INFLUENCE OF WALL TEMPERATURE ON COMBUSTION INSTABILITIES

ISA, IMFT
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WHAT DO WE STUDY?

✦ Experimental combustion,
✦ Gaseous fuel,
✦ Premixed laminar flame,
✦ 2D slot burner, wedged flame
✦ Thermo-acoustic instabilities,
✦ Impact of wall-temperatures interaction on flame dynamics
EXPERIMENTAL SET-UP

Bunsen burner, Helmholtz resonator
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Bunsen burner, Helmholtz resonator
We show a naturally unstable experiment with controlled wall temperatures and demonstrate that wall temperatures do change the level of combustion instability.
EVIDENCE OF WALL TEMPERATURE ON CI’s?

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Direct view to visualize flame movement.
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**EVIDENCE OF WALL TEMPERATURE ON CI’s?**

- **Direct view to visualize flame movement**
- **IR Camera**
  - Side image to visualize temperature field in combustor wall
  - $T_{amb} \ (15 - 25 \ ^\circ C)$
EVIDENCE OF WALL TEMPERATURE ON CI’s?

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Direct view to visualize flame movement

Side image to visualize temperature field in combustor wall

$T_s$ (45 - 150 °C)

$T_w$ (1 - 99 °C)

$T_{amb}$ (15 - 25 °C)
EVIDENCE OF WALL TEMPERATURE ON CI’s ?

Laminar Premixed Flame

- $\phi = 0.92$
- $U_0 = 1.6 \text{ m/s}$
- $P = 0.96 \text{ bar}$
- $T_f = 293 \text{ K}$

Cooling System: OFF

- Relative heat release fluctuation
- Thermography

PM + CH*
CCD Camera
Side image to visualize temperature field in combustor wall

$T_s$ (45 - 150 °C)
$T_w$ (1 - 99 °C)
$T_{amb}$ (15 - 25 °C)
EVIDENCE OF WALL TEMPERATURE ON CI’s? 

$T_s$ (45 - 150 °C) 

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Direct view to visualize flame movement 

Side image to visualize temperature field in combustor wall 

vendredi 14 février 14
EVIDENCE OF WALL TEMPERATURE ON CI’s?
EXPERIMENT

vendredi 14 février 14
EXPERIMENT

Slot Temperature (Thermocouple)

$T_1$

Graph showing the temperature $T_s$ over time $t$ [s].

- $T_s$ on the graph indicates the slot temperature.
- The graph shows a significant increase in temperature followed by a decrease.
- The y-axis represents temperature in °C, ranging from 0 to 100.
- The x-axis represents time in seconds, ranging from 0 to 800.
EXPERIMENT

Slot Temperature (Thermocouple)

$T_1$

Cooling OFF

Temperature $T_s$ vs. Time $t$ [s]
EXPERIMENT

Slot Temperature (Thermocouple)

$T_1$

$T_s$

Cooling OFF

Cooling ON

$\sigma$

$T_s$

$[\sigma] \ [L]$
Heat release fluctuation magnitude (Photomultiplier + CH* filter)

\[ T_1 \]

Slot Temperature (Thermocouple)

Heat release fluctuation magnitude (Photomultiplier + CH* filter)

\[ \sigma = \frac{I_{rms}}{I_{CH^*}} \]
Slot Temperature (Thermocouple)

$T_1$

Heat release fluctuation magnitude (Photomultiplier + CH* filtre)

$\sigma = \frac{I_{CH*}^{rms}}{I_{CH*}^{c}}$

Velocity fluctuation magnitude (Hot wire)

$\varepsilon = \frac{\nu_1^{rms}}{\bar{\nu}}$
EXPERIMENT

Slot Temperature (Thermocouple)

\[ T_s \]

Heat release fluctuation magnitude
(Photomultiplier + CH* filtre)

\[ \sigma = \frac{I_{CH^*}^{rms}}{I_{CH^*}} \]

Velocity fluctuation magnitude (Hot wire)

\[ \varepsilon = \frac{v_1^{rms}}{\bar{v}} \]
EXPERIMENT

Slot Temperature (Thermocouple)

\[ T_s \]

Heat release fluctuation magnitude (Photomultiplier + CH* filter)

\[ \sigma = \frac{I_{CH^*}^{rms}}{I_{CH^*}} \]

\[ \varepsilon \]

The flame natural instability can be suppressed increasing Ts by only 30 K.
LITERATURE REVIEW

• The coupling between wall temperatures and thermoacoustics is known from experimentalists in laboratories but also in industry

• some studies address the problem indirectly:
  ✦ Rook (2002, 2003),
  ✦ Preetham (2004),
  ✦ Schmitt (2007),
  ✦ Kaess (2008),
  ✦ Noiray (2008),
  ✦ Altay (2009),
  ✦ Kornilov (2009),
  ✦ Duchaine (2010),
  ✦ Kedia (2011),
  ✦ Cuquel (2013),
  ✦ Hong (2013),

• but no studies address it directly.
OBJECTIVES

• Understand and anticipate when combustors will be submitted to acoustically coupled combustion instabilities.

• Quantify the influence of the combustion chamber wall temperature on combustion instabilities.
THERMO-ACOUSTIC INSTABILITY

Combustion Dynamics

\[ \dot{q}' \]
\[ \dot{v}' \]

Combustion Noise

\[ p' \]
\[ \dot{q}' \]
\[ \dot{v}' \]
\[ \int_{V} p' \dot{q}' dV > 0 \]

Burner Acoustics

\[ v' \]
\[ p' \]
In order to understand and predict combustion instabilities we need a model!
Burner Acoustics

Helthomtz resonator

\[ \nu'_{ext}, p'_{ext} \]

\[ h_s \]

\[ A_s \]

\[ F_1^+, F_1^- \]

\[ F_2^+, F_2^- \]
Burner Acoustics

Helthomtz resonator

Wave equation

\[ \nabla^2 p' - \frac{1}{c^2} \frac{\partial^2 p'}{\partial t^2} = 0 \]

\[ p'(y, t) = F^+ e^{i(ky - \omega t)} + F^- e^{i(-ky - \omega t)} \]

\[ v'(y, t) = \frac{1}{\rho c} \left( F^+ e^{i(ky - \omega t)} - F^- e^{i(-ky - \omega t)} \right) \]
**Burner Acoustics**

Helthomtz resonator

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Acoustic networks of compact elements

\[ \frac{d^2 p'_0}{dt^2} + 2\delta \frac{dp'_0}{dt} + \omega_0^2 p'_0 = \omega_0^2 p'_{ext} \]
Crocco (1951)

Modele \( n - \tau \)

\[ \dot{q}' = n \left[ v'_1 \right]_{t - \tau_c} \]

★ Combustion Dynamics
★ Combustion Noise
★ Burner Acoustics
Modèle \( n - \tau \)

\[ \dot{q}' = n [v'_1]_{t - \tau_c}^* \]

Flame Transfer Function approach

\[ \nu' \rightarrow F(\omega) \rightarrow \dot{q}' \]

★ Crocco (1951)
COMBUSTION DYNAMICS

Modele \( n - \tau \)

\[ \dot{q}' = n [v'_1]_{t - \tau_c} \]

 Flames Transfer Function approach

\[ \mathcal{F}(\omega) = \frac{\dot{q}' / \bar{q}}{v'_1 / \bar{v}} = \frac{A' / \bar{A}}{v'_1 / \bar{v}} \]

★ Crocco (1951)
Combustion Dynamics

Modele \( n - \tau \)

\[ \dot{q}' = n \left[ v'_1 \right]_{t - \tau_c} \]

Flame Transfer Function approach

\[ \mathcal{F}(\omega) = \frac{\dot{q}' / \dot{\bar{q}}}{v'_1 / \bar{v}} = \frac{A' / \bar{A}}{v'_1 / \bar{v}} \]

\[ G = |\mathcal{F}(\omega)| \]

\[ \varphi = \arg[\mathcal{F}(\omega)] \]

\[ \mathcal{F}(\omega) = G(\omega)e^{i\varphi(\omega)} \]

★ Crocco (1951)
COMBUSTION NOISE
\[ p'(x, t) = \frac{\gamma - 1}{4\pi |x| c^2} \int_V \frac{\partial \dot{q}}{\partial t}(x_0, t - \tau_{ac})dV(x_0) \]

\[ \text{Strahle (1971)} \]
Combustion Noise

\[ p'(\mathbf{x}, t) = \frac{\gamma - 1}{4\pi |\mathbf{x}| c^2} \int_V \frac{\partial \dot{q}}{\partial t} (\mathbf{x}_0, t - \tau_{ac}) dV(\mathbf{x}_0) \]

- Compact flame,
- Perfect premixed combustion,

\[ \int_V \dot{q} dV = \int_A \rho Y_F s_D (-\Delta h_f^0) \, dA \]

★ Strahle (1971)
\[ p'(\mathbf{x}, t) = \frac{\gamma - 1}{4\pi |\mathbf{x}| c^2} \int_{V} \frac{\partial \dot{q}}{\partial t}(\mathbf{x}_0, t - \tau_{ac}) dV(\mathbf{x}_0) \]

- Compact flame,
- Perfect premixed combustion,

\[ \int_{V} \dot{q} dV = \int_{A} \rho Y_F s_D (-\Delta h^0_f) dA \]

- Stretch and curvature are ignored,
- Isobaric flame,

\[ p'_{ext}(t) = \frac{\rho(E - 1) s_L}{4\pi r} \left[ \frac{d A'}{d t} \right]_t \]

\textit{Strahle (1971)}

\textit{Clavin and Siggia (1991)}


\( F(\omega) = G(\omega) e^{i \varphi(\omega)} \)

\[ p'_{\text{ext}} = \frac{\rho(E - 1)s_L}{4\pi r} \left[ \frac{dA'}{dt} \right]_t \]

\[ \frac{d^2 p'_0}{dt^2} + 2\delta \frac{dp'_0}{dt} + \omega^2 p'_0 = \omega^2 p'_{\text{ext}} \]
**DISPERSION EQUATION**

\[ F(\omega) = G(\omega)e^{i\varphi(\omega)} \]

\[ p'_{ext} = \frac{\rho(E - 1)s_L}{4\pi r} \left[ \frac{dA'}{dt} \right]_t \]

\[ \frac{d^2 p'_0}{dt^2} + 2\delta \frac{dp'_0}{dt} + \omega_0^2 p'_0 = \omega_0^2 p'_{ext} \]

Harmonic perturbations

\[ \omega^2 + 2i\delta \omega - \omega_0^2 = -\frac{A_s}{4\pi h_e} \frac{E - 1}{r} \omega^2 \]

\[ \left[ 1 + C \frac{1}{r} ne^{i\varphi} \right] \omega^2 + 2i\delta \omega - \omega_0^2 = 0 \]

\[ C = \frac{1}{4\pi h_e} \frac{A_s}{(E - 1)} \]
The system will develop combustion instabilities if:

\[
\omega_i > 0
\]
The system may develop self-induced oscillations when the acoustic energy produced by unsteady combustion is fed into the system.

A low order model gives a stability criteria:
STABILITY CRITERIA

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\text{if } \delta \neq 0 \quad \sin(\omega_0 \tau) < 0
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\[ \text{if } \delta \neq 0 \quad \sin(\omega_0 \tau) < 0 \]

\[ \text{if } \delta = 0 \quad \frac{C}{r} n \sin(\omega_0 \tau) < -\frac{2\delta}{\omega_0} \]
STABILITY CRITERIA

The system may develop self-induced oscillations when the acoustic energy produced by unsteady combustion is fed into the system.

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if $\delta \neq 0$ \quad $\sin(\omega_0 \tau) < 0$

if $\delta = 0$ \quad $\frac{C}{r} n \sin(\omega_0 \tau) < -\frac{2\delta}{\omega_0}$

To solve the proble one neds to determine: $r, \delta, \omega_0, n$ and $\tau$. 
METHODOLOGY

Combustion instabilities

- Experimentally
- Analytically
- Numerically

Self-sustained oscillations
- Limited to one frequency
- Needs a stable configuration for all cases.

Forced oscillations
- Wide range of frequencies
A simple method to stabilize the flame is to increase the length of the feeding duct: This increases the acoustic dissipation and decrease the Helmholtz frequency bringing back the configuration to an unconditionally stable region.

**Stabilizing the flame**

**METHODOLOGY**

Combustion instabilities

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A simple method to stabilize the flame is to increase the length of the feeding duct: This increases the acoustic dissipation and decrease the Helmholtz frequency bringing back the configuration to an unconditionally stable region.

Stabilizing the flame

\[ \varphi = 2\pi f_0 \tau \neq [\pi, 2\pi] \]
### EXPERIMENTAL MEASUREMENTS

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With flame, water is used to cool the walls
Without flame, water is used to heat the walls
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$\Phi = 0.95 \quad \bar{v} = 1.6 \text{ ms}^{-1} \quad \varepsilon = 0.1$
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It is parametrized here by \( T_s \)
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\]

In all cases, the wall temperature is controlled. It is parametrized here by \( T_s \).

**Code for experiments:**

- Wall temperature \([\degree C]\)
- \( c \): cold (non reacting)
- \( h \): hot (reacting)
COMBUSTION NOISE
Validation of combustion noise theory
COMBUSTION NOISE

Validation of combustion noise theory

Combustion noise characterization

$\Delta$SPL [dB]

$f$ [Hz]

T50h
T90h
T120h
COMBUSTION NOISE
Validation of combustion noise theory

Combustion noise characterization

- $\Delta SPL$ [dB]
- $p_1'$ [Pa]
- $f$ [Hz]
- $t$ [ms]

Top view
Front view

Harmonic Signal
COMBUSTION NOISE
Validation of combustion noise theory

Combustion noise characterization

\[ p'_1(x, t) = \mathcal{K}(x) \left[ \frac{d I_{CH^*}}{dt} \right]_{t - \tau_{ac}} \]

\[ \mathcal{K}(x) = \frac{\rho(E - 1)}{4\pi |x|} \kappa \]
**Validation of combustion noise theory**

\[
p'(\mathbf{x}, t) = \mathcal{K}(\mathbf{x}) \left[ \frac{d I_{CH^*}}{dt} \right]_{t-\tau_c}
\]

\[
\mathcal{K}(\mathbf{x}) = \frac{\rho (E-1)}{4\pi |\mathbf{x}|} \kappa
\]
COMBUSTION NOISE

Estimation of the pinching distance "r"
COMBUSTION NOISE

Estimation of the pinching distance “r”
COMBUSTION NOISE

Estimation of the pinching distance “r”
COMBUSTION NOISE

Estimation of the pinching distance “r”

\[ p'_{\text{ext}} \]

\[ I_{\text{CH}}^* \]

\[ \frac{p'}{p} \text{[Pa]} \]

\[ f_{\text{ex}} = 58 \text{ Hz} \]

\[ \phi [\text{rad}] \]

\[ p'_{\text{ext}} \]

\[ I_{\text{CH}}^* \]

\[ A/A_0 \]
COMBUSTION NOISE

Estimation of the pinching distance “r”

In the model r is assumed to be the stationary flame height $h_f$. 

$r = 22 \text{ mm}$
EXPERIMENTAL MEASUREMENTS

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<td>$r = 22$ mm</td>
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<td>Acoustics</td>
<td>$\delta$</td>
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<tr>
<td>Combustion dynamics</td>
<td>$\eta$</td>
<td>$\phi$</td>
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Harmonic Response

\[ \delta = \pi \Delta f \]
BURNER ACOUSTICS

Harmonic Response

\[ \frac{(\tilde{\pi}_0 / \tilde{\pi}_{\text{ext}})_{\text{max}}}{(\tilde{\pi}_0 / \tilde{\pi}_{\text{ext}})^2} \]

\[ \delta = \pi \Delta f \]

\[ f / f_0 \]

\[ f [\text{Hz}] \]

\[ \text{T50c} \]

\[ \text{T90c} \]

\[ \text{Air} \]

\[ \text{Air} \]

\[ \text{M}_1 \]

\[ \text{M}_0 \]
BURNER ACOUSTICS

Impulse Response

\[ e^{(\delta/2)t} \]

\( t \) [ms]

\( t_{ss} \)

\( v_1' / v_{1max} \)

HW signal

Exponential Fit
BURNER ACOUSTICS

Impulse Response

\[ v_1'/v_1'_{\text{max}} = e^{(t/2)\tau} \]

\[ t \text{ [ms]} \]

\[ T_{50c} \quad T_{90c} \]
BURNER ACOUSTICS

Impulse Response

\[ e^{(\delta/2)t} \]

<table>
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<tr>
<th>Method</th>
<th>HR [ \delta \ [s^{-1}] \ f_0 \ [Hz] ]</th>
<th>IR [ \delta \ [s^{-1}] \ f_0 \ [Hz] ]</th>
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<tbody>
<tr>
<td>T50c</td>
<td>15.7 52.0</td>
<td>16.9 52.4</td>
</tr>
<tr>
<td>T90c</td>
<td>16.0 52.0</td>
<td>17.1 53.1</td>
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For the model $\omega_0 = 2\pi f_0$ and $\delta$ is an intermediate value between the two methods.
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<td>$\eta$, $\varphi$</td>
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Flame Transfer Function

\[
F(\omega, T_s) = \frac{\dot{q}'/\bar{q}}{v'_1/\bar{v}} = \frac{A'/\bar{A}}{v'_1/\bar{v}} = \frac{I'_{CH^*}/I_{CH^*}}{v'_1/\bar{v}}
\]

\[
G = |F(\omega, T_s)|
\]

\[
\varphi = \text{arg}[F(\omega, T_s)]
\]
COMBUSTION DYNAMICS

Flame Transfer Function

\[ \mathcal{F}(\omega, T_s) = \frac{\dot{q}'/\bar{q}}{v'_1/\bar{v}} = \frac{A'/\bar{A}}{v'_1/\bar{v}} = \frac{I'_{CH^*}/\bar{I}_{CH^*}}{v'_1/\bar{v}} \]

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\[ \mathcal{F}(\omega, T_s) = \frac{\dot{q}'/\bar{q}}{v'_1/\bar{v}} = \frac{A'/\bar{A}}{v'_1/\bar{v}} = \frac{I'_{CH^*}/\bar{I}_{CH^*}}{v'_1/\bar{v}} \]

\[ \mathcal{G} = |\mathcal{F}(\omega, T_s)| \]

\[ \phi = \arg[\mathcal{F}(\omega, T_s)] \]
COMBUSTION DYNAMICS

Flame Transfer Function

\[ \mathcal{F}(\omega, T_s) = \frac{q'/\bar{q}}{v'_1/\bar{v}} = \frac{A'/\bar{A}}{v'_1/\bar{v}} = \frac{I'_{CH^*}/I_{CH^*}}{v'_1/\bar{v}} \]

\[ G = |\mathcal{F}(\omega, T_s)| \]

\[ \varphi = \arg[\mathcal{F}(\omega, T_s)] \]
\[ \mathcal{F}(\omega, T_s) = \frac{\dot{q}'/\bar{q}}{\nu_1'/\bar{\nu}} = \frac{A'/\bar{A}}{\nu_1'/\bar{\nu}} = \frac{I_{CH*}'/\bar{I}_{CH*}}{\nu_1'/\bar{\nu}} \]

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COMBUSTION DYNAMICS

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\[ F(\omega, T_s) = \frac{\dot{q}'/\bar{q}}{v'_1/\bar{v}} = \frac{A'/\bar{A}}{v'_1/\bar{v}} = \frac{I'_{CH}/I_{CH}}{v'_1/\bar{v}} \]

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COMBUSTION DYNAMICS

Flame Transfer Function

\[ \mathcal{F}(\omega, T_s) = \frac{\dot{q}'/\ddot{q}}{v_1'/\ddot{v}} = \frac{A'/A}{v_1'/\ddot{v}} = \frac{I_{CH}^*/I_{CH}^*}{v_1'/\ddot{v}} \]

\[ G = |\mathcal{F}(\omega, T_s)| \]

\[ \varphi = \arg[\mathcal{F}(\omega, T_s)] \]
COMBUSTION DYNAMICS

Flame Transfer Function

$$\mathcal{F}(\omega, T_s) = \frac{\dot{q}'/\bar{q}}{v_1'/\bar{v}} = \frac{\mathcal{A}'/\bar{A}}{v_1'/\bar{v}} = \frac{I_{CH^*}'/I_{CH^*}}{v_1'/\bar{v}}$$

$$\mathcal{G} = |\mathcal{F}(\omega, T_s)|$$

$$\phi = \text{arg}[\mathcal{F}(\omega, T_s)]$$

![Graphs showing flame transfer function and its parameters](image)
COMBUSTION DYNAMICS

Flame Transfer Function

T50h  f_{ex} = 50 \text{ Hz}  T120h

T50h  f_{ex} = 150 \text{ Hz}  T120h
COMBUSTION DYNAMICS

Flame Transfer Function
## Experimental Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Combustion noise</th>
<th>Acoustics</th>
<th>Combustion dynamics</th>
</tr>
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<tbody>
<tr>
<td>$r$</td>
<td>$22$ mm</td>
<td>$\delta = 16$ s$^{-1}$</td>
<td>$\omega_0 = 327$ rad</td>
</tr>
<tr>
<td>Depends on $T_s$ ?</td>
<td>NO</td>
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- Combustion noise
  - $r = 22$ mm
  - Depends on $T_s$ ?: NO

- Acoustics
  - $\delta = 16$ s$^{-1}$
  - $\omega_0 = 327$ rad
  - Depends on $T_s$ ?: NO

- Combustion dynamics
  - $n = \begin{pmatrix} 50 \\ 90 \\ 120 \end{pmatrix} = \begin{pmatrix} 0.87 \\ 0.77 \\ 0.75 \end{pmatrix}$
  - $\varphi = \begin{pmatrix} 50 \\ 90 \\ 120 \end{pmatrix} = \begin{pmatrix} 1.13\pi \\ 1.09\pi \\ 1.05\pi \end{pmatrix}$
  - Depends on $T_s$ ?: YES
SOLUTION OF THE DISPERSION EQUATION

\[
1 + \frac{1}{r} ne^{i\varphi} \omega^2 + 2i\delta \omega - \omega_0^2 = 0
\]

\(\omega_r\) → Frequency of resonance

\(\omega_i\) → Growth rate

<table>
<thead>
<tr>
<th></th>
<th>T50</th>
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# SOLUTION OF THE DISPERSION EQUATION

\[
\left[ 1 + C \frac{1}{r} ne^{i\varphi} \right] \omega^2 + 2i\delta\omega - \omega_0^2 = 0
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<td>T50h</td>
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### Solution of the Dispersion Equation

\[
1 + C \frac{1}{r} n e^{i\varphi} \omega^2 + 2i\delta\omega - \omega_0^2 = 0
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- \(\omega_r\) → Frequency of resonance
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#### Combustion Noise
- \(r\) [mm] 22

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- \(\omega_0\) [rad/s] 327
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- \(n\) [1] 0.87 0.77 0.75
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SOLUTION OF THE DISPERSION EQUATION

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A low order model is able to predict the stability of the system!

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WHY COMBUSTION DYNAMICS IS AFFECTED BY THE WALL TEMPERATURE?

The combustion instabilities are suppressed by the combined effect of the wall temperature on both, the gain and the phase of the flame response!
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The combustion instabilities are suppressed by the combined effect of the wall temperature on both, the gain and the phase of the flame response!

Elongated flames (EM2C)

\[ \dot{q} = f(A') \]

\[ \bar{v} + v' \]

- Baillot et al. (1992)
- Ducruix et al. (2000)
- Schuller et al. (2003)
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\[ \dot{q}' = f(A') \]

\[ \dot{q}' = f(\dot{q}_i) \]
WHY COMBUSTION DYNAMICS IS AFFECTED BY THE WALL TEMPERATURE?

The combustion instabilities are suppressed by the combined effect of the wall temperature on both, the gain and the phase of the flame response!

Elongated flames (EM2C)

Flat flames stabilized over porous media (TUE)

Perforated-plate stabilized flames (MIT)

- Baillot et al. (1992)
- Ducruix et al. (2000)
- Schuller et al. (2003)
- Rook et al. (2002)
- Schreel et al. (2002)
- Rook and de Goey (2003)
- Altay et al. (2009)
- Murat et al. (2010)
- Kedia et al. (2011)
IMPORTANCE OF THE ANCHORING POINT DYNAMICS

- Kornilov *et al.* (2007)
- Karimi *et al.* (2009)
IMPORTANCE OF THE ANCHORING POINT DYNAMICS

Kornilov et al. (2007)  
Karimi et al. (2009)  
Cuquel et al. (2013)
IMPORTANCE OF THE ANCHORING POINT DYNAMICS

Kornilov et al. (2007)  
Karimi et al. (2009)  
Cuquel et al. (2013)

\[ \mathcal{F}(\omega) = \mathcal{F}_A(\omega) + \mathcal{F}_B(\omega) \]

\[ \mathcal{F}_A(\omega) \rightarrow \text{Flame surface contribution} \]

\[ \mathcal{F}_B(\omega) \rightarrow \text{Flame base contribution} \]
Flame front dynamics is controlled by two adimensional frequencies that only depend on the stationary flame geometry:

\[ \omega_\ast = \frac{\omega}{s_L \cos \alpha} \frac{w_s}{2} = \frac{\omega}{\bar{v} \cos \alpha} l_f, \]

\[ \kappa_\ast = \omega_\ast \cos^2 \alpha = \frac{\omega}{\bar{v}} h_f, \]

\* Ducruix (2000)

\* Cuquel (2013a)
I. Flame Surface Contribution

Flame front dynamics is controlled by two adimensional frequencyes that only depend on the stationary flame geometry:

\[ \omega_* = \frac{\omega}{s_L \cos \alpha} \frac{w_s}{2} = \frac{\omega}{\bar{v} \cos \alpha} \ell_f, \]

\[ \kappa_* = \omega_* \cos^2 \alpha = \frac{\omega}{\bar{v}} h_f. \]

\* Ducruix (2000)
\* Cuquel (2013a)

If the flame surface contribution that is affected by the wall temperature is because one of this parameters has changed:

\* Flame geometry,
\* bulk velocity.

Stationary Flame Front

Axis of symmetry
PRE-HEATING OF FRESH GASES?
PRE-HEATING OF FRESH GASES?
PRE-HEATING OF FRESH GASES?

\[ T_u [\degree C] \]

\[ x/w_s \]

\[ T_{50c} \]

\[ T_{90c} \]

\[ B15 \]
PRE-HEATING OF FRESH GASES?

1. Does it affects the bulk velocity?
PRE-HEATING OF FRESH GASES?

1. Does it affects the bulk velocity?

$$\bar{v}^{T90c} = \bar{v}^{T50c} \frac{T_u^{T90c}}{T_u^{T50c}}$$

$$\frac{T_u^{T90c}}{T_u^{T50c}} = 1.01$$
PRE-HEATING OF FRESH GASES?

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\[ \bar{v}^{T90c} = \bar{v}^{T50c} \frac{T_u^{T90c}}{T_u^{T50c}} \]

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PRE-HEATING OF FRESH GASES?

1. Does it affects the bulk velocity?

\[ \bar{v}_{T90c} = \bar{v}_{T50c} \frac{T_{u,T90c}}{T_{u,T50c}} \]

\[ \frac{T_{u,T90c}}{T_{u,T50c}} = 1.01 \]

FTF at \( f_{ex} = 58 \) Hz
PRE-HEATING OF FRESH GASES?

2. Does it affects the flame speed?
2. Does it affects the flame speed?

\[ s_L \propto \left( \frac{T_u}{T_{u0}} \right)^{\alpha_T}, \alpha_T = 1.9 \]

\[ \frac{s_L^{T90h}}{s_L^{T50h}} = 1.03 \]
2. Does it affects the flame speed?

\[ s_L \propto \left( \frac{T_u}{T_0} \right)^{\alpha T}, \quad \alpha_T = 1.9 \]

\[ \frac{s_{L50h}}{s_{L90h}} = 1.03 \]

\[ s_L \propto 1/l_f \]

\[ \frac{l_{f50h}}{l_{f90h}} = 1.03 \]
PRE-HEATING OF FRESH GASES?

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FTF at \( f_{ex} = 58 \text{ Hz} \)
PRE-HEATING OF FRESH GASES?

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\[ s_L \propto 1/l_f \]

FTF at \( f_{ex} = 58 \) Hz
Phase decrease with $T_s$ is due to the increase on the flame speed by the effect of the pre-heating of fresh gases.
2. FLAME ANCHORING POINT CONTRIBUTION
Analytical Model

Perturbed Flame Front

Flame root motion contribution

Velocity perturbation contribution

\[ \xi(x) \]

\[ \bar{v} + v'(x) \]

\[ s_L + \xi_L(\psi_f) \]

\[ \bar{v} + v'(\psi_f) \]

\[ \psi_f \]

\[ \xi(0) \]

\[ \bar{v} + v' \]

Cuquel et al. (2013)
2. FLAME ANCHORING POINT CONTRIBUTION

Analytical Model

Flame speed fluctuation at the flame base model:

\[
S(\hat{\omega}) = \frac{\tilde{s}_L(\psi_f)}{\tilde{v}(\psi_f)} = \left[1 - \frac{i\hat{\omega}}{Ze} \sinh(\Psi_f) e^{-\Psi_f(1+(1-4\hat{\omega})^{1/2})}\right]^{-1},
\]

\[
\hat{\omega} = \omega \frac{\delta_f}{s_L} \quad Ze = \frac{T_a T_b - T_u}{T_b - T_u},
\]

\[
\Psi_f = \frac{\psi_{f_0}}{2\delta_f} = \frac{1}{2} \log \left(\frac{T_{ad} - T_u}{T_{ad} - T_b + T_s - T_u}\right),
\]

G-Equation at: \(x = \psi_{f0}\)

\[
\frac{\partial \xi(0)}{\partial t} = v'(\psi_{f0}, t) - s_L'(\psi_{f0})(t),
\]

Flame base transfer function

\[
\Xi(\hat{\omega}) = \frac{\tilde{\xi}(0)/(w_s/2)}{\tilde{v}/\bar{v}} = -4\delta_* \frac{1 - S(\hat{\omega})}{i\hat{\omega} \cos \alpha} \left(1 - i \frac{1}{4 \delta_*} \cos^2 \alpha \left(1 - 2\delta_* \Psi_f \tan \alpha\right)\right) e^{i\frac{1}{2} \hat{\omega} \Psi_f \cos \alpha \sin \alpha}
\]

\[\downarrow \text{Cuquel et al. (2013)}\]
2. FLAME ANCHORING POINT CONTRIBUTION

Analytical Model

Flame speed fluctuation at the flame base model:

\[ S(\hat{\omega}) = \frac{\tilde{s}_{L}(\psi_{f0})}{\hat{v}(\psi_{f0})} = \left[ 1 - \frac{i\hat{\omega}}{Ze} \sinh(\Psi_{f}) e^{-\Psi_{f}(1+(1-4\hat{\omega})^{1/2})} \right]^{-1} \]

\[ \hat{\omega} = \omega \frac{\delta_{f}}{s_{L}} \]

\[ Ze = \frac{T_{a} T_{b} - T_{u}}{T_{b}} \]

\[ \Psi_{f} = \psi_{f0} \frac{2\delta_{f}}{2\delta_{f}} = \frac{1}{2} \log \left( \frac{T_{ad} - T_{u}}{T_{ad} - T_{b} + (T_{s} - T_{u})} \right) \]

G-Equation at: \( x = \psi_{f0} \)

\[ \frac{\partial \xi(0)}{\partial t} = v'(\psi_{f0}, t) - s'_{L}(\psi_{f0})(t), \]

Flame base transfer function

\[ \Xi(\hat{\omega}) = \frac{\tilde{\xi}(0)/(w_{s}/2)}{\hat{\omega}} = -4\delta_{*} \frac{1 - S(\hat{\omega})}{i\hat{\omega} \cos \alpha} \left( 1 - i \frac{1}{4 \delta_{*}} \cos^{2} \alpha (1 - 2\delta_{*} \Psi_{f} \tan \alpha) \right) e^{i\frac{1}{2} \hat{\omega} \Psi_{f} \cos \alpha \sin \alpha} \]

\( \Rightarrow \) Cuquel et al. (2013)

\( \Rightarrow \) Rook et al. (2002)
2. FLAME ANCHORING POINT CONTRIBUTION

Analytical Model

Flame speed fluctuation at the flame base model:

\[ S(\hat{\omega}) = \frac{s_L(\psi_f)}{v_f} = \left[ 1 - \frac{i\hat{\omega}}{Ze} \sinh(\Psi_f)e^{-\Psi_f(1+(1-4\hat{\omega})^{1/2})} \right]^{-1}, \]

\[ \hat{\omega} = \omega \frac{\delta_f}{s_L}, \quad Ze = \frac{T_a T_b - T_u}{T_b}, \quad \Psi_f = \frac{\psi_f}{2\delta_f} = \frac{1}{2} \log \left( \frac{T_{ad} - T_u}{T_{ad} - T_b + T_s - T_u} \right), \]

G-Equation at: \( x = \psi_f(0) \)

\[ \frac{\partial \xi(0)}{\partial t} = v'(\psi_f, t) - s'_L(\psi_f(0)), \]

Flame base transfer function

\[ \Xi(\omega) = \frac{\tilde{\xi}(0)/(w_s/2)}{\hat{v}/\bar{v}} = -4\delta_s \frac{1 - S(\hat{\omega})}{i\hat{\omega} \cos \alpha} \left( 1 - i \frac{1}{4 \delta_s} \cos^2 \alpha (1 - 2\delta_s \Psi_f \tan \alpha) \right) e^{i\frac{1}{2} \hat{\omega} \Psi_s \cos \alpha \sin \alpha}. \]

\[ \begin{bmatrix} T50h \cr T90h \cr T120h \end{bmatrix} \]

\[ \begin{bmatrix} \varphi_f \cr \varphi_f \end{bmatrix} = \begin{bmatrix} \Xi(\omega, T_s) \cr \Xi(\omega, T_s) \end{bmatrix}, \]

Cuqel et al. (2013)

★ Rook et al. (2002)
2. FLAME ANCHORING POINT CONTRIBUTION

Experimental

Stationary Stand-off distance

\[ \psi_{f_0} \]

\[ T_{50h} \]

\[ T_{120h} \]

\[ T_{90h} \]

\[ f_0 \]

\[ f_0 \]

\[ 0.8 \]

\[ 1.0 \]

\[ 1.2 \]

\[ 300 \]

\[ 350 \]

\[ 400 \]

\[ 450 \]

\[ \psi_{f_0} \]

\[ T_\text{s} [\degree\text{C}] \]

\[ \Delta T_{50h} \]

\[ \circ T_{90h} \]

\[ \times T_{120h} \]
2. FLAME ANCHORING POINT CONTRIBUTION

Experimental

Stationary Stand-off distance

\[ \psi_{f_0} = \frac{1}{2} \delta_f \log \left( \frac{T_{ad} - T_u}{T_{ad} - T_b + T_s - T_u} \right), \]

\[ T_s [°C] \]

\[ \psi_{f_0} \]

Model
- T50h
- T90h
- T120h

vendredi 14 février 14
2. FLAME ANCHORING POINT CONTRIBUTION

Experimental

Stationary Stand-off distance

\[ \psi_{f_0} = \frac{1}{2} \delta_f \log \left( \frac{T_{ad} - T_u}{T_{ad} - T_b + T_s - T_u} \right), \]

The flame root location is chosen as the intersection of the crest of light intensity with the iso-contour at 65 % of the maximum pixel value over the whole image.
DYNAMICS OF THE FLAME
ANCHORING POINT

Experimental

T50h
DYNAMICS OF THE FLAME
ANCHORING POINT

Experimental

$T_{50\text{h}} \quad f_{ex} = 60 \text{ Hz}$
DYNAMICS OF THE FLAME ANCHORING POINT

Experimental

T50h $f_{ex} = 60$ Hz
Experimental

\[ f_{ex} = 60 \text{ Hz} \]
DYNAMICS OF THE FLAME ANCHORING POINT

Experimental

\[
\Xi(\omega) = \frac{\xi(0)/\langle w_s/2 \rangle}{v'/\bar{v}}
\]

\[
G_f = |\Xi(\omega, T_s)|
\]

\[
\varphi_f = \arg|\Xi(\omega, T_s)|
\]

\[
f_{ex} = 60 \text{ Hz}
\]
DYNAMICS OF THE FLAME ANCHORING POINT

Experimental

\[ \Xi(\omega) = \frac{\xi(0)/(w_s/2)}{v'/\bar{v}} \]

\[ G_f = |\Xi(\omega, T_s)| \]

\[ \phi_f = \text{arg} |\Xi(\omega, T_s)| \]

\[ F(\omega) = \frac{\ddot{q}/\ddot{q}}{v_1'/\bar{v}} \]

\[ G = |F(\omega, T_s)| \]

\[ \phi = \text{arg}[F(\omega, T_s)] \]

\[ f_{ex} = 60 \text{ Hz} \]
Gain decrease with $T_s$ is due to the switch toward the higher frequencies on the flame root response to velocity perturbations.
COMPARATION

<table>
<thead>
<tr>
<th>Test</th>
<th>$f_p$ [Hz]</th>
<th>Model</th>
<th>$f_p$ [Hz]</th>
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<td>110</td>
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</tr>
<tr>
<td>T120h</td>
<td>118</td>
<td></td>
<td>120</td>
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$\theta_r$ [rad]

$\phi_r$ [Hz]

$\pi/2$

$0$

$0$

$0$

$0$

$0$

$0$
Where to measure the velocity fluctuation?
FTF
Where to measure the velocity fluctuation?

Zoom on the slot

Harmonic Signal

Reference point

142 mm

π
2π

0
2π

0

\(\phi_v\) [rad]

\(y/w_f\)

\(T_{50c, f_{ex}=50 \text{ Hz}}\)

\(T_{50c, f_{ex}=130 \text{ Hz}}\)
Where to measure the velocity fluctuation?

Zoom on the slot

Reference point

$\phi_v [\text{rad}]$

$v_{\text{end}}$
FTF
Where to measure the velocity fluctuation?

Where to measure the velocity fluctuation?

Zoom on the slot

Reference point

 Harmonic Signal

Air

Air

HW

LS

142 mm

$\phi_v$ [rad]

$\gamma_e$

$y/w_f$

$T_{50c} \; f_{ex} = 50 \; Hz$

$T_{50c} \; f_{ex} = 130 \; Hz$

$T_{90c} \; f_{ex} = 50 \; Hz$

$T_{90c} \; f_{ex} = 130 \; Hz$

vendredi 14 février 14
FTF
Where to measure the velocity fluctuation?
Where to measure the velocity fluctuation?
Where to measure the velocity fluctuation?
Different Flame Transfer Functions

\[ y = -10 \text{ mm} \]

\[ y = 0 \text{ mm} \]
CONCLUSIONS
CONCLUSIONS

Do wall temperatures modify the...
CONCLUSIONS

Do wall temperatures modify the...

1. Combustion Noise: NO,
CONCLUSIONS

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1. Combustion Noise: NO,

2. acoustics: NO,
CONCLUSIONS

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1. Combustion Noise: NO,

2. acoustics: NO,

3. flame dynamics: YES.
CONCLUSIONS
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- A low order model is able to predict the stability of the system,
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• self excited modes as well as the FTF are highly affected by the temperature of the combustion chamber walls,
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  ✦ local modifications of flame speed in boundary layers,

  ✦ modification of the flame base dynamics.
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• the place where the velocity fluctuation is measured is a key parameter in for an accurate measure of the FTF.
Merci de votre attention

Questions ??

Premixed laminar flame
\( \Phi = 0.95 \)
\( U_b = 1.7 \text{ m/s} \)

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