Bifurcations in combustors

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We hope (expect ?) flames to depend on a limited number of parameters

Fuel:
- Flow rate
- Temperature

Air:
- Flow rate
- Temperature

Pilot Gas Nozzle
In practice, there are hidden parameters:

Fuel:
- Flow rate
- Temperature

Air:
- Flow rate
- Temperature

Wall Temperatures?
Time?
Humidity of air
Leaks
Composition
Etc...

Combustor ‘variability’

Quite often, combustors exhibit variability phenomena which are difficult to master:
- Most of them are due to ‘uncontrolled’ parameters which change and which we can’t control
- But even when all input parameters are well controlled, the flow itself may exhibit multiple ‘states’. Bifurcations are possible

INPUT PARAMETERS

FLAME

Efficiency
Pollutants
Thermoacoustics

‘STATE’
The ‘transition’ from one state to another is required to reach full power without excessive instability.
Swirling flows: make bifurcations more likely

Swirling flows exhibit multiple instabilities.

They also exhibit bifurcations: multiple states can be obtained for the same flow conditions: true with and without combustion

The experiment of Vanierschot:

Increasing swirl:

S=0
S=0.33
S=0.4
d  
\[ S = 0.56 \]  

\[ S = 0.69 \]  

\[ S = 0.9 \] 

g  
\[ S = 0.56 \]  

\[ S = 0.5 \]  

\[ S = 0.0 \]
TWO FLOW STATES FOR THE SAME SWIRL:

$S = 0.56$

when $S$ increases

$S = 0.56$

when $S$ decreases

PRESSURE LOSSES ALSO SHOW HYSTERESIS PATTERN:
Bifurcating flame in an industrial gas turbine

- Two dynamic phenomena already discussed in swirled confined flames: the Precessing Vortex Core (PVC)\textsuperscript{[1,2]}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{flame_image.png}
\end{figure}


2 - Thermo-acoustic instabilities \textsuperscript{[3,4,5]}

- Resonant feedback between combustion and acoustic waves

\begin{figure}
\centering
\begin{tikzpicture}
\node [align=center] at (0,0) {Heat release oscillations};
\node [align=center] at (2,0) {Acoustic oscillations};
\node [align=center] at (0,-1) {Flow and mixture perturbations};
\end{tikzpicture}
\end{figure}

Is there a link between PVC and instabilities?

- PVC and combustion
  - The PVC can interact with the flame \[14,15\]
  - Combustion can suppress the PVC \[16,17,18\]

- PVC and combustion instabilities
  - The PVC can provoke thermo-acoustic instabilities \[16\]
  - Acoustic oscillations can suppress the PVC \[14,15\]


The link between PVC and thermoacoustics can also be more complex:

- The swirled flow can be bistable, leading to the existence of two states for the same regime
- This leads to:
  - Different mean flows
  - Different stability behaviors
  - The flame can switch from one state to another (with changing fuel rate or acoustic oscillations) and trigger bifurcations
Target configuration

- Heavy-duty industrial gas turbine
  - Power ~300 MW
  - Reynolds number > 1,000,000

Annular combustion chamber [19]  LES of one sector

[19] Ansaldo Energia
Target configuration

Burner
4 air inlets 2 CH₄ inlets

Film cooling
Diagonal swirler
Axial swirler
Lance cooling
Pilot gas nozzle
Premixing gas nozzle

Operating conditions

- Lean combustion
- High pressure (p > 15 bar)
- High Reynolds number (Re > 1.000.000)

Mesh & Boundary conditions

- Computational grid: 10.5 M tetrahedral elements
- Boundary conditions:
  - All inlets and the outlet: NSCBC formulation [20]
  - Chamber side walls: Axi-periodic
  - All other walls: logarithmic wall-law [21]

The flame has two stable positions: it is **bistable**
Mean reacting flow fields: temperature

- **Attached case**
  - High temperature at the lance due to pilot injection

- **Detached case**
  - More uniform temperature distribution

Mean reacting flow fields: velocity

- **Attached case**
  - High velocities at the burner exit: the flame reduces the section
  - Two recirculation zones

- **Detached case**
  - Lower velocities at burner exit
  - Inner recirculation zone not closed
Temperature profiles

Axial velocity profiles
Radial velocity profiles

\[ U_{rad} = \frac{v \cdot r}{|r|} \]

Tangential velocity profiles

\[ U_{tang} = \frac{v \times r}{|r|} \]
Turbulent kinetic energy profiles

\[ k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \]

RMS temperature profiles

- Detached flame: RMS temperature higher over a wider range
- This suggests that NO production would differ.
**Instantaneous reacting flow fields**

- **Attached case**
  - No PVC present

- **Detached case**
  - Strong PVC turning around a ‘finger-like’ flame structure
  - PVC explains strong values of $k$

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**How is forcing applied?**

- Sinusoidal modulation of the ingoing acoustic wave at the diagonal swirler [29]
- Small forcing amplitude
- Four forcing frequencies $f_1 < \ldots < f_4$

\[
F(\omega) = \frac{\hat{q}(\omega)}{\bar{u}(\omega)} \frac{\hat{u}(\omega)}{\bar{u}} = n e^{-i\omega \tau}
\]

Pulsating the *detached* flame at small amplitudes:
Flame Transfer Function

- Detached flame: higher gain and lower phase response
- Predicting stability will lead to different conclusions

![Flame Transfer Function Diagram](image)

Bifurcation: change in fuel flow rate

- The pilot flame is known to have a strong influence on the flame stabilization.
- Is it possible to change the flow state by increasing or decreasing the fuel flow rate in the pilot flame?

- Define pilot fuel ratio \( pfr \):

\[
pfr = \frac{\text{Pilot fuel flow rate}}{\text{Reference value}}
\]

- Increase \( pfr \) from 1 to 4, starting either from Attached or Detached Flame

![Bifurcation Image](image)
Attached flame - increasing the pilot flame flow rate:

- Detached flame remains detached with increasing OR decreasing pilot fuel mass flow rate
- Attached flame detaches with decreasing pfr and for pfr=4.0 (previous movie)
**Bifurcation: effects of pulsation**

- If we ‘shake’ these flames sufficiently (for example during a combustion instability), is it possible for the flame to change state?

- *Start from Attached or Detached unforced state and force the combustor with increasingly larger acoustic waves (up to 45 % of the mean flow speed)*

- *See whether the flame state can change*

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**Attached flame: pulsation amplitude 45 % at f_4**
Detached flame: pulsation amplitude 45% at $f_4$
Bifurcation: change of the pulsation amplitude at $f_4$

- Detached flame reattaches with increasing forcing amplitude
- Attached flame remains attached

### Conclusion

- In certain chambers, the flame can have different states with very different mean flows, performances and pollution levels
- The FTFs between the two states also differ suggesting different thermoacoustic effects
- The transition between the two states observed in the present gas turbine can be triggered by changing:
  - The pilot fuel rate
  - The forcing amplitude
- This can explain complex behaviours observed in gas turbines where the flame may trigger different acoustic responses for the same regime.