Flame / wall interactions in combustion chambers

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FLAMES AND WALLS: WHY DO WE CARE?

FLAMES  →  WALLS  →  POLLUTANTS

INSTABILITIES  ←  ACOUSTICS
Context: gas turbines chambers but all combustors face similar problems
Combustion chambers in a gas turbine:

1- Must burn all the injected fuel with high efficiency (99 %)

2- Must limit pollutant emission

3- Must **NOT** burn walls.

1 is easy
2 is difficult
3 is mandatory
CATASTROPHIC FLAME-WALL INTERACTION

Thermocouple cone

Oxygen swirler

Oxygen lip
Which walls?

Aero-engine combustor sector

Which walls?
Which walls?

Developed surface

High Pressure Stator walls

Chamber walls

Temperature [K]
800 1750 2700
1275 2225
Which walls?

• Combustion chamber walls see very high gas temperatures: must be cooled and protected by multiperforated films

• High Pressure stator walls: cooled by internal air circulation (and sometimes films)

• Turbine vanes: cooled in aircraft engines but not in helicopters

The design of these cooling systems controls the engine lifetime
Which type of flame wall interaction?

• In this talk: walls do NOT (should not...) burn: no chemistry takes place at the wall surface.

• The problem is to make sure that this does not happen. The wall must remain cold -> this requires simultaneous computations of flow around walls and temperatures within walls.
WHAT IF THE WALL CANNOT REMAIN COLD?

Then chemical reactions will take place at the wall: the wall ... burns

Sometimes, this is done on purpose: for example, in carbon/carbon nozzles for rocket engines
Protecting walls by air: multiperforation (effusion cooling)

Effusion cooling:
Cooling air injected through small holes (typically 0.5 mm)
=> Protecting film at the wall
Multiperforated chamber
Flow in ONE hole:

This thin layer is the only protection of the wall
High Pressure stator: can be multiperforated too!
Not only a fluid mechanics problem

The temperature of the walls is controlled by the flow inside the chamber AND by heat diffusion within the solid: need to couple LES and heat transfer in solids -> we need to discuss coupling between solvers

Strong interaction with acoustics: multiperforated plates also act like acoustic damping systems: cannot modify them without modifying the chamber acoustic eigenmodes
Outline

- Flame / wall interactions: general features
- Coupled LES / heat transfer simulations
- Effects of wall temperatures on unsteady flames

Will focus on smooth walls (no multiperforated cases)
Flame / wall interactions: general features

Coupled LES / heat transfer simulations

Effects of wall temperatures on unsteady flames
When flames meet walls:

Three types of events on a dry (no fuel film), inert, non multiperforated wall:

1. Wall is touched by non-reacting gases: no problem

2. Wall is touched by burnt gases: high fluxes for long times

3. Wall is touched by a flame front: very high heat fluxes for very short times
Flame-wall interactions:
Phase 3 events: an active flame touches a wall

(a): Head On Quenching (HOQ)

(b): Side Wall Quenching (SWQ)
Head on quenching simulation:

PROPAINE / AIR FLAME AT 1 BAR
Classical head on quenching (HOQ)

![Diagram showing classical head on quenching (HOQ)]

- Flame position
- Flame speed
- Heat flux

Wall

- y (wall distance)

Cold premixed gas

Flame front

Burnt gas

T₂

Abscissa

Tₜₖ
Simple scaling for maximum wall heat fluxes during flame-wall interaction:

<table>
<thead>
<tr>
<th>Initial reference</th>
<th>Overall reaction</th>
<th>Approach</th>
<th>Chemical model</th>
<th>Flux $\Phi$ $MW/m^2$</th>
<th>Reduced flux $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wichman &amp; Bruneaux</td>
<td>$F + O \rightarrow P$</td>
<td>Theory</td>
<td>Simple</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Poinset et al 1993</td>
<td>$F + O \rightarrow P$</td>
<td>DNS</td>
<td>Simple</td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td>Popp &amp; Baum 1997</td>
<td>$CH_4/air - 1\text{ bar}$</td>
<td>DNS</td>
<td>Complex</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Vermorel 1999</td>
<td>$H_2/O_2 - 1\text{ bar}$</td>
<td>DNS</td>
<td>Complex</td>
<td>4.85</td>
<td></td>
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<tr>
<td>Hasse et al 2000</td>
<td>$C_8H_{18}/air\ 10\text{ bar}$</td>
<td>DNS</td>
<td>Complex</td>
<td>10</td>
<td>0.41</td>
</tr>
</tbody>
</table>

The maximum flux through the wall scales like the flame power:

$$F = \frac{\text{Maximum wall heat flux}}{\text{Flame Power}}$$

When a flame touches a wall, it delivers 1/3 of its power to the wall (and it dies...)

- 0.33
- 0.34
- 0.4
- 0.13
- 0.41
Simple scaling for minimum distance between flame and wall

\[ P = \frac{y}{\delta} \]

\[ PQ = 3.4 \]

During Head On quenching, the flame stops at approx 3 flame thicknesses away from the wall.
CONSEQUENCES:

• During HOQ, the flame never really touches the wall (if the wall is cold)

• There is unburnt fuel left near the wall: this will lead to pollution (CHx). In a piston engine for example, this fuel will leave the walls during the exhaust phase. This phenomenon is amplified by fuel trapped in crevices
SIDE-WALL INTERACTION

Less studied

Leads to smaller fluxes \( (F=0.15) \) and larger minimum flame wall distances \( (Pe=7) \)
TURBULENT FLOW: both HOQ and SWQ

- Head on quenching
- Side wall quenching
In a duct, with a wall on each side, the flame speed is modified and goes to zero if the two sides are too close. Critical distance: $P_Q = \frac{2R}{\delta} = 50$

This was discovered in the early days of laminar flame studies because experimentalists were obtaining different flame speed values in tubes: they were using different tube diameters.
LEONARD FIGURE 1: MEASUREMENTS OF QUENCHING DIAMETER IN TUBES

Lewis and von Elbe, 1987

(a): Head On Quenching (HOQ)

(b): Side Wall Quenching (SWQ)

(c): Tube Quenching

Cold premixed gas

2R

Flame front

Burnt gas

(c): Tube Quenching
TWO APPLICATIONS OF TUBE QUENCHING

- 1 Flashback protection

- 2 Mine lamps
Application 1: flashback protection by a perforated plate - flame arrestors

Flames cannot propagate upstream of this grid

\( U >> sL \)
Useful for a case like this

Careful: this usually works only once!
After a flashback, the flame arrestor may be burnt and not able to work a second time
Application 2: mine lamp

Stephenson Davy 1817
A (nice ?) example of combustion science: premixed, diffusion flames, triple flames and mine’s lamps: explosions in mines

Mine: coal everywhere + gas (lighter than air)

When you have gas (usually CH4) in a mine, you cant work anymore. The boss says it is your fault and he stops paying you... Need to get this gas out!

You cant pump the gas but... you can burn it!
Good and bad methods to burn the gas trapped in the mine:

- **Explosion**: any accidental spark can ignite the gas and lead to an explosion.
<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
<th>Location</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 avril 2007</td>
<td>Mine illégale du village de Liujiacun, comté de Yuxian (Shanxi)</td>
<td>Chine</td>
<td>14</td>
</tr>
<tr>
<td>05 mai 2007</td>
<td>Mine de Pudeng à Linfen, comté de Puxian (Shanxi)</td>
<td>Chine</td>
<td>28</td>
</tr>
<tr>
<td>23 mai 2007</td>
<td>Mine Xinglong, comté de Luxian, ville de Luzhou (Sichuan)</td>
<td>Chine</td>
<td>13</td>
</tr>
<tr>
<td>24 mai 2007</td>
<td>Mine Ioubleïnaïa, à Novokouznetsk (Sibérie)</td>
<td>Russie</td>
<td>38</td>
</tr>
<tr>
<td>04 juin 2007</td>
<td>Mine de Niheling, comté de Jingle (Shanxi)</td>
<td>Chine</td>
<td>13</td>
</tr>
<tr>
<td>25 juin 2007</td>
<td>Mine Komsomolskaïa à Vorkouta (Russie)</td>
<td>Russie</td>
<td>11</td>
</tr>
<tr>
<td>08 novembre 2007</td>
<td>Mine de Qunli, province de Guizhou</td>
<td>Chine</td>
<td>32</td>
</tr>
<tr>
<td>18 novembre 2007</td>
<td>Mine de Zasyadko (oblast de Donetsk)</td>
<td>Ukraine</td>
<td>101</td>
</tr>
<tr>
<td>06 décembre 2007</td>
<td>Mine au nord de la Chine</td>
<td>Chine</td>
<td>environ 100</td>
</tr>
<tr>
<td>22 février 2009</td>
<td>Mine de Tunlan (Shanxi)</td>
<td>Chine</td>
<td>73</td>
</tr>
<tr>
<td>21 novembre 2009</td>
<td>Houillère de Hegang dans la province chinoise du Heilongjiang</td>
<td>Chine</td>
<td>au moins 104</td>
</tr>
<tr>
<td>23 février 2010</td>
<td>Mine d’Odakliy dans la province turque de Balikesir</td>
<td>Turquie</td>
<td>29</td>
</tr>
<tr>
<td>05 avril 2010</td>
<td>Mine d’Upper Big Branch, dans l’état de Virginie</td>
<td>États-Unis</td>
<td>29</td>
</tr>
<tr>
<td>16 octobre 2010</td>
<td>Mine de Yuzhou, dans la province de Henan</td>
<td>Chine</td>
<td>au moins 20</td>
</tr>
<tr>
<td>26 janvier 2011</td>
<td>Mine La Preciosa à Sardinata</td>
<td>Colombie</td>
<td>14</td>
</tr>
<tr>
<td>29 octobre 2011</td>
<td>Mine Xiaiuchong à Hengyang</td>
<td>Chine</td>
<td>29</td>
</tr>
<tr>
<td>10 novembre 2011</td>
<td>Mine Shizong province du Hunan</td>
<td>Chine</td>
<td>34</td>
</tr>
</tbody>
</table>
Good and bad methods to burn the gas trapped in the mine:

- BAD: Explosion: any accidental spark can ignite the gas and lead to an explosion.

- GOOD: Controlled combustion: burn the methane «slowly»
If you wait long enough, gas and air will be segregated by gravity.

In this segregated situation, a diffusion flame can burn the fuel slowly and safely.

How can you ignite it?

Solution:
- take the youngest worker
- give him a Davy lamp
- send him (crawling) in the mine
- at the place where there is fuel, remove the grid from the Davy lamp
- stand up and raise hand!
TWO SOLUTIONS

1/ Fuel and air were really segregated. The lamp ignites a triple flame which propagates and leaves a diffusion flame. All the fuel is burnt. No one dies. The mine can start operating again.

2/ Fuel and air were not segregated! In this premixed zone, the lamp ignites a fast premixed flame which might go to detonation. All the fuel is burnt. The young guy dies. The mine can start operating again.

In all cases, it works...
Back to ‘normal’ cases and interaction between walls and flames
To predict the temperature field within the walls:

Fluxes during flame/wall interaction are very high but are usually not a problem for the walls because they are maintained for short times.

Can forget about flame/wall interaction (phase 3) and concentrate on heat transfer during phase 2: the next example corresponds to a case where the wall has to sustain hot burnt gases but no active flame front.
Outline

- Flame wall interactions: general features
- Coupled LES / heat transfer simulations
- Effects of wall temperatures on unsteady flames
Computing the reacting flow or the HPS alone is not enough when one is interested in wall temperatures.

Integrated RANS / LES Computations of a Jet Engine

Stanford University ASC Center
Computing turbine temperatures:

Every day’s life in gas turbine companies: what is the skin temperature of the HPS (high pressure stator)?
This problem cannot be solved by computing the reacting flow in the chamber only. Need to couple this simulation with a computation of the HPS temperature.
COUPLING REQUIRED:

We need a **coupling** of the codes used for the combustion chamber, the turbine and the heat transfer within the solid walls.
COUPLING REQUIRED:

This can be:

- **a weak coupling**: the mean temperatures and velocities at the outlet of the combustor are the inlet temperatures and velocities at the turbine inlet.

- **a strong coupling**: the instantaneous temperatures and velocities at the outlet of the combustor are the inlet temperatures and velocities at the turbine inlet (much more difficult).

Will show examples of weak and strong coupling in following results.
An underlying issue: HPC

None of this is possible without parallel computing

- ANL INTREPID, Bluegene P
- PRACE/TGCC, CURIE, BullX
- GENCI/CINES, JADE, SGI Altix ICE
- PRACE/JSC, JUQUEEN, Bluegene Q
- INCITE/ARNL, INTREPID, Bluegene P
- HLRS/PRACE, HERMIT, CRAY XE6

Ideal performance:

1. 93M Tetrahedra case - 1 step Chemistry - 2 tasks per node
2. 200M Tetrahedra case - 2 step Chemistry
3. 29M Tetrahedra case - 7 step Chemistry
4. 75M Tetrahedra case - No chemistry - 64 tasks per node
5. 75M Tetrahedra case - No chemistry - 4 tasks per node
Coupling makes parallel difficult...

+ Heat transfer

CPUs
Additional question: can we really forget radiation? It depends on the expected precision...:
Which precision is expected in practice?  
The example of the High Pressure Stator

When the HPS temperature goes up:
★ the engine efficiency goes up (can increase pressures and temperatures in the combustor)
★ lifetime of HPS goes down: increasing HPS temperature by 25 K means 50 percent smaller lifetime

★ Need to be precise! (25 K?)
Wall temperature in a High Pressure Stator in a helicopter engine (Turbomeca)
NEED MULTIPHYSICS TOOLS:

- Combustion LES solver AVBP
- Conduction solver AVTP
- Radiation solver PRISSMA
- OpenPALM (open source coupling tool)
Temperature field

UNCOUPLLED SIMULATION
Hot spots produced by the chamber impinging on the High Pressure Stator

UNCOUPLLED SIMULATION
TWO COUPLED SIMULATIONS

A/ ‘TWO CODES’ SIMULATION:
- Combustion
- Conduction

B/ ‘THREE CODES’ SIMULATION:
- Combustion
- Conduction
- Radiation
INSIDE COOLING OF BLADE:

- Normally, blades are cooled through complex air passages

- Here (confidentiality and simplicity) we will assume that blade cooling is much simpler:
Thermal conditions on High Pressure Stator

INSIDE: Imposed convection coefficient ($h$) and cooling temperature ($T_{cooling}$):

$$\phi = h(T_{wall} - T_{cooling})$$

OUTSIDE: coupled computation with LES solver. Law-of-the-wall (Schmitt et al, JFM 2007) for flow and heat transfer + radiative flux
‘TWO-CODES’ SIMULATION (steady state): history of HPS temperatures
Hot (stagnation point)

Hot (trailing edge, not cooled enough)
'THREE-CODES’ SIMULATION: INCLUDING RADIATION

• Radiation changes the HPS temperature field in two ways:

➡ **DIRECT EFFECT:** the HPS ‘sees’ the flame radiation

➡ **INDIRECT EFFECT:** radiation changes the temperature field in the flame zone and therefore the temperature profile of the gases impinging the HPS
RADIATIVE SOURCE TERM:
total=4.8% of total heat release

This means typically 50 K less for outlet temperatures
DIRECT EFFECT: RADIATIVE FLUXES ON WALLS

Strong radiative flux in the combustion chamber

But very limited flux on HPS

DIRECT EFFECT IS NEGLIGIBLE BECAUSE OF THE SPECIFIC SHAPE OF THIS CHAMBER
TEMPERATURES WITHIN BLADE:

At some places, the blade loses heat through radiation towards the cooler walls.

Radiation should be included...
But this is not the only issue:

We have seen that the flame controls the temperature of the walls. However, the wall can also control and change the flame behavior. The last part of this talk will focus on one example: the effect of wall temperature on the response of a flame to acoustic excitation.
Outline

- Flame wall interactions: general features
- Coupled LES / heat transfer simulations
- Effects of wall temperatures on flame transfer functions
Most experimentalists and engineers know that the temperature of the combustor plays a role in thermoacoustics.

This has also been shown using simulations:

- Kaess et al CTR Summer Program. 2008, p. 289

Why? There are zones where the flame is very sensitive to heat losses.
The sensitive zones of a flame: anchoring points
The link between heat transfer and instabilities remains an open issue: is it important but how do we introduce this effect in our models?

Example: the IMFT laminar flame setup, a flame with thermally adjustable walls, designed to study the interaction between walls and flames in terms of thermoacoustics.
THERMALLY CONTROLLED UNSTABLE FLAME

IMFT PhD of D. Mejia

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EVIDENCE OF WALL TEMPERATURE ON CI’S?

CCD Camera
Direct view to visualize flame movement

PM + CH*

TS=320 - 400 K

Side image to visualize temperature field in combustor wall

Laminar Premixed Flame

φ=0.92
U₀=1.6 m/s
P= 0.96 bar
T₀=293 K
Cooling System: OFF
EVIDENCE OF WALL TEMPERATURE ON CI’S?

Laminar Premixed Flame

\[
\begin{align*}
\phi &= 0.92 \\
U_b &= 1.6 \text{ m/s} \\
P &= 0.96 \text{ bar} \\
T_g &= 293 \text{ K}
\end{align*}
\]

Cooling System: OFF

Relative heat release fluctuation

Thermography

\[\begin{array}{c}
\text{Relative heat release fluctuation} \\
\text{with time} [\text{s}]
\end{array}\]
PRESSURE OSCILLATIONS AMPLITUDE vs TIME

\[ p' \text{ [dB]} \]

\[ t \text{ [s]} \]

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THE NEED TO ANALYZE ALL MECHANISMS CONTROLLING INSTABILITIES

- Heat transfer does play a role on instabilities
- Should’nt we care about OTHER mechanisms ?
- Since codes predicting instabilities give a yes/no answer, industry needs to know the precision level we have when we say that a combustor is stable…

![Graph showing stability vs. growth rate](image)
Uncertainty Quantification of simulations of flame transfer functions (FTF)

WHAT IS A COMBUSTION INSTABILITY?

Isocontour of methane

Stable

AIR

CH4

Fuel iso-surface

HR iso-surface

Air

CH4

Fuel iso-surface

HR iso-surface

Unstable

Schmitt et al., J. Fluid Mech. 2007
WHAT ARE FTFs?

- FTFs describe the response of the flame (measured through the total heat release fluctuations $Q'$) to an inlet velocity perturbation $u'$.
WHAT ARE FTFs?

- FTFs depend on the excitation pulsation $\omega$ and are quantified by:

$$F(\omega) = \frac{Q'/\bar{Q}}{u'/\bar{u}}$$

- F is a complex number: a gain $n$ and a delay $\tau$

-> The most important parameter controlling the stability is the FTF delay $\tau$
We need to compute the delay and to know the precision of this computation.
FTFs are essential to predict stability but what does it take to compute them?

Recent observation: too many uncertainties in the prediction of FTFs for turbulent flames. Check the question in a case where you can't blame turbulence: laminar flames. Study FTFs on two \textit{laminar} flame experiments of flames stabilized on plates:

- Conical flames of Boudy/Noiray (JFM 2008)
- Slot Flames of Kornilov (CF 2009)
EXPERIMENTAL SETUPs:

• BOUDY: 49 premixed flames stabilized on cylindrical holes

• KORNILOV: 8 premixed flames stabilized on two dimensional slots
• BOUDY: comparison of reaction rate given by DNS and direct view of flame

• Kornilov: comparison of reaction rate given by DNS and view of radical image in experiment
Effects of the wall temperature on the flame response:

Fields of reaction rate for a forced flame:

FLAME WALL INTERACTION AT THE FLAME BASE CHANGES THE FLAME RESPONSE
 COMPUTED FTF delays successfully

Phase = $2\pi \tau$

Lines = expt, symbols = DNS

Kornilov (slot flames)

Boudy (conical flames)
Computed sensitivity of the FTF delay to five parameters:

1/ Flame speed $s_L$
2/ Flow expansion $\alpha$
3/ Air temperature $T_a$
4/ Inlet duct wall temperature $T_d$
5/ Combustor wall temperature $T_w$
Certain parameters do NOT play a significant role: for ex. radiation from the flame to the walls.

Start from fully coupled DNS of flame and heat transfer in plate.

Use radiative solver to obtain heat flux on plate:

- **Radiative flux**
  - (max=15 000 W/m², min=13 000 W/m²)

- **Convective flux**
  - (max=100 000 W/m², min=20 000 W/m²)
Sensitivity results for the FTF delay $\tau$:

Sensitivity to parameters for each frequency:

- Inlet duct wall temperature $T_d$
- Air temperature
- Combustor wall
- Flame speed $s_i$
- Flow expansion $\alpha$
- $100$ Hz
- $200$ Hz
- $300$ Hz
- $400$ Hz
- $500$ Hz
- $600$ Hz

Graphical representation showing sensitivity to parameters $S_L$, $\alpha$, $T_a$, $T_d$, and $T_w$ for each frequency.
Sensitivity averaged on all frequencies

Averaged sensitivity to parameters:

1/ Flame speed $s_L$
2/ Flow expansion $\alpha$
3/ Air temperature $T_a$
4/ Inlet duct wall temperature $T_d$
5/ Combustor wall $T_w$
To compute the FTF of a laminar flame, focus on:

- the model for flame speed
- the inlet duct temperature
- the wall temperature

Can forget:
- radiation
- inlet air temperature
- flow expansion

1/ Flame speed $s_L$

2/ Flow expansion $\alpha$

3/ Air temperature $T_a$

4/ Inlet duct wall temperature $T_d$

5/ Combustor wall temperature $T_w$

--> KINETICS

--> DUAL HEAT TRANSFER
• The interaction between flames and walls can be computed rather simply for inert walls
• The strongest effect of the flame on the walls temperature is through the burnt gas, not through flame wall interaction
• The response of flames to acoustic forcing depends on the wall temperatures
• Dual heat transfer / flame simulations are needed.