Renaud Jalain¹, Benoît Fond², Guillaume Pilla¹

1: DMPE-LPA, ONERA, Université Paris Saclay FR-91123 Palaiseau, France

2: DAAA-MAPE, ONERA, Université Paris Saclay FR-91190 Meudon, France

* Correspondent author: eugene.laporte@onera.fr

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ABSTRACT

Kerosene substitution by hydrogen is promising to reduce aviation carbon footprint, but requires to design new combustion chamber architectures and injection systems. The specificities of hydrogen combustion could lead to increase wall thermal stress, due to fast transient events such as flashback (for premixed injection) and flame-wall interactions (FWI) (imposing unsteady wall heat fluxes up to several MW/m²). Therefore, experimental temperature measurements at high frequency rates are required to better understand wall heat fluxes under such events. Lifetime-based phosphor thermometry (PT) is suitable for high frequency surface temperature measurements. With the current development of high-speed and affordable laser diodes, the development of laser diode-based PT setup is an opportunity to make high frequency measurements ($\geq$ kHz) commonplace in combustion applications. In this work, using laser diode-based PT up to 1 kHz, we investigate the endwall thermal signatures associated with the flame dynamics for a new design of lean H₂/air partially premixed injection for aeronautical applications. This design consists of generating a lean fully premixed swirled flame, stabilized with a pilot injection. The flame dynamics and topologies are characterized by high-speed OH* chemiluminescence and OH planar laser induced fluorescence (OH-PLIF), respectively. The tests are conducted on test bench MICADO at ONERA, allowing to conduct experiments at a chamber pressure up to 9 bar and an inlet air temperature above 700 K. Findings are presented for two different cases, i.e. fully premixed flame and partially premixed flame (pilot injection below 10% of the total hydrogen mass flowrate). In fully premixed conditions, the flame is lifted far from the endwall, and the heating effect of the flame is acceptable regarding thermal stress. However, flashback events can occur and lead to significant temperature fluctuations and wall thermal stress. In partially premixed conditions, significant temperature peaks are highlighted due to interactions between the pilot flame and the endwall, imposing wall heat fluxes above 5 MW/m². This work demonstrates the feasibility of laser diode-based phosphor thermometry for high frequency measurements in high-pressure combustion.

1. Introduction

Reducing the aviation carbon footprint while improving the energy efficiency of motors is one of the main challenges for the aeronautical industry. Therefore, the development of lighter and more compact combustion chamber architectures is considered. This can lead to an increase of the energy density within the combustion chambers, and walls more exposed to the flames. Thus, the importance of understanding processes leading to wall thermal stress is increasing (Tyacke et al., 2019), in order to guarantee the materials thermo-mechanical strength and lifetime.

Kerosene substitution by hydrogen is one promising way to reduce aviation carbon footprint of short and medium-haul flights while improving performances. Such a fuel change requires to design new injection systems (Du Toit et al., 2018). Lean premixed injection is one of the most promising strategies for ensuring low flame temperature and NO_x mitigation (Hu et al., 2023). However, due to the specificities of hydrogen (high mass diffusivity, low density, high laminar flame velocity), the flame instabilities are challenging to mitigate. In particular, the higher propensity to flashback (Aniello et al., 2022) addresses important safety issues and can lead to significant wall temperature increase and wall thermal stress (Pers et al., 2023).

Besides, greater wall heat fluxes can be observed for hydrogen flame-wall interaction (FWI) than for hydrocarbon fuels (Ojo et al., 2024; De Nardi et al., 2024). When a flame evolves near a wall, a significant wall heat flux is observed (up to several MW/m²) (Boust et al., 2007; De Nardi et al., 2024), leading to a weakening of the flame (decrease of the flame propagation speed and reaction rates, flame quenching) (Bruneaux et al., 1996; Lai et al., 2022). As a result, FWI plays a major influence on near-wall pollutant formations (Fuyuto et al., 2010; Lai et al., 2022) and wall thermal stress within gas turbine and internal combustion engines (Dabireau et al., 2003; Padhiary et al., 2023). Hydrogen FWI is consequently a crucial topic to address for aeronautical applications.

Indeed, the majority of previous FWI studies dealt with premixed flames propagating toward or near the wall in well-known canonical configurations called head-on quenching and side-wall quenching, providing a fundamental understanding of the phenomena (Dreizler et al., 2015). However, these configurations can be less relevant for aeronautical combustion chambers, where the coupling between wall and near-wall combustion is mostly driven by the highly turbulent flow field (De Lataillade et al., 2002; Wang et al., 2021; Zhong et al., 2025), which can lead to greater and strongly unsteady wall heat fluxes (De Lataillade et al., 2002; Gruber et al., 2010; Yin et al., 2017),

and therefore wall thermal stress and fatigue. Recent studies have shown that this coupling is of major importance on the injector lips and the endwall of the combustion chamber (Massey et al., 2021; Wang et al., 2025; Zhong et al., 2025). Moreover, most of FWI numerical studies are made considering an isothermal (or even adiabatic) wall boundary conditions, which can induce significant differences in wall heat fluxes estimation and therefore FWI understanding (Mari et al., 2016, De Nardi et al., 2024). Consequently, experimental wall temperature measurements are required to better understand unsteady wall heat fluxes associated with FWI in aeronautical combustion chamber geometries and turbulence levels.

Lifetime-based phosphor thermometry (PT) is an optical experimental technique for surface temperature measurements, suitable for combustion chamber environments. The lifetime method consists in inducing the thermosensitive luminescence of inorganic particles (phosphors), using a pulsed light source (Brübach et al., 2008). The suitability of high-speed PT ($\geq$ kHz) to resolve the wall temperature temporal evolution during FWI has been demonstrated (Moussou, 2019; Ojo et al., 2022), using expensive kHz diode pumped solid state lasers emitting below 300 nm. With the current development of simple and affordable high average power LED and laser diodes with near UV or visible emissions, which can be modulated up to MHz rates, combined with the possibility to excite some phosphors efficiently in this spectral range (Shao et al., 2013; Piotrowski et al., 2021), there is an opportunity to make high frequency measurements ($\geq$ kHz) more accessible and commonplace in combustion research. However, the feasibility of laser diode-based phosphor thermometry in very harsh environments still has to be explored.

In this work, laser diode-based phosphor thermometry up to 1 kHz is used to investigate the endwall thermal signatures associated with the flame dynamics for a new design of lean H₂/air premixed injection for aeronautical applications. This design consists of generating a fully lean premixed swirled H₂/air flame, stabilized with a direct pilot injection (Pilla et al., 2026). Using this method, it is possible to extend the stability domain of the flame while keeping an overall low flame temperature (Ruan et al., 2023). This injection system was implemented on the high-pressure high temperature test bench MICADO at ONERA, allowing to conduct experiments at operating conditions representative of aeronautical conditions (Touzeau et al., 2025). The topologies and dynamics of the flames are simultaneously described using OH planar laser induced fluorescence (OH-PLIF) and high-speed OH* chemiluminescence. Findings are presented to highlight the thermal signatures associated with two different flames structures and dynamics, i.e fully premixed flame and partially premixed flame (with a pilot injection rate below 10% of the total hydrogen

mass flowrate). In both cases, specific operating conditions are selected to study the influence of transient events on the endwall temperature, such as flashbacks in the fully premixed case, and interactions between the pilot flame and the endwall in the partially premixed case. This study concludes by estimating the wall heat flux associated with FWI event. This work demonstrates the feasibility of laser diode-based phosphor thermometry for high frequency temperature measurements in very harsh environments.

2. Experimental methods

2.1 MICADO test bench

The test bench MICADO at ONERA (Figure. 1-A) allows to conduct experiments in conditions representative of aeronautical operating conditions, i.e. high pressure and temperature (up to 20 bar and 850 K inlet air temperature), and high turbulence levels.

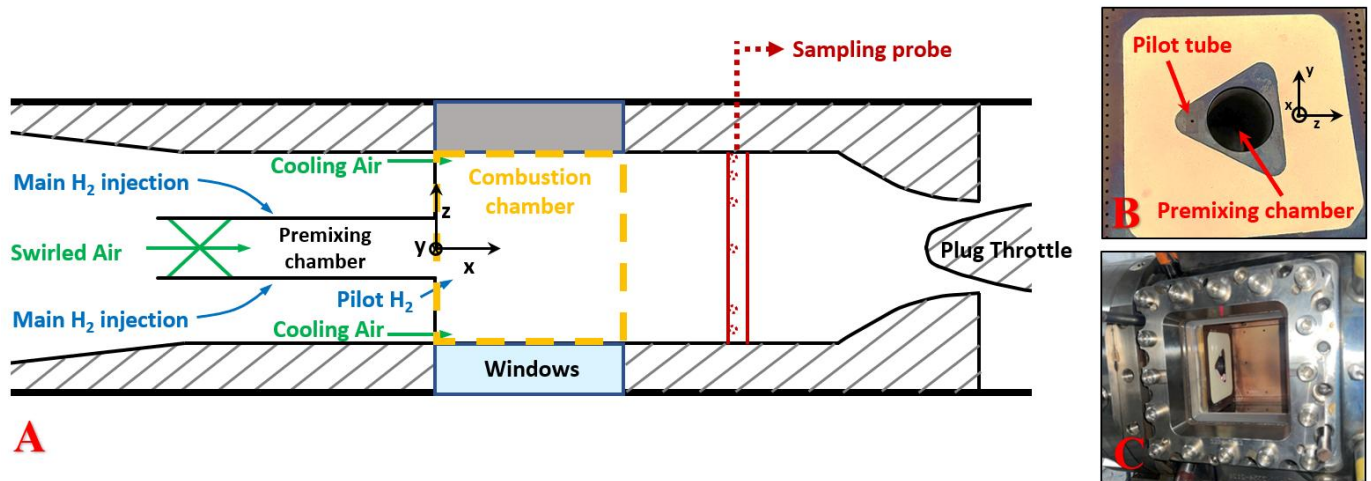


Figure. 1 (A) Schematic of the MICADO test bench. Green arrows represent the air flow, while blue ones are for the H₂. The origin of the reference basis is set in the endwall plane, at the center of the exit of the premixing chamber **(B)** Front view of the endwall and both the premixing chamber and the pilot tube exits **(C)** View of the side optical access of the combustion chamber

The injection system consists of two separated injections, schematized in Figure. 1-A. The main injection consists of generating a preheated inlet swirled air flow (swirl number around 0.3), premixed with hydrogen within the premixing chamber. The premixing chamber admits approximatively 60% of the total air mass flowrate injected in the combustion chamber. The remaining 40% are used to cool down the endwall ($\approx 10\%$) and to provide a thermal protecting layer to the windows ($\approx 30\%$).

The pilot injection consists of generating a direct hydrogen jet, close to the premixing chamber exit, allowing to stabilize the combustion over a wide operating condition range. When used, this direct injection can account up to 10% maximum in total hydrogen mass flowrate. The exit of the pilot injection is a small hole (2 mm diameter) located in the endwall ($x=0\text{mm}$, $y=0\text{ mm}$, $z\approx-15\text{mm}$), close to the premixing chamber tube (22 mm diameter) outlet, as shown in Figure. 1-B. Previous studies have demonstrated that a fully lean premixed combustion is achievable for a narrow range of equivalence ratios, anchoring the premixed flame in the inner recirculation zone of the swirl (Ruan et al., 2023; Pilla et al., 2026). These studies have also demonstrated the interest of using a direct pilot injection to mitigate the risk of flashback thus enabling to extend the operability range of the injector up to equivalence ratio representative of target aeronautical conditions, without significantly changing the NO_x emissions.

The combustion chamber is equipped with large optical accesses (Figure. 1-C), allowing the use of several optical diagnostics concomitantly (Touzeau et al., 2025). Two fused silica observation-windows of $88 \times 89 \text{ mm}^2$ are positioned 90° apart, providing a direct view of the combustion chamber inside (yellow square in Figure. 1-A and Figure. 1-C). The other metallic blind window is water-cooled. The chamber ends with a throttling plug enabling to regulate the chamber pressure.

2.2 Operating conditions

Several operating conditions are selected (Table. 1) to study the endwall thermal signatures associated with two hydrogen injection strategies, fully lean premixed and partially premixed (using the pilot direct injection). For the fully premixed conditions, the inlet air temperature (T_{air}) is targeted at 730 K, the chamber pressure (P_{ch}) is set at 4 bar, and the global equivalence ratio (ϕ_{tot}) at 0.22, calculated using the total hydrogen ($\dot{m}_{H_2 tot}$) and air mass flowrates ($\dot{m}_{air tot}$). These operating conditions allow to study the endwall thermal signatures during flashback events of the fully premixed flame. For the partially premixed conditions, the inlet air temperature is targeted at 710 K and the experiments are conducted under chamber pressures of 4 and 9 bar. The global equivalence ratio is 0.24. The pilot injection rate (R_{pilot}) is defined as in Equation 1, and accounts for less than 10% of the total hydrogen mass flowrate. These operating conditions allow to study the thermal signatures associated with the interactions between the pilot flame and the endwall.

$$R_{pilot} = \frac{\dot{m}_{H_2 \text{ pilot injection}}}{\dot{m}_{H_2 tot}} \times 100 \quad (1)$$

	$T_{air}(K)$	$P_{ch}(bar)$	$\dot{m}_{H_2\ tot}(g/s)$	$\dot{m}_{air\ tot}(g/s)$	ϕ_{tot}	$R_{pilot}(\%)$
<i>Fully premixed</i>	730	4	0.95	148	0.22	0
<i>Partially premixed</i>	710	4 ; 9	1.15 ; 2.60	165 ; 375	0.24	< 10%

Table. 1 Selected operating condition for both the fully or partially premixed injection strategies

3. Laser diagnostics

3.1 Phosphor thermometry

To study the thermal signatures occurring on the endwall of the combustion chamber, non-intrusive optical measurement through the flame are required. Phosphor thermometry (PT) is used here to obtain time-resolved wall temperature point measurements (lifetime method). The thermographic phosphor $Mg_4FGeO_{5,5}:Mn^{4+}$ (MFG) allowing measurements from the ambient temperature up to 1000 K (Brübach et al., 2008) is used in this study. Several studies have demonstrated the suitability of this phosphor for harsh environments such as combustion chambers (Euler et al., 2014; Yin et al., 2017). Furthermore, a change in the oxygen concentration of the surrounding environment does not affect the luminescence properties of MFG for its entire temperature range (Brübach et al., 2007), which can be critical issue when using PT in combustion applications (Brübach et al., 2007; Yang et al., 2018). In this study, we aim to study wall thermal signatures in a representative aeronautical combustion chamber using laser diode-based phosphor thermometry. Consequently, the phosphor is excited by a 375 nm laser diode high frequency pulse (Toptica, IBeam smart, 70 mW max power), which can be pulsed between 10 Hz and 100 kHz. To the authors' knowledge, this work reports the first kHz rate measurements application using MFG excited by a near-UV laser diode, combined with a very harsh environment application.

Two different locations on the endwall surface are coated with the MFG (supplied by OSRAM) phosphor (mixed with the temperature resistant HPC binder from ZYP coatings) using an airbrush (RM 350).

For the fully premixed conditions, the coating is located near the exit of the premixing chamber ($x=0\text{mm}$, $y=-15\text{mm}$, $z\approx 10\text{mm}$) (Figure. 1-A and 2-A). For the partially premixed conditions, the coating is located under the outlet of the premixing chamber ($x=0\text{mm}$, $y=-13\text{mm}$, $z=0\text{mm}$) (see Figure. 1-A, 2-B, 3), in order to be spatially included in the (x, y) plane as the OH-PLIF laser sheet, providing valuable information on the flame-endwall distance (at the temperature measurement location).

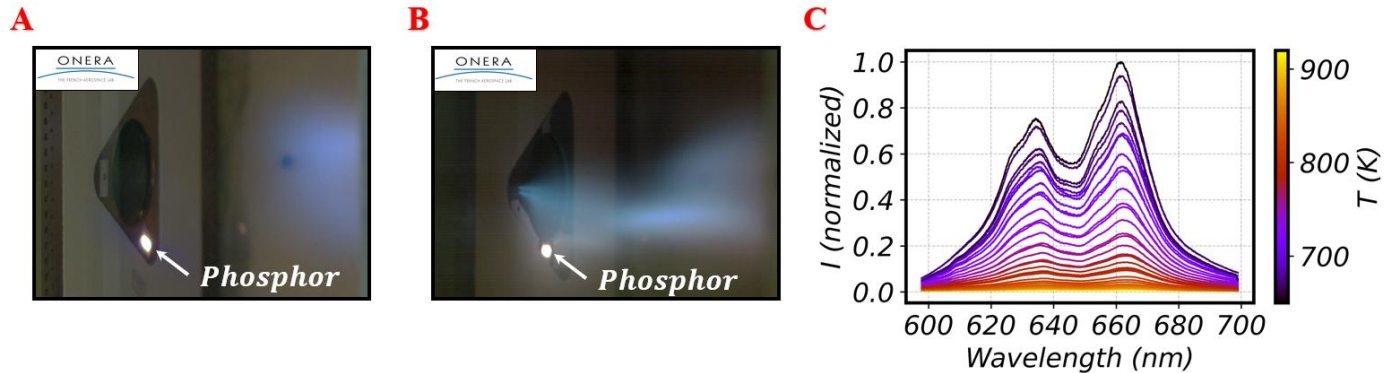


Figure. 2 Front view of the endwall and the phosphor coating location for the fully premixed conditions **(A)** and partially premixed conditions **(B)**. **(C)** Collected luminescence spectrum between 650 K and 900 K from the MFG phosphor with the PT setup used in this study. Note that only the PMT is substituted by an Ocean Optics HR4 spectrometer in order to record the phosphor emission spectrum.

The 375 nm laser beam is directed using a set of dielectric coated mirrors to the measurement location, to induce the phosphor luminescence. The temperature dependent luminescence signals are collected through the lateral window, using a collimator coupled with an optical fiber (800 μm diameter) mounted with a bandpass filter allowing wavelengths between 600 nm and 700 nm. Therefore, the entire luminescence emission spectra of MFG is collected (Figure. 2-C) in order to increase the signal-to-noise ratio (SNR) for such harsh environment. For hydrogen combustion, a broad band collection in the red region does not result in large amount of flame emission interfering with the luminescence signal (Schefer et al., 2009). A Hamamatsu H6780 photomultiplier tube (PMT) is used to detect the photon rate for the fully premixed conditions, while a Hamamatsu H1072 PMT, later purchased, is used for the partially premixed conditions (more details are provided in section 3.2). Finally, a Lecroy HDO6104B oscilloscope is used to acquire the detected signals. Luminescence decays were processed on single-shot basis to evaluate individual luminescence lifetimes, then converted to individual temperatures. The entire laser diode-based PT

setup is presented in Figure. 3. The luminescence collection and signals acquired by the other sensors of the test ring were synchronized using digital signals.

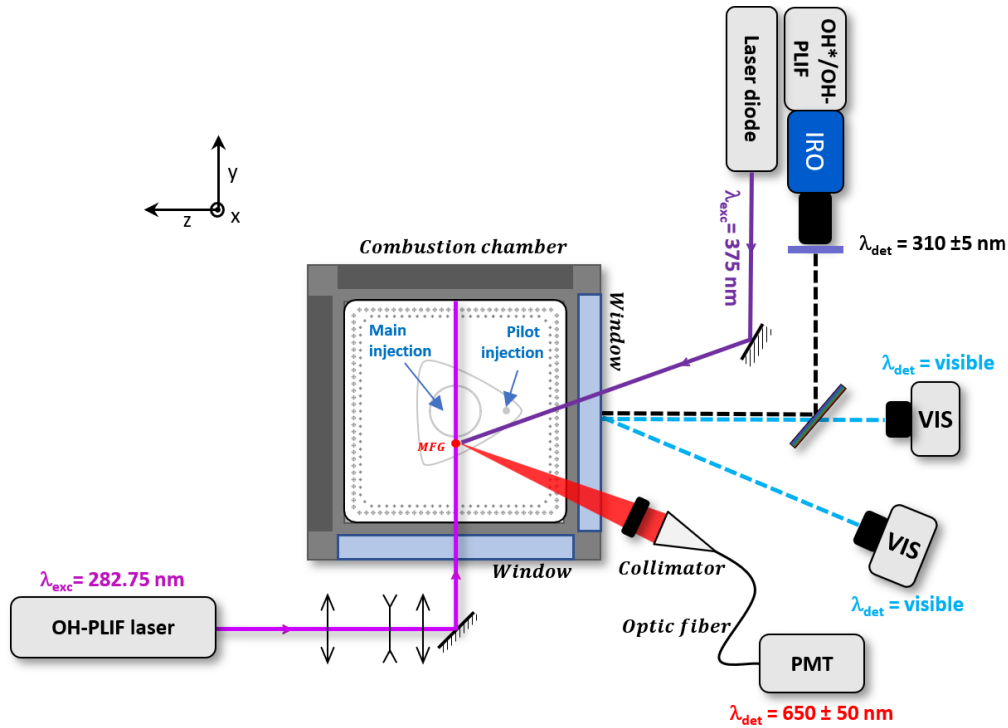


Figure. 3 Schematic of the optical diagnostics setup. The 282.75 nm laser sheet is in the (x, y) plane and propagates along the y axis

3.2 Laser diode-based PT calibrations

For the fully premixed conditions, a H6780-03 PMT is used to collect the MFG luminescence decays, as the more suitable H1072 model was not available. Due to the very low sensitivity of its photocathode between 600 nm and 700 nm, the PMT current is read out using a high input resistance of 1 MΩ, which deteriorates the response time of the acquisition system. Consequently, for luminescence decay time of the same order of magnitude that the detection system response time, temperature sensitivity of the measured decay time is worsened, but at the expense of a sufficient SNR. An accurate calibration of the phosphor with the exact same optical setup was therefore performed using a high temperature furnace and a K-type thermocouple. The results are presented Figure. 4-A. Each red dot is the averaged lifetime obtained from 100 single-shot individually evaluated, always using the same algorithm routine as Brübach et al., 2009 with $c_1 = 0.5$ and $c_2 = 3$ in this study.

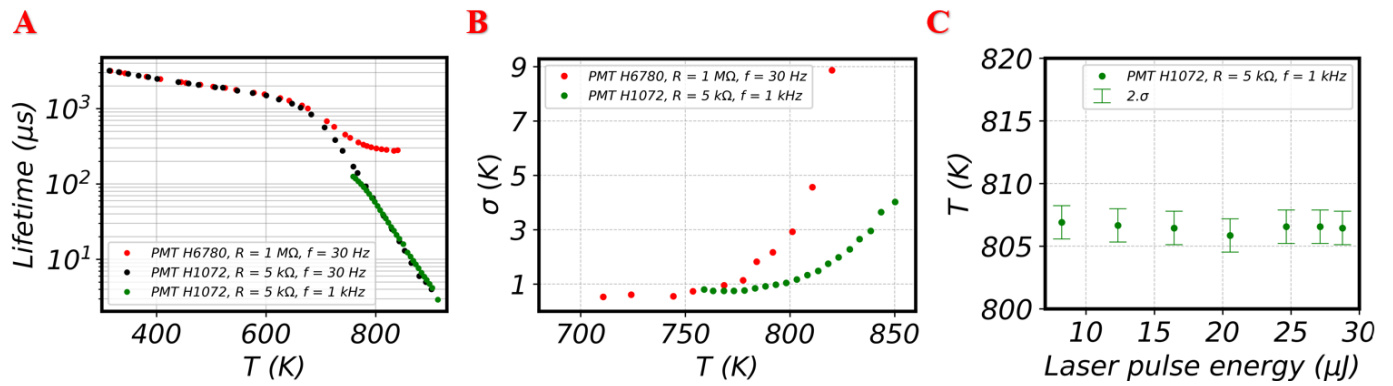


Figure. 4 (A) Lifetime calibration curves in function of temperature obtained for three different setups. (B) Standard deviation (1σ) in function of temperature obtained during the phosphor calibrations. (C) Measured temperature dependency to the laser pulse energy. Note that the red dots are associated with a H6780 PMT and an input resistance of $1 \text{ M}\Omega$. The black and green dots are associated with a H1072 PMT and an input resistance of $5 \text{ k}\Omega$.

The measured lifetime of the phosphor is consistent with the literature (Brübach et al., 2008) up to 650 K, but a plateau effect is then observed as expected (Degeneve et al., 2018). Indeed, the low pass filtering involves that the shortening of the decay times is not reproduced by the PMT, and that the effective temperature sensitivity is significantly reduced. However, the temperature sensitivity can still be exploited up to 800 K. The measured temperature standard deviation during the phosphor calibration is presented Figure. 4-B from 710 K to 850 K. A sub-Kelvin precision (1σ) is obtained up to 770 K, but a clear increase of the standard deviation is observed above 800 K. During the test, the laser diode pulse frequency is 30 Hz with 1.1 mJ/pulse (flat-top pulse, 50% duty cycle) at the laser exit, with up to 400 single-shots acquired during 13.33 s.

For the partially premixed conditions, the setup is improved using a H1072-01 PMT, which has a much more sensitive photocathode between 600 nm and 700 nm. The significantly increased SNR allows to read out the PMT current using a lower input resistance of $5 \text{ k}\Omega$, resulting in a much wider bandwidth of the detection system than for the $1 \text{ M}\Omega$ resistance. In Figure. 4-A, the calibration curve obtained with this change of setup but keeping the same laser pulse frequency and energy is presented (black dots). The results are then consistent with the literature (Brübach et al., 2008; Yin et al., 2017; Degeneve et al., 2018) for the entire temperature range of MFG, and shorter lifetimes can be measured.

The laser diode pulse frequency is therefore increased at 1 kHz (27 μJ /pulse, flat-top pulse, 42% duty cycle), in order to better resolve the temporal evolution of the endwall temperature for partially premixed conditions during the test. An accurate calibration of the phosphor is then

performed from 755 K up to 900 K (Figure. 4-A). Each green dot is the averaged lifetime obtained from 1 000 single-shot individually evaluated. The measured lifetimes at 1 kHz (green dots) are strongly consistent with those measured at 30 Hz (black dots) above 780 K. It should be noticed that a small plateau trend is observed between 755 K and 780 K. This could be associated with a not large enough acquisition window compare to the MFG luminescence decays in this temperature range. A small underestimation of the lifetime is possible in this temperature range, due to the phosphor not fully deexcited before each new pulse (Moussou, 2019), although the criteria ($5. \tau. f_{pulse} < 1$) proposed by Moussou, 2019 is well respected here. However, this observation does not affect the repeatability of the measurements. A sub-Kelvin precision (1σ) is obtained up to 790 K (Figure. 4-B), and then decreases down to 4 K at 850 K. During the test, the laser diode pulse frequency is kept at 1 kHz for partially premixed conditions, and up to 6 000 single-shots are acquired during 6 s.

Finally, because it can change during the test due to the experimental operating conditions, the dependence of measured temperature on laser pulse energy is evaluated for the 1 kHz PT setup (Figure. 4-C). A temperature of 807 K (order of magnitude of the endwall temperature, see section 4) is maintained using thermocouples in the calibration furnace, and PT measurements are performed for different laser pulse energies. Because a change in the laser pulse energy modifies the collected luminescence intensity level, an iris is placed between the luminescence coating and the PMT to keep the detector irradiance constant between measurement to isolate laser pulse energy effect from any detector non-linearity effects. As shown in Figure. 4-C, a decrease of the laser diode pulse energy received by the thermographic phosphor MFG does not affect significantly the measured temperature at ≈ 800 K, which is consistent with a previous study (Brübach et al., 2008).

3.3 Visible cameras

Two visible cameras are used to observe the flame shape and locations. First, the visible emission is collected at 20 Hz by a low-speed camera (Basler) through a dichroic mirror only transmitting visible wavelengths (UV is reflected to the OH* camera), in front of the lateral window (Figure. 3) The exposure time is set to 4 ms, the gain is adapted to optimize the signal dynamic. To better distinguish the pilot flame in partially premixed conditions, the visible emission is also collected through the lateral window but non-normal (Figure. 3), using a high-speed camera (Miro). The

frequency rate is 200 Hz, and the exposure time is 5 ms. The gain is kept constant. No optical filters are used.

3.4 OH* chemiluminescence

High-speed OH* chemiluminescence imaging is used to characterize the flames dynamics and structures. The OH* radical is naturally produced in the flame front at the excited state $X^2\Pi$ and emits a photon to return at the ground state $A^2\Sigma$. Although some differences exist between the heat release rate (HRR) and OH* locations in the flame front for H₂ flames (Schiavone et al., 2024), the presence of this radical is a valuable marker of the reactive zone location (Bedard et al., 2020). The OH* emission is collected through the lateral window, after being reflected on a dichroic mirror by a high-speed camera (Phantom VEO1010) coupled with a high-speed image intensifier (Lavision IRO X, photocathode S20, P46). The intensifier is mounted with a Cerco f/2.8 100 nm UV lens and a bandpass filter transmitting wavelengths between 305 and 315 nm ahead of the lens. The complete setup is presented in Figure. 3. Because the OH* emission is volumetric, the images obtained are actually an integrated view of the flame along the z-axis (Figure. 1-A and Figure. 3).

For the fully premixed conditions, 20 000 images are acquired at 5 kHz (total acquisition duration of 4 s). The exposure time is set to 20 μ s, and the image magnification is 120 μ m/pixel. For the partially premixed conditions, the acquisition frequency is increased at 16 kHz in order to fully resolve the pilot flame dynamic. Consequently, 42 449 images are acquired with a cumulated acquisition duration of 2.653 s. The exposure time is 13 μ s, and the image magnification is 115 μ m/pixel. The intensifier gain is always kept constant. The OH* collection and signals acquired by the other sensors of the test ring were synchronized using digital signals. Background is subtracted from the images.

3.5 OH-PLIF

The OH radical is excited at 30 Hz through the Q₁(5) transition of the A-X system. A frequency-doubled Nd:YAG laser (Quantel YG981) is used to pump Rhodamine 6G diluted in pure ethanol in a dye laser (Quantel TDL). Using a BBO crystal, the 565.50 nm beam obtained is frequency-doubled to obtain a 282.75 nm laser beam with $\approx$ 12 mJ/pulse. The beam is directed to the combustion chamber location using a set of dielectric-coated mirrors. Finally, a 70 mm laser sheet is obtained using a combination of a fused silica lenses: a convex spherical lens (f=+1000 mm), a concave

cylindrical lens ($f=-25$ mm) and a convex cylindrical lens ($f=+300$ mm). The laser sheet is finally sent to the combustion chamber through the bottom window using a dichroic mirror (see section 3.3 and Figure. 3). The sheet is located in the centerline of the chamber ($z=0$) and is perpendicular with the endwall. The probed zone is in the (x , y) plane, starting from the center of the endwall ($x=0$) up to 70 mm downstream. Consequently, the sheet is aligned with the center of the outlet of the premixing chamber, and the pilot injection exit is not in the measurement plane, but located in the foreground. The OH fluorescence emission is collected using the exact same optical setup as high-speed OH* chemiluminescence (Figure. 3). Between 1 500 and 3000 images are acquired with an exposure time of 150 ns. The intensifier gain is adjusted to use the full sensor dynamics.

4. Results and discussion

4.1 Fully premixed flame

Averaged flame visible emission is shown Figure. 5-A. The fully premixed flame appears lifted and detached from the endwall. The combination between high-speed OH* chemiluminescence and OH-PLIF instantaneous images (Figure. 5-B and 5-C) shows that the fully premixed flame is stable and lifted, which results from an anchoring of the reaction zone in the inner recirculation zone of the swirl and a flame foot located at $x \approx 40$ mm downstream the endwall. A typical swirled premixed flame shape (curved toward the swirl center of fresh gas flow, flame rising between the arms of the swirl) is observed in the OH-PLIF single shot presented Figure. 5-C. More details about the flame topology can be found in Pilla et al., 2026.

When the fully premixed flame is stabilized far from the endwall as described above, phosphor thermometry indicates a mean endwall temperature such as $T_{endwall} = 758.5 \pm 3.3$ K (2σ , 100 single shots), which is ≈ 28 K above the targeted inlet air temperature. The low laser diode pulse frequency (30 Hz) for the PT setup used in fully premixed conditions does not permit to resolve the endwall temperature temporal evolution. Considering the measurement precision obtained at 760 K during the setup calibration ($2\sigma_{calibration} \approx 1.6$ K, see Figure. 4-B), small temperature fluctuations could be observed. However, no significant temperature peaks were measured. The single shots are equitably distributed on either side of the mean temperature, and the maximum temperature is measured at 762 K. Therefore, under fully premixed conditions, the endwall temperature can be considered steady, and the heating effect of the flame is sufficiently small to establish that the

thermal stress induced by the combustion is not critical regarding the endwall or the injection system integrity.

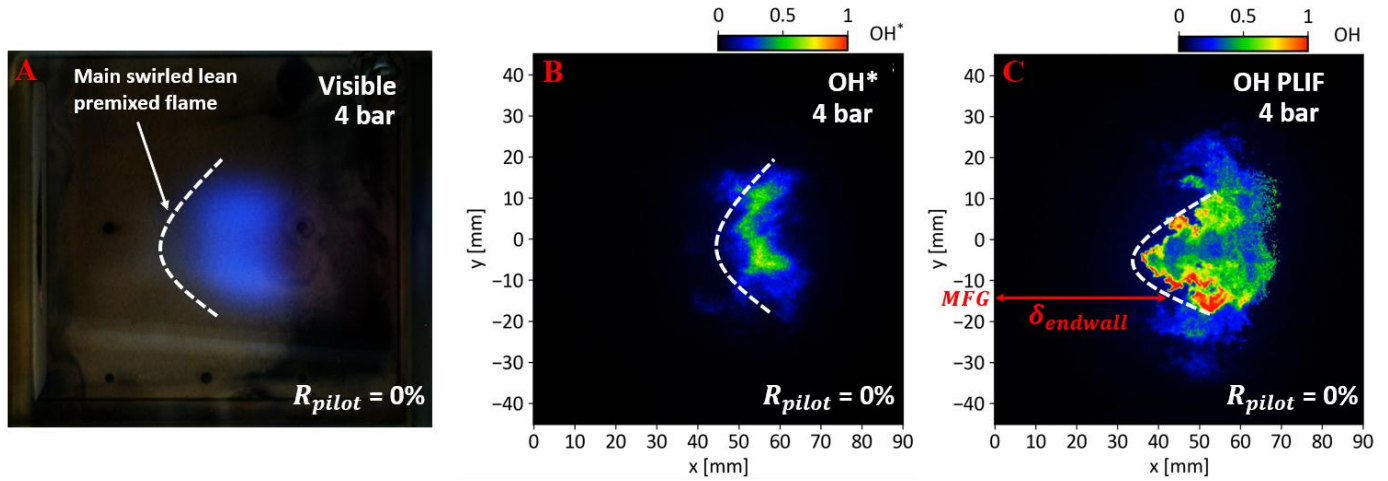


Figure. 5 (A) Averaged visible emission of the flame in fully premixed conditions. (B) OH* chemiluminescence instantaneous image of the flame in fully premixed conditions. (C) OH-PLIF instantaneous image of the flame in fully premixed conditions. The red arrow indicates the distance between the flame and the phosphor coating location.

4.2 Flashback events

For specific operating conditions, flashback events of the fully premixed flame can be observed. A flashback happens when locally the flame speed is higher than the flow velocity. During such event, the flame gets closer to the endwall and combustion occurs inside the premixing chamber. This is highly transient lasting, typically in less than a second. This can be described as a transition between 3 phases. Figure. 6 presents typical OH* chemiluminescence images for each of these phases, and the endwall temperature temporal evolution during the flashback process.

First, before the flashback occurs at $t = 6.3$ s (yellow part), the swirled fully premixed flame is stable and lifted far from the wall as described in section 4.1. Consequently, a constant endwall temperature around 760 K is measured.

When the flashback event occurs at $t = 6.3$ s (red part), phosphor thermometry tends to indicate fast endwall temperature fluctuations in a range of 20 K, which is significant compare to the measurement precision ($2\sigma_{calibration} \approx 1.6$ K). These fluctuations are associated with the premixed flame located much closer to the endwall, and its position fluctuating during the flashback. Such fast wall temperature transitions imply strongly unsteady wall heat fluxes (Boust et al., 2007), and can lead to increase wall thermal stress. Moreover, this amplitude of 20 K measured at the endwall

surface could be much higher upstream inside the premixing chamber, which could lead to serious damage of the injector.

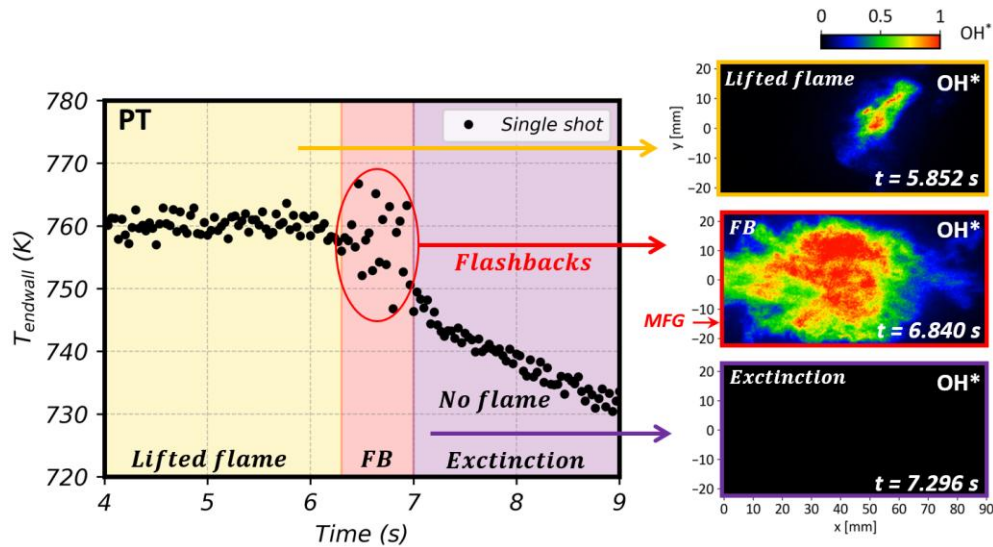


Figure. 6 Wall temperature temporal evolution (at 30 Hz) and OH* chemiluminescence instantaneous images during a transient event (premixed flame flashback)

Shortly after the flashback, the hydrogen mass flowrate is turned off to prevent irreversible damage to the injection system. The flame is therefore extinguished at $t \approx 7$ s (purple part), causing the wall temperature to drop until it reaches the inlet air temperature.

The correlation between the observed flame behavior and the measured surface temperature shows the ability of the PT measurements to observe thermal events inside the combustion chamber. However, this flashback event shows that temperature fluctuations associated with the flame dynamics are faster than the acquisition frequency used. Therefore, higher laser diode pulse frequency rates ($\geq$ kHz) are needed to fully understand and characterize thermal transient events within the combustion chamber.

4.3 Partially premixed flame

In this section, the results are presented for partially premixed conditions (see section 2.2), with a laser diode frequency of 1 kHz. At 4 bar, a small amount (6%) of the total hydrogen mass flowrate is injected through the pilot tube. Using a thermocouple at the exhaust of the combustion chamber, the mean exhaust gas temperature is 1 115 K for the fully premixed conditions while it is 1 118 K for the partially premixed conditions, indicating almost identical burnt gas temperature between both hydrogen injection strategies. In contrast, phosphor thermometry indicates a mean endwall

temperature of 771.8 ± 4.1 K (2σ , 1000 single shots), which is approximately 62 K above the targeted inlet air temperature and 13 K higher than the mean endwall temperature measured for fully premixed conditions. Consequently, the mean endwall temperature appears greater for partially premixed conditions. To explain this observation, the influence of FWI occurrences (Figure. 7) on the endwall temperature evolution is investigated. The chamber pressure is increased at 9 bar and the pilot injection rate fixed at 4% to obtain more significant interactions.

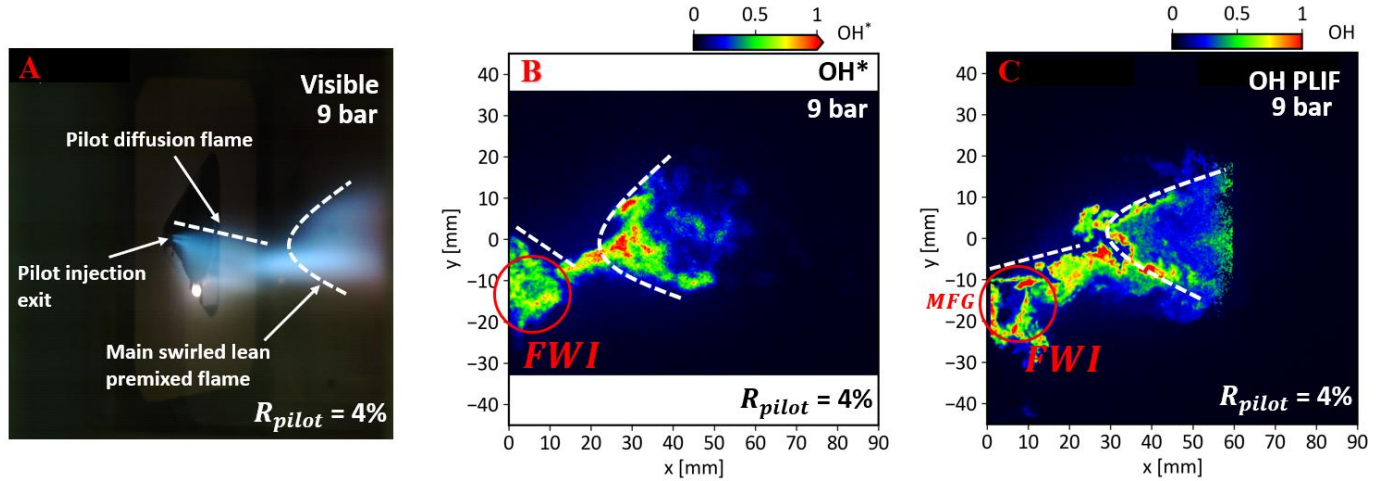


Figure. 7 (A) Averaged visible emission of the fully premixed flame and the direct pilot injection (B) OH* chemiluminescence instantaneous image of the flames in partially premixed conditions. (C) OH-PLIF instantaneous image of the flames in partially premixed conditions.

Averaged flame visible emission is shown Figure. 7-A. The fully premixed flame still appears lifted and detached from the endwall (dashed paraboloid curves in Figure. 7). High-speed OH* chemiluminescence instantaneous images (Figure. 7-B) show that the stabilized position of the lifted premixed flame is similar as observed in fully premixed conditions, i.e. far from the endwall ($x \approx 30$ mm downstream of the premixing chamber outlet). At the exit of the pilot injection hole, the flame shape is typical of a jet diffusion flame (Figure. 7-A), as expected for a direct injection in such configuration. Analyzing the full high-speed OH* chemiluminescence instantaneous images dataset, significant fluctuations in the pilot flame development can be observed (Pilla et al., 2026).

This section focuses on low pilot injection rates ($R_{pilot} \approx 4\%$), when the pilot flame is observed oscillating near the endwall, as shown in Figure. 7-B. This leads to the sporadic presence of the pilot flame very close to the wall. This fluctuating FWI is attributed to the significant difference in momentum fluxes between the main swirled H₂/air premixed flow and the direct H₂ pilot injection.

In Figure. 7-C, a typical instantaneous OH-PLIF image during such an event is shown. The swirled premixed flame is lifted and stabilized at $x \approx 30$ mm, and can be clearly distinguished from the reaction zone due to the direct H₂ pilot injection, located very close to the endwall. It is important to note that the reaction zone attached at the exit of the pilot injection is not in the laser sheet plane (Figure. 3), and therefore cannot be seen on the OH-PLIF images. The near-wall spatial resolution obtained with the current OH-PLIF setup does not permit to measure the distance between the pilot flame reaction zone and the endwall. However, it appears clearly that the pilot flame approaches the endwall close enough ($x < 1$ mm, Figure. 7-C) to consider a flame-wall interaction (FWI) phenomenon, which could lead to significant endwall temperature and wall heat flux increase (De Lataillade et al., 2003; Ojo et al., 2024)

4.4 Pilot flame - endwall interactions

In this section, the temporal evolution of the endwall temperature is investigated at high temporal resolution under partially premixed conditions, with a chamber pressure of 9 bar. It is investigated when FWI phenomenon occurs, as shown in Figure. 7-B and 7-C. In Figure. 8-A, several high-speed OH* chemiluminescence instantaneous images are shown during such an event, from 286 ms to 294 ms. The simultaneously measured endwall temperature is presented from 280 ms to 301 ms in Figure. 8-B, using the laser diode frequency pulse set to 1 kHz.

From 280 ms to 287 ms, the flames are stable as shown in (Figure. 8-A1). We can observe the swirled premixed flame lifted and stabilized around $x \approx 30$ mm, and the pilot diffusion flame attached at the pilot injection exit, straight and potentially mixing with the outer part of the swirled flow. In Figure. 8-B, phosphor thermometry indicates an endwall temperature of 793 K, which is considered constant in view of the associated measurement precision ($2\sigma_{calibration} \approx 2.0$ K, indicated by the colored band).

Starting at 287 ms, the pilot flame migrates toward the endwall (Figure. 8-A2), remaining in its vicinity until 290 ms (Figure. 8-A3, A4, A5). OH* chemiluminescence instantaneous images exhibit a significant decrease of the pilot flame-endwall distance, highlighting FWI phenomenon as explained in section 4.3 using OH-PLIF instantaneous images. The red arrows indicate the thermographic phosphor MFG location on the endwall surface, which matches spatially with the FWI occurring. Simultaneously, phosphor thermometry indicates a clear temperature peak (Figure.

8-B), the endwall temperature rising from 793 K to 822 K. A fast-rising wall temperature is a typical experimental observation during FWI (Padhiary et al., 2023).

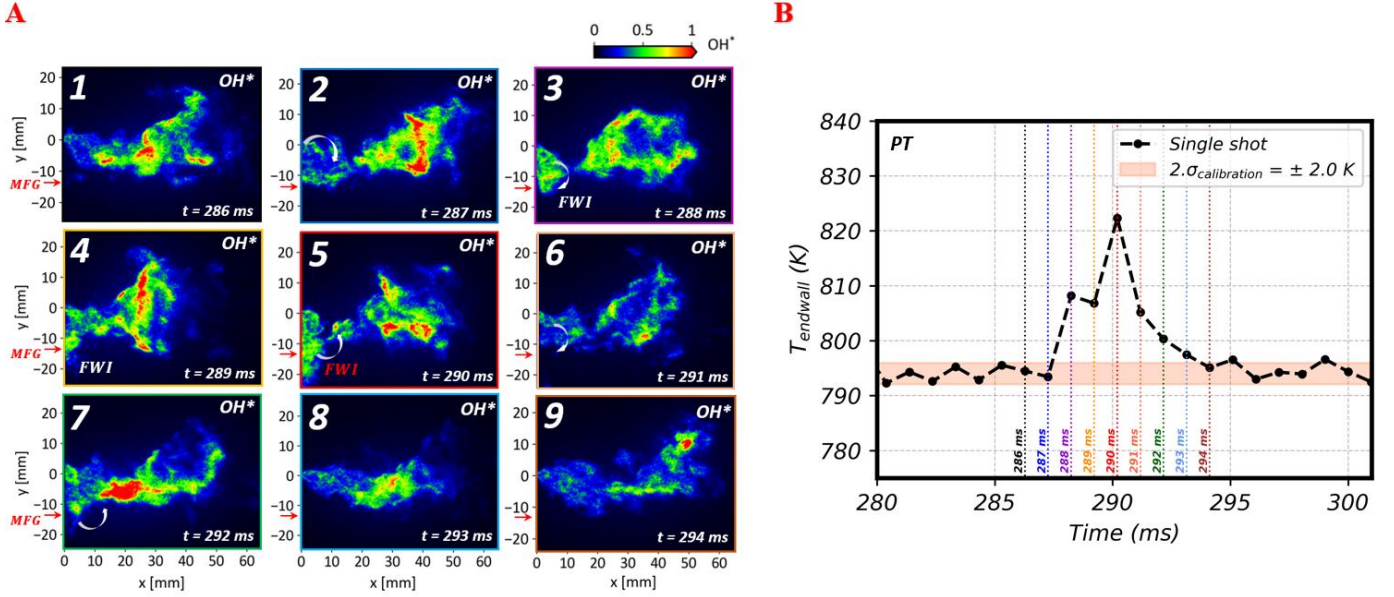


Figure. 8 (A) OH* chemiluminescence instantaneous images of the flames in partially premixed conditions during a FWI phenomenon. Red arrows indicate the phosphor coating location on the endwall surface. **(B)** Associated endwall temperature temporal evolution measured at 1 kHz using laser diode-based PT. The colored band indicates the measurement precision estimated at 793 K during the calibration.

The associated maximum wall heat flux (Q_w) is estimated using the Duhamel integral defined in Equation 2, with $e = \sqrt{\lambda \cdot \rho \cdot C_p}$ the thermal effusivity of the solid material (λ , ρ , C_p are respectively the thermal conductivity, the density and the specific heat capacity), τ is the time variable of integration.

$$Q_w(t) = \frac{e}{\sqrt{\pi}} \int_0^t \frac{\left(\frac{dT_{endwall}(\tau)}{d\tau} \right)}{\sqrt{t-\tau}} d\tau \quad (2)$$

This formulation is obtained considering a time-dependent, one-dimensional, and transient heat conduction problem of a semi-infinite solid (Cook et al., 1970; Sotton, 2003), often used in FWI studies to provide the time evolution of Q_w (Boust et al., 2007; Ojo et al., 2022). In this work, the numerical integral resolution proposed by Sotton, 2003 and Moussou, 2019 is used to compute the transient wall heat flux during the interaction, considering a thermal effusivity of $7843 \text{ J.K}^{-1}.\text{m}^{-2}.\text{s}^{-1/2}$ (stainless-steel material). Thus, a maximum wall heat flux of $\approx 5.4 \text{ MW/m}^2$ is estimated during the observed FWI phenomena. This highlights that the flame leads to a significant thermal stress when interacting with the endwall, which is critical regarding the endwall integrity. However, it is important to note that recent studies have shown the importance to consider the presence of the

phosphor coating when considering the thermal properties of the material (Moussou, 2019; Witkowski et al., 2024) to avoid an over-estimation of wall heat fluxes. In consequence, further estimation of the coating thermal properties is required for a more accurate estimation of wall heat fluxes during FWI.

At 290 ms, the interaction starts to end with the pilot flame straightens up again. This is not instantaneous, with the pilot flame-endwall distance observed fluctuating during 2 more milliseconds (Figure. 8-A6, A7), but staying at least few millimeters from the endwall. After 292 ms, the pilot flame is fully straight and stable again (Figure. 8-A8, A9). Phosphor thermometry indicates a temperature decrease down to 793 K at 290 ms.

During the totality of the acquisition, a multitude of similar temperature peaks are observed, presenting the same consistent behavior between the measured endwall temperature and the flame dynamic, indicating an elevated FWI occurrence rate, which could lead to strong thermal stress and fatigue on the endwall surface.

5. Conclusions

To conclude, this work demonstrates the applicability of high frequency laser diode-based phosphor thermometry for combustion applications. Using a 375 nm laser diode to excite the MFG phosphor, we investigated the endwall temperature of a high temperature and pressure aeronautical combustion chamber, mounted with a new lean H₂/air partially premixed injection system (using a direct pilot H₂ injection). Coupled with high-speed OH* chemiluminescence and OH-PLIF, the PT wall temperature measurement precision (up to $1.\sigma = 0.8$ K at 760 K) allowed to better understand the endwall temperature temporal evolution for two different flame structures and dynamics, namely fully premixed and partially premixed flames.

When operating the injector in fully premixed conditions, a lean fully premixed swirled and lifted flame is generated, stabilized far from the endwall. The mean endwall temperature could be considered steady and the heating effect of the flame is acceptable regarding thermal stress. However, flashback events of the fully premixed flame can occur. During such events, the premixed flame is burning much closer to the endwall. PT measurements at 30 Hz show significant endwall temperature fluctuations in a range of 20 K, which could lead to high wall thermal stress.

The laser diode pulse frequency is increased at 1 kHz when operating the injector in partially premixed conditions (using the direct pilot injection). A greater mean endwall temperature is measured due to the occurrence of interactions between the pilot flame and the endwall. The high pulse frequency of the laser diode allows to highlight significant temperature peaks (≈ 30 K in less than 3 ms) when the pilot flame interacts with the endwall, leading to wall heat flux above 5 MW/m². This is critical regarding thermal stress and the endwall integrity.

Even if providing valuable information for the wall temperature behavior understanding and wall heat flux estimation, the maximum pulse frequency used in this study (1 kHz) does not permit to fully resolve the transient endwall temperature during FWI. Consequently, the maximum temperature peak reached during FWI could be higher and attained in a shorter time. The use of phosphors with shorter lifetimes (< 10 μ s) could allow to increase measurement frequency up to several kHz (Fuhrmann et al., 2011; Ojo et al., 2022), and subsequently to better resolve the wall temperature evolution during FWI. To find such phosphors, as suitable as MFG for combustion application in very harsh environments (luminescence brightness when excited in the near-UV region, insensitivity to oxygen partial pressure and laser energy pulse, etc.) would be a major improvement for the development of laser diode-based phosphor thermometry in the future, but is very challenging for temperature above 750 K. This would allow both the coupling between wall temperature and flame dynamics to be closely monitored, and wall heat fluxes during FWI to be more accurately estimated with further estimation of the coating thermal properties.

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