Friday: Combustion instabilities (growl) and extinction

Turbulent Combustion
Experiments and Fundamental Models

J. F. Driscoll, University of Michigan

R. Sankaran, E. Hawkes, Jackie Chen T. Lu, C. K. Law premixed

Bell, Day, Driscoll “corrugated” premixed
Outline for the week

Mon: **Physical concepts** faster mixing, faster propagation, optimize liftoff, flame surface density, reaction rate, PDF

Tues: **Kilohertz PLIF, PIV measurements of flame structure** - to assess models

Wed: **Non-Premixed and Premixed flames** - measurements, models gas turbine example

Thurs: **Partially premixed flames** - and some examples

Fri: **Future challenges**: Combustion Instabilities (Growl), Extinction
Some Future Challenges

Tradeoff: low NOx (partially premixed) versus combustion instabilities (growl

Biggest driver in jet engine industry is still NOx -

total fuel flow and air flow is fixed, cannot change
can change location where fuel is injected – staged combustion,
can change location of flame: lifted = more partially premixed

Auto industry: turbo diesel, HCCI, some variation of HCCI?

Predict and understand flame liftoff, flame blowout

Model and understand premixed flame turbulent burning velocity, role of integral scale

Understand and model complex fuels such as Jet – A, liquid synfuels or syngas

Spray combustion – DNS of dense spray formation (!)
V. Le Chenadec, Atomiz and Sprays 23, 12, p. 1139

Umemura, A.
PROCI 35, 1595
Combustion Instabilities ⇒ in partially premixed GT

PPC improves NOx but triggers combustion instabilities (growl)

Avoid Combustion Instability

what is the lean limit?
effects of high pressure and swirl?

Fuel flexibility

differences between natural gas, syngas, propane, ethylene, higher HC

Advantage of partially-premixed

some flame liftoff is good

Reduce NOx

with lean, partially-premixed combustion in swirl burner

lean
Base of a lifted non-premixed jet flame - is partially-premixed

DNS of Mizobuchi, Takeno
red = rich premix, blue = lean premix
green = non-premix
PROCI 30, 2005

Base of a lifted Swirl flame in a gas turbine combustor

Premixed and non-premixed flamelets
Rosenberg, Driscoll
Comb Flame 162, 2808
Tradeoffs: Lean $\rightarrow$ lower NOx but combustion instability

Graph showing NOx emissions (PPM) and Pressure Oscillations (kPa) vs. Equivalence ratio for 0% and 50% hydrogen. Sanusi, et al. J. Energy Res. 2015

Graph showing Pressure RMS (kPa) vs. Equivalence Ratio. Gutmark, J. Sound Vibr. 2008
2. Problem: NOx and combustion instability

a) We cannot predict how lean - before the beginning of instability - instability occurs when damping less than driving mechanism

b) What is the physical mechanism causing instability?
   Standing waves? Helmholtz? Vortex shedding?

c) CFD of instability not yet satisfactory (V. Yang, Menon, Ihme)
   Reduced model can be done (Lieuwen, Ghoniem)

d) What measurements needed to improve the model?
   → kilohertz imaging of flame, flow velocity
Research issue: scaling laws for larger/smaller combustors

Cylindrical combustor
Fuel injector
Flow Straightener
Quartz windows

400 kW, air flow = 0.25 kg/s
15 atm. pressure
700 K preheated air
syngas, natural gas, Jet-A fuel
Lean premixed technology
Michigan large GT combustor - 80 Hz growl

Steady

Engine “Growl”

Temme, Driscoll, PROCI 33, 2011
Combust. Flame 2014
Unstable - when flame base is lifted too far

GE TAPS
Measured frequencies

Power  Spectral density

Pressure  Liftoff height  Flame intensity

0  100  200  300  Frequency  Hz

0  -5  -15  -25
Michigan experiment #2    GTMC of Meier, DLR

Fuel type
- Methane
- Propane
- Ethylene
- Syngas 10% H₂
- Syngas 15% H₂
- Syngas 20% H₂

Laminar flame speed cm/s

Frequency Hz

Air velocity

Frequency Hz
What is the physical mechanism causing growl?

Organ tones = standing waves?
Helmholtz resonance?
Vortex shedding?
Fuel feed line instability?

U. Cambridge
Ecole Centrale Paris
Georgia Tech
U. Michigan
Proof that “growl” is a Helmholtz resonance

\[ C = \frac{1}{T} \int_0^T \frac{p'(x)}{p_{rms}(x)} \frac{p'(x + \Delta x)}{p'_{rms}(x + \Delta x)} \, dt \]

only a Helmholtz resonator has this correlation function

\[ f = \frac{c}{2\pi} \sqrt{\frac{A}{V L}} \]

Measured \( f \sim \frac{1}{\sqrt{V}} \)
What is the physical mechanism causing growl?

Helmholtz resonator but with a flame “forcing function”

Flame Attached

Vortex Puff
- flame lifted
- combustor pressure rises
- orifice velocity +

Liftoff region fills with reactants

Flame flashback acts like a piston
- combustor pressure decreases
- orifice velocity negative
Helmholtz resonator = simple harmonic oscillator = 2\textsuperscript{nd} order ODE

Conservation of mass, energy and momentum

\[
V \frac{d \rho_c}{dt} = \dot{m}_i - \dot{m}_e \\
V \frac{d(\rho_c e_c)}{dt} = \dot{m}_i \left(h_i + \frac{u_i^2}{2}\right) - \dot{m}_e \left(h_e + \frac{u_e^2}{2}\right)
\]

\[
\rho_i \frac{\partial u'_i}{\partial t} + \frac{p'_i - p'_0}{L_1} = 0
\]

Convert density ($\rho$) to pressure using $\rho = p / RT$
Convert energy to temperature using $e_2 - e_1 = c_v (T_2 - T_1)$
Combine conservation equation $\Rightarrow$ eliminate velocity, get 2\textsuperscript{nd} order ODE for $p'$

\[
\frac{d^2 p'_c}{dt^2} + 2 \zeta \frac{dp'_c}{dt} + \omega_c^2 p'_c = 0
\]

Harmonic oscillator with damping $\zeta$ and natural frequency

\[
\omega_c = c \left(\frac{A}{V L}\right)^{1/2}
\]
Plenum volume + combustor volume + a flame = DRIVEN harmonic oscillator = two coupled differential equations

\[ \frac{d^2 P'_0}{dt^2} + 2\zeta_0 \cdot \omega_0 \cdot \frac{dP'_0}{dt} + \omega_0^2 \cdot P'_0 = \omega_0^2 \cdot P'_2, \]

\[ \frac{d^2 P'_2}{dt^2} + 2\zeta_2 \cdot \omega_2 \cdot \frac{dP'_2}{dt} + \omega_2^2 \cdot P'_2 = \frac{\gamma_b - 1}{V_2} \cdot \frac{dQ'}{dt}, \]

which submodel for heat release is best?

A. \( p'(t - \tau) \)
B. \( d\frac{p'}{dt} \)
C. \( d^2\frac{p'}{dt^2} \)
Three key questions

1. When is acoustic damping term overcome by forcing term? Instability first occurs.

2. What is damping term?

3. Which submodel best for heat release term?

\[ \frac{d^2 P'_0}{dt^2} + 2\zeta_0 \cdot \omega_0 \cdot \frac{dP'_0}{dt} + \omega_0^2 \cdot P'_0 = \omega_0^2 \cdot P'_2, \]

\[ \frac{d^2 P'_2}{dt^2} + 2\zeta_2 \cdot \omega_2 \cdot \frac{dP'_2}{dt} + \omega_2^2 \cdot P'_2 = \frac{\gamma_b - 1}{V_2} \cdot \frac{d\dot{Q}'}{dt} \]

\[ \frac{d\dot{Q}'}{dt} \sim \frac{d p'/dt}{dt}, \]

A: \( p'(t - \tau) \)

B: \( d p'/dt \)

C: \( d^2 p'/dt^2 \)
What kilohertz laser measurements - to answer three key questions?

1. **spectrum** of flame surface density oscillations – kHz PLIF

2. **spectrum** of velocity fluctuations kHz PIV

3. **phase angle** of pressure - heat release (Rayleigh index)

4. **phase angle** of velocity – heat release (phase avg PIV)

5. **time delay** $\tau$ is it convective time $h / U$ ?

6. which of three submodels of heat release term is best ?

7. what is the acoustic damping ?
Measure phase-averaged velocity

air velocity pulses with pressure phase angle
Measured phase angle of heat release rate

Phase angle of velocity oscillations

Phase angle of heat release (Rayleigh index)

air velocity oscillations

from PIV

from kilohertz PLIF
Measured phase angles - compare to theory

Conclude: submodel “A” for heat release term gives good agreement with measured frequencies, phase angles
Measure phase angle of heat release with kHz PLIF.

Quantronix Hawk laser 355 nm 4,000 /sec

Phantom v711 camera
Flame and pressure - have periodic oscillations
Flame surface density - from kHz formaldehyde PLIF

spectrum of flame surface density oscillations

mean flame surface density
Chemiluminescence - pulsing at 310 Hz
Rayleigh criterion – we must know where flame is located

Formaldehyde gradient
flame surface density

Velocity (PIV)
Measurements determine the best submodel

\[ \frac{d^2 p'}{dt^2} + 2 \zeta \omega_0 \frac{dp'}{dt} + \omega_0^2 p' = \beta p'(t - \tau) \]

damped harmonic oscillator

submodel A = best for heat release fluct.

Model Predicts:

\[ f \sim \frac{1}{\tau} = \frac{S_L}{L_1} + \frac{U}{L_2} + \frac{a}{L_2} \]

Flame speed
Gas velocity
Speed of sound

Solution to this ODE is in agreement with our measurements

Allison et al.
PROCI 35, 2014
Model explains several of the measured trends.
Lean premixed combustion is important for the future low NOx, CO, soot; power from natural gas, synfuel

“Growl” combustion instabilities depend on:
  fuel type, flame speed, fuel-air, flow velocity, pressure, geometry syngas instability more likely and more severe (for H₂ < 20%)

Model was developed for one simple geometry
  measured phase angles, damping, heat release, spectra, kHz PLIF model predicts measured trends

Still need:
  CFD-LES for realistic geometries
  Predict onset of instabilities
Ways to avoid instabilities - to reduce NOx by operating leaner

• Anchor - the premixed “main” flame better, more H₂

• Change the location of fuel injection

• Add friction - (damping, Δp) to smallest air orifices

• Alter wall geometry to avoid acoustic resonance
What causes distributed reactions?

HCCI: Alden
zero mean velocity
large residence time
preheated reactants
fully distributed

GT Combustor: Meier
small mean velocity = merging
large residence time
preheated reactants
flamelets + distributed

MILD combustion – Industrial furnace
Preheated reactants
strong recirculation
large residence time
fully distributed?
Are distributed reactions at High Reynolds number?

Large Karlovitz number 
\( \left( \frac{u'}{\lambda_1} \right) \)
Large u’ but 
Small integral scales

Broken Flamlets?

Klimov-Williams

Large Reynolds number

\( \text{Re}_T = \frac{u' \lambda_1}{\nu} \)
Large u’ and 
Large integral scales

Distributed Reactions?

Turbulence integral scale 
\( \lambda_1 / \delta_{\text{flame}} \)

Turbulence intensity

corregated flamelets

thin flamelets

thick preheat
How to achieve “distributed reaction zones”

Cannot use room Temp. reactants - flame extinguishes before eddies enter reaction zone

1. HCCI: use piston to rapidly heat to $T > T_{ig}$

2. Highly pre-heated burners:
   - Preheat air to $T > T_{ig}$, rapidly mix in fuel
   - Create large strain to lift flame for good premixing

Examples: Berkeley Cabra burner

Ramjet: jet in preheated crossflow

![Diagram showing flame and reaction zones](image-url)
Are “broken” and “distributed” regimes related?

broken flamelets → allow reactants to mix with products
→ promotes distributed reactions?
A. Many Previous Turbulent Premixed Flame Studies

- Low reactant temperature $T_R$
- No stratification of react. or prod. no entrained air, large co-flow
- Short resid. time (Bunsen base)
- Densely packed flamelets [4]
- Continuous corrugated flamelets [1-3]

B. Partial Premixing

- Stratified products or reactants by air entrainment or partial premixing
- Short resid. time base of lifted partially premixed
- Broken flamelets [5-10]
- Broken and partially distrib. [7,11-14]
- Long resid. time swirl flame, Bunsen tip, jet tip
C. Engine-like conditions

B. Preheated $T_R$, just below $T_{ig}$
- no stratification of react. or prod. no entrained air
- stratified products or reactants
- short resid. time (Bunsen, jet)
- long resid. time well-stirred reactor
- long resid. time (recirculation = gas turbine, MILD)
- continuous corrugated flamelets?
- densely packed flamelets and part. distrib.?
- broken and partially distributed?

D. Shock tube Studies
C. Highly preheated $T_R > T_{ig}$
- shock tube or HCCI
- Fully Distributed Reactions [15-18]
MILD / flameless combustion regimes

Wunning and Wunning

FLAMELESS OXIDATION TO REDUCE THERMAL NO-FORMATION

MILD COMBUSTION, Antonio Cavaliere, Prog. Energy Combust Sci 30, 329

temperature peaks can be avoided
thermal NO-formation is suppressed

Flameless = high air preheat + strong recirculation of exhaust gases (EGR)

MILD = moderate or intense low-oxygen dilution

Fig. 7. NOx-reducing by reburning.
LASER OPTICAL INVESTIGATION OF HIGHLY PREHEATED COMBUSTION WITH STRONG EXHAUST GAS RECIRCULATION, T PLESSING, N PETERS, J WUNNING PROCI 27, p. 3197

Achieve a well-stirred reactor:

Wall temperatures must be kept above 800 C

Strong recirculation since flow goes up on centerline, down near walls

Low air dilution: Exhaust gases exit furnace and are cooled in heat exchanger then mixed with air and forced back into furnace

Air preheat by the EGR mixed with the air

NOx drops to one-third of its initial value it had before recirculation and preheating
Low NO\textsubscript{x} strategies of GE and Pratt

Turbofan engine NOx ratings:
- NOx = NO + NO\textsubscript{2}  nitric oxide + nitrogen dioxide    100 ppm is lethal
- NOx emission index: EINOX = (50 grams/sec NOx)/(kg/sec fuel)
- Specific emission index: (0.5 grams/sec NOx) / (kN thrust)

NOx cycle:
NO produced in engine where T > 1700 K and lean, NO\textsubscript{2} not produced in engine, but later

O\textsubscript{2} + N\textsubscript{2} \rightarrow 2\ O + N  Oxygen molecule dissociates at high temperature
O + N\textsubscript{2} \rightarrow NO + N  Zeldovich thermal NO formed in engine
N + O\textsubscript{2} \rightarrow NO + O  Zeldovich thermal NO formed in engine

NO + O\textsubscript{2} \rightarrow NO\textsubscript{2} + O  photochemical smog (NO\textsubscript{2}) produced in atmosphere
NO\textsubscript{2} + O\textsubscript{2} \rightarrow NO + O\textsubscript{3}  ozone (O\textsubscript{3}) produced at lower altitudes (BAD)

NO + O\textsubscript{3} \rightarrow NO\textsubscript{2} + O\textsubscript{2}  ozone (O\textsubscript{3}) destroyed at upper altitudes in ozone layer (BAD)
NO\textsubscript{2} + H\textsubscript{2}O \rightarrow HNO\textsubscript{3} + H  acid rain falls on plants (BAD) but scrubs NO\textsubscript{2} out of air (GOOD)
\[
\frac{d [NO]}{dt} = 2 k [O][N_2] \quad O_2 \leftrightarrow 2 O \quad K_p = \left[\frac{[O]}{[O_2]}\right] (R_u T)
\]

\[
[NO] = k K_p^2 (R_u T)^{-\frac{1}{2}} [O_2]^{\frac{1}{2}} [N_2] \Delta t
\]

Assume lean combustion (\(\phi = 0.8\)) of Jet-A (C_{10}H_{20}), products are: CO_{2}, H_{2}O, O_{2}, N_{2}
Assume a residence time of 30 msec, dilution air is six times primary air

C_{10}H_{20} + 18.75 O_{2} + 18.75 (79/21) N_{2} \rightarrow 10 \text{CO}_{2} + 10 \text{H}_{2}O + 3.75 \text{O}_{2} + 18.75 (79/21) \text{N}_{2}

X_{N2} = 0.75, \ X_{O2} = 0.04, \ T = 2200 \text{ K}

\[
[N_2] = X_{N2} \frac{p}{(R_u T)} = 61.5 \text{ mol/m}^3 \quad [O_2] = X_{O2} \frac{p}{(R_u T)} = 3.3 \text{ mol/m}^3
\]

Then: \([NO] = 3.1 \times 10^{-4} \text{ mol/m}^3\)
so \(X_{NO} = 1200 \text{ ppm, dilute with air to 200 ppm in exhaust}\)
NOx Strategies

GE: LPP = lean premixed prevaporized = TAPS = twin annular premixed swirler

Pratt: RBQQ = rich burn, quick quench (stratified)

Industrial: Staged combustion – inject fuel in many optimum locations
EGR - exhaust gas recirculation after gas is cooled

After treatment (for ground based power)
catalytic converter (platinum),
ammonia reburn

\[
\begin{align*}
\text{NH}_3 & \rightarrow \text{NH} + \text{H}_2, \\
\text{NH} + \text{CH}_4 & \rightarrow \text{HCN} + 2 \text{H}_2, \\
\text{HCN} + \text{NO} & \rightarrow \text{N}_2 + \text{HCO}
\end{align*}
\]
LPP = lean premixed prevaporized  GE TAPS

Used in GEnX engine in Boeing 787
Lower NOx, better fuel economy
Designed entirely by trial and error, not CFD
Has a growl problem at certain conditions, but don’t go there!
RBQQ of Pratt and Whitney = rich burn, quick quench

Idea: reduce the residence time ($\Delta t$) of gas in the “near stoichiometric” zone. In the primary zone, fuel and air burn rich, then as dilution air is added through the liner walls the gases are accelerated to quickly pass through the stoichiometric region.

Then they pass into the lean region where is is below 1700 K and no more NOx is produced.

Rich primary zone = good flame stability
Rapid velocity in near stoichiometric zone = low NOx
Long residence time in lean dilution zone = low CO
RBQQ = rich burn
quick quench

Numerical Analysis of the Flowfields in a Staged Gas Turbine Combustor

Michael C. Cline*
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
Gerald J. Micklow†
University of Florida, Gainesville, Florida 32601
S. L. Yang‡
Michigan Technological University, Houghton, Michigan 49931
and
H. Lee Nguyen§
NASA Lewis Research Center, Cleveland, Ohio 44135

Fig. 1 Combustor configuration.
Staged Combustors and EGR

T = 2200 K stoichiometric isotherm

fuel
rich

air

T = 1700 K lean isotherm

Staged combustion: add pipes that inject fuel or air or cooled exhaust products at optimized locations to reduce the size of the NOx formation region

All NOx is produced in grey region between these two isotherms

EGR: extract some of the products, remove their heat and re-use this energy to heat up the incoming air, then inject the cool, inert products into the hot zone shown above to reduce the local temperature to reduce NOx