Combustion dynamics of inverted conical flames

Confined flames
- Combustion chambers
- Gas turbine combustors

Unconfined flames
- Domestic burners
- Radiant burners

Low emission systems operating in premixed lean modes. Flames are less well stabilized and more susceptible to external perturbations.
**Experimental set-up**

For certain flow conditions, equivalence ratios and geometry

**Self-induced Instability**

Self-excited flame
at $f = 172$ Hz
Eq. Ratio : 0.92
Flow velocity : 2.05 m/s
$\nu' = 0.14$ m/s
Transfer function

\[
\frac{\Delta Q}{Q} = f\left(\frac{\Delta v}{v}\right)
\]

Self-excited flame
at \( f = 100 \) Hz
Eq. ratio : 0.92
Flow velocity : 2.05 m/s
\( v' = 0.14 \) m/s

Describing function

\( \Phi = 0.92 \quad V_d = 2.05 \) m/s

\( \varphi \) is nearly linear
convective lag
\( \tau_c = 8.6 \) ms

\[
I'_{CH^*}(t) = G[v'_1]t - \tau_c
\]
Flame dynamics

Laser tomography of fresh stream seeded with oil droplets.

\[ f = 70 \text{ Hz} \]

\[ \Phi = 0.8 \]
\[ V_d = 1.87 \text{ m/s} \]
\[ v'_1 = 0.15 \text{ m/s} \]

Flame dynamics

\[ f = 150 \text{ Hz} \]

\[ \Phi = 0.8 \]
\[ V_d = 1.87 \text{ m/s} \]
\[ v'_1 = 0.15 \text{ m/s} \]
Unsteady vorticity field

The vortices are convected at a velocity \( U_c \approx 0.5v_{max} \)

Helmholtz resonator
Bulk oscillation inside the burner

Mechanism of instability

 Bulk oscillation inside the burner

Mechanism of instability

Helmholtz resonator
Bulk oscillation inside the burner

Mechanism of instability
Mechanism of instability

Helmholtz resonator with driving

\[ M \frac{d^2v'_1}{dt^2} + R \frac{dv'_1}{dt} + kv'_1 = -S_1 \frac{dp'_1}{dt} \]

\[ M = \bar{\rho}S_1 L_{eff} \]

Effective mass of gases

\[ R = \bar{\rho}S_1 v_1 \]

System damping

\[ k = \bar{\rho}c^2 S_1^2 / V \]

Stiffness of the gas volume

The resonator is driven by external fluctuations \( p'_1 \)

Signals measured in self-sustained instability case

\[ \Phi = 0.92 \quad V_d = 2.05 \text{ m/s} \quad v'_1 = 0.14 \text{ m/s} \quad f = 172 \text{ Hz} \]

\[ p'_1(t) \approx B \left[ I_{CH^*} \right]_{t-\tau_a} \]

\[ p'_1(t) \approx E \left[ \frac{dQ'}{dt} \right]_{t-\tau_a} \]
**Mechanism of instability**

\[ I'_{CH*}(t) = G[v_1']t - \tau_c \]

\[ p'_1(t) = B[I'_{CH*}](t - \tau_a) \]

Time lag model

**Steady flow streamlines**

Average location of the flame front in the absence of perturbation

Averaged image of the flame front positions with a perturbation at 70 Hz

\[ v'_1 = 0.15 \text{ m/s} \]

\[ f = 70 \text{ Hz} \]

\[ \Phi = 0.8 \]

\[ V_d = 1.87 \text{ m/s} \]

The dot corresponds to

\[ h = \tau_c U_c \simeq \tau_c(0.5v_{max}) \]

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Mechanism of instability

\[ M \frac{d^2 v_1'}{dt^2} + R \frac{dv_1'}{dt} + kv_1' = -S_1 \frac{dp_1'}{dt} \]

\[ p_1'(t) = B[I_{CH*}'(t-t_\alpha)] \]

\[ I_{CH*}'(t) = G[v_1'(t)] \]

\[ \omega_0^2 = \frac{S_1 c^2}{V L_e} \quad 2\delta \omega_0 = \frac{R}{M} \]

\[ \Omega = \frac{GBS_1}{M} \]

If \( \delta \) and \( \Omega \) are small, a linear analysis indicates that a necessary condition to have an instability is:

\[ \omega_0 \tau \text{ belongs to } [\pi/2, 3\pi/2] \text{ modulo } 2\pi \]
Mechanism of instability

Frequency peak at the resonance

- $v' = 0.14 \text{ m/s}$
- $v' = 0.20 \text{ m/s}$
- $v' = 0.30 \text{ m/s}$
- $v' = 0.38 \text{ m/s}$

Instability frequency $f = 172 \text{ Hz}$

Gain

Phase Difference (rad)

$\Phi = 0.92 \quad V_d = 2.05 \text{ m/s}$

Conclusions

- ICF's are sensitive to low frequency acoustic excitations.
- They behave like an amplifier in a broad frequency range.
- The transfer function phase grows linearly: the process involves a convective delay.
- The main wrinkling of the flame front is due to vortex structures created in the shear layer.
- The strong rolling-up of the flame induces a mutual annihilation of neighboring reactive elements:
  - Rapid variation of flame surface area
  - Important source of pressure wave.
- With ICF's, at low amplitude modulation, entrainment of air modifies the equivalence ratio near the flame tip and the light emission ceases to be proportional to the heat release.