Flame / wall interactions in combustion chambers

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FLAMES AND WALLS: WHY DO WE CARE?

FLAMES → WALLS → POLLUTANTS

INSTABILITIES ← ACOUSTICS

Ch. 7
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**
Which walls?

Aero-engine combustor sector

Which walls?

Developed surface

High Pressure Stator walls

Chamber walls

Temperature

800 1750 2700

1275 2225

PERIODIC

20°
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

![Diagram showing cooling air, combustion products, and flame.]
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)
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)

Flame position

Heat flux

Flame speed

Maximum heat flux through the wall

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 Φ MW/m²</th>
<th>Reduced flux F</th>
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</thead>
<tbody>
<tr>
<td>Wichman &amp; Bruneaux</td>
<td>$P + O \rightarrow P$</td>
<td>Theory</td>
<td>Simple</td>
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<td>$P + O \rightarrow P$</td>
<td>DNS</td>
<td>Simple</td>
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<td>CH₄/air - 1 bar</td>
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<td>Complex</td>
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</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...)

Simple scaling for minimum distance between flame and wall

$$P = \frac{y}{\delta}$$

$$P_Q = 3.4$$

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

ANOTHER INTERESTING FLAME WALL INTERACTION CASE: Tube 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.
MEASUREMENTS OF QUENCHING DIAMETER IN TUBES

Lewis and von Elbe, 1987

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

Useful for a case like this

Careful: works only once!
A (nice ?) example of combustion science: premixed, diffusion flames, triple flames and mine’s lamps: explosions in mines

When you have gas (usually CH4) in a mine, you can’t work anymore. The boss says it is your fault and he stops paying you... Need to get this gas out!

You can’t 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.

- **Controlled combustion**: burn the methane «slowly»

### BAD WAY: EXPLOSIONS IN MINES:

<table>
<thead>
<tr>
<th>Date</th>
<th>Location Description</th>
<th>Country</th>
<th>Death Toll</th>
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<tr>
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<td>Mine Xinglong, comté de Luxian, ville de Lushan (Sichuan)</td>
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<tr>
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<td>Mine Ioubienina, à Novokouznetsk (Sibérie)</td>
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<tr>
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<td>Mine de Niheling, comté de Jingle (Shaanxi)</td>
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<td>13</td>
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<tr>
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<td>Mine Komsomolskaia à Yerkoula (Russie)</td>
<td>Russie</td>
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</tr>
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<tr>
<td>18 novembre 2007</td>
<td>Mine de Zasyadko (oblast de Donetsk)</td>
<td>Ukraine</td>
<td>101</td>
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<tr>
<td>06 décembre 2007</td>
<td>Mine au nord de la Chine</td>
<td>Chine</td>
<td>environ 100</td>
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<tr>
<td>22 février 2009</td>
<td>Mine de Tunian (Shaanxi)</td>
<td>Chine</td>
<td>73</td>
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<tr>
<td>21 novembre 2009</td>
<td>Houillère de Huating 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’Otkiady dans la province turque de Balkiiskaie</td>
<td>Chine</td>
<td></td>
</tr>
<tr>
<td>06 avril 2010</td>
<td>Mine d’Upper Big Branch, dans l’État de Virginie</td>
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<tr>
<td>16 octobre 2010</td>
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<td>Chine</td>
<td>au moins 20</td>
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<tr>
<td>25 janvier 2011</td>
<td>Mine La Preciosa à Bardineta</td>
<td>Colombie</td>
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</tr>
<tr>
<td>29 octobre 2011</td>
<td>Mine Xiaoluchang à Hangyang</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>
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

CONTEXT: Towards coupled simulations in gas turbines

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

Additional difficulty: can we forget about radiation?

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
None of this is possible without parallel computing.

An underlying issue: HPC

But coupling makes parallel difficult...

+ Heat transfer

CPUs
COMPUTING TURBINE TEMPERATURE:

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?)
Two examples of coupled LES / heat transfer simulations:

1 - Temperature field within a laboratory blade (Von Karmann Institute): lab scale experiment with small temperature differences -> to check precision of LES coupled to heat transfer

2 - Wall temperature within a High Pressure Stator in a helicopter engine (Turbomeca): real engine data -> to predict the lifetime of the HPS

VKI blade cooling:

• Specific experiment to measure blade temperature
• Experimental data available... (Cp, temperature at pressure side) for a cooled blade (300 K) in a 330 K flow: EC Project AITEB 2

Difficult test case: the cooling air injected inside is ejected from the blade to mix with the hot air and protect the walls (similar to effusion but with larger holes)

Field of mixture fraction between the two streams:

Pole T120D
Re = 390000
Mach 0.87 bord de fuite
Contours d'azote du plenum

Time: 0.070371 s
Field of density gradients

Profiles on isentropic Mach number on blade:
DUAL HEAT TRANSFER:

• USUAL COUPLED SIMULATIONS CORRESPOND TO RANS + HEAT TRANSFER: BOTH CODES RUN IN STEADY MODES

• HERE WE NEED TO COUPLE LES AND HEAT TRANSFER. TO GO TO STEADY STATE, THIS RAISES A NEW PROBLEM:

LOCAL HEAT FLUX (LES) VS TIME

HEAT TRANSFER SOLVER

Need to adjust averaging time in LES between two coupling events with the heat transfer solver

Coupling solvers -> steady state

Compute the flow for $\alpha_f$ flow-through time (using imposed $T$ on walls)
Obtain fluxes
Impose fluxes on solid skin

Compute the solid for $\alpha_s$ solid characteristic time (using imposed fluxes on walls)
Obtain skin temperatures
Impose temperatures on fluid BC

$\alpha_s$ and $\alpha_f$ of order unity

Note: The solid time scale is $o(10s)$, the fluid time scale is $o(1 ms)$. We solve only for the steady state solution: This is a weakly coupled problem.
Heat fluxes on the blade:

Time / solid time

Total flux

Temperature evolution

Pressure side -->
Flow cooling efficiency $FCE = \frac{(T_{air} - T)}{(T_{air} - T_{cooling})}$:

FCEs are averaged over the span of the blade.

Unsteady interaction of a hot spot with the blade

A pocket of hot gases is injected in the main air. The question is: What is the maximum temperature reached in the blade during the interaction? This is a **fully coupled** problem.
Flames produced in real combustors will produce such hot/cold pockets with very large gradients.

There is only one method to take these into account: compute the combustor and the HPS simultaneously.

Wall temperature in a High Pressure Stator in a helicopter engine (Turbomeca)
CONFIGURATION: Helicopter engine

Air → Kerosene → High Pressure Stator

NEED MULTIPHYSICS TOOLS:

- Combustion LES solver AVBP
- Conduction solver AVTP
- Radiation solver PRISSMA
- O-PALM (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
- Radiation
- Conduction

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
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:
\[ \text{total} = 4.8\% \text{ of total heat release} \]

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
INDIRECT EFFECT

MAXIMUM TEMPERATURE

With radiation
Without radiation

MEAN TEMPERATURE

With radiation
Without radiation

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
WALLS CHANGE THE DYNAMICS OF FLAMES

- 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 and 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.
EVIDENCE OF WALL TEMPERATURE ON CI's?

Laminar Premixed Flame

$\phi = 0.92$
$U = 1.6 \text{ m/s}$
$P = 0.96 \text{ bar}$
$T_0 = 293 \text{ K}$

Cooling System: OFF

Relative heat release fluctuation

Thermography

Cooling System
$T_2 \text{O}_2 = 1 - 95 \text{ °C}$

$T_s = 320 - 400 \text{ K}$
PRESSURE OSCILLATIONS AMPLITUDE VERSUS TIME

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DNS of the effects of combustor wall temperature on flame transfer functions (FTF)
WHAT IS A COMBUSTION INSTABILITY?

Stable vs. Unstable

Isocontour of methane

AIR

CH4

AIR

CH4

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 $u'$

Temperature field

$u'(t)$

$u$ (m/s)

$Q$ (Watts)
**WHAT ARE FTFs?**

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

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

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

-> The most important parameter controlling the stability is the FTF delay $\tau$

---

**UNCERTAINTY QUANTIFICATION**

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 *laminar* flame experiments of flames stabilized on plates:

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

In both cases, strong flame / wall interactions at the flame base control the FTF.

**EXPERIMENTAL SETUPs:**

- **BOUDY:** 49 premixed flames stabilized on cylindrical holes

- **KORNILOV:** 8 premixed flames stabilized on two dimensional slots
STEADY FLAMES

• **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 CHANGE THE FLAME RESPONSE**
COMPUTED FTF delays successfully

$\text{Frequency (Hz)}$

$\text{Phase} = 2\pi \tau$

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 $\tau$:
1. Flame speed $s_L$
2. Flow expansion $\alpha$
3. Air temperature $T_a$
4. Inlet duct wall temperature $T_d$
5. Combustor wall

Sensitivity to parameters for each frequency:

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>$s_L$</th>
<th>$\alpha$</th>
<th>$T_a$</th>
<th>$T_d$</th>
<th>$T_w$</th>
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</thead>
<tbody>
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</table>
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

--> KINETICS
--> DUAL HEAT TRANSFER
CONCLUSIONS

- 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.