Insights on MILD Combustion from DNS and its Modelling

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Outline

- Brief Introduction – motivation
- Methodology – DNS
- Insights gained, Examples for modelling
- Summary & Conclusion
Introduction

- MILD (Moderate or Intense Low-Oxygen Dilution) combustion

Typically Da < 1

Introduction

- Recirculation of hot gases – external or internal (internal is easy to setup without additional plumbing)

(Cavaliere, de Joannon, 2004)  
(Winning, Winning, 1987)

- Staged combustion – combustion in vitiated air

- Presence of intermediate radicals in the oxidiser stream, typically O2 level < 5% by vol.
Introduction

- Advantages ("Green" combustion)
  1. Heat recovery – over all system efficiency
  2. Dilution – O2 level & temperature rise drop => very low NOx
  3. “Silent” combustion
- Common in furnace application, considerable interest is evolving for GT by OEMs
- Science – is not fully explored, perhaps not well understood yet

Objectives

- Typical questions are
  1. Inception of MILD combustion
  2. Flame or ignition, which one is preponderant?
  3. Is it Mixed Mode combustion?
  4. What are typical morphological and topological features of reactions zones?
  5. Are standard experimental diagnostics (developed & tested using typical flames) adequate?
  6. … etc., & of course, what is correct modelling approach?
DNS Amenable Configuration – Schematic

Computational Domain for DNS

Methodology – Inflowing Mixture

(PROCI 2012, CnF 2014, CnF 2018)

Step 1: Turbulence field generation
Step 2 to 4: Scalar fields generation
Step 5: Tying turbulence & scalar fields together for consistencies

19 species & 58 Rxn CH4/air chemistry
Includes OH* chemistry
512x512x512 First of its kind simulation
Inflowing Mixture

0 \leq \phi \leq 11

Y_i(Z, c)

MILD vs Conventional Comb. – from DNS

MILD
Conventional – lean premixed
MILD Combustion Inception

(Doan & Swaminathan PROCI 2019)

\[ \theta_{st} = \frac{(T_{st} - T_{st,u})}{\Delta T_{st}} \]

\[ \beta = \frac{E_{eff}}{(R^0 T_{st,b})} = \frac{T_a}{T_{st,b}} \]

Radicals in the incoming flow play important role in initiating the combustion

Revised theory for S-type curves under MILD conditions – open question
Visualisation

- Complex topology & morphology
- Interacting reaction zones
- Complex dynamics
- How to describe these structures?

Morphology of Rxn Zones

(CnF 2014, 161, 2801-2814)
Morphology Characterisation

(Leung et al. JFM 710, 2012, 453-481)

N dimensional object has (N+1) Minkowski Functionals : from Integral Geometry

\[
F_0 = V, \quad F_1 = \frac{S}{6}, \quad F_2 = \frac{1}{3\pi} \int_S \frac{\kappa_1 + \kappa_2}{2} dS, \quad F_3 = \frac{1}{2\pi} \int_S \kappa_1 \kappa_2 dS,
\]

Thickness, \(T \equiv \frac{F_0}{2F_1}\); Width, \(W \equiv \frac{2F_1}{F_2}\);

Length, \(L \equiv \frac{3F_3}{4(G+1)}\) \(G = 1 - 0.5F_3\)

Planarity, \(P \equiv \frac{W - T}{W + T}\)

Filamentarity, \(F \equiv \frac{L - W}{L + W}\)

Morphology of Reaction Zones

(CnF 2014, 161, 2801-2814)
How do We Characterise the Structure?

(CnF 2018, 189, 173-189)

➢ there isn’t a unique feature!!

Mixture Fraction Space Structure

(CnF 2018, 189, 173-189)

- Spatial/temporal propagation of Autoignition front
- Some features of flames – both premixed and non-premixed
How About Scalar Gradient?

Flames:
normal gradient >> tangential gradients

Scalar Gradients & Rxn. Rate – JPDF

(CnF 2014, 161, 1063-1075)

Shares some common features with conventional combustion, while having some distinctive features
Flame or Ignition? – $B$ Analysis

$B = |C - D| - |R|$

Variety of scenario is observed

Flame Index Analysis

$FI = \frac{Z - Z_{st}}{2|Z - Z_{st}|} \left(1 + \frac{\nabla Y_{CH_4} \cdot \nabla Y_{O_2}}{\| \nabla Y_{CH_4} \| \| \nabla Y_{O_2} \|} \right)$

(Briones et al. Phys. Fluids 2006)

= 0 for non-premixed

= 1 for rich premixed

= -1 for lean premixed
PDF of FI

Relative contributions of LP, RP, NP, & MM

\[ \nu_{NP} = \int_{-\xi_1}^{\xi_1} p(\psi) \, d\psi \quad \nu_{LP} = \int_{-1}^{-\xi_2} p(\psi) \, d\psi \quad \nu_{RP} = \int_{\xi_2}^{1} p(\psi) \, d\psi \]

<table>
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<th>Case</th>
<th>( \nu_{NP} )</th>
<th>( \nu_{RP} )</th>
<th>( \nu_{LP} )</th>
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<td>0.206</td>
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Modelling – Reaction rate

\( \dot{\omega}_c = \int \int \omega_c^-(\xi, \eta, \zeta) P(\xi, \eta, \zeta) \, d\xi \, d\eta \, d\zeta \)

\( P(\xi, \eta, \zeta) = \beta(\xi; \tilde{Z}, \tilde{Z}^n) \delta(\eta - \tilde{h}) \beta(\zeta; \tilde{c}, \tilde{c}^n) \)

Minamoto & Swaminathan,
Validation – RANS – Adelaide JHC

(Proci, 36, 2017, 4279-4286)

[Diagram showing computational domain and pressure outlet with isotherms labeled T (K).

Fuel jet
U=62m/s
T=305K

Hot coflow
U=3.2 m/s
T=1300K

Air entrainment
U=3.2 m/s
T=305K

Graphs showing temperature (K) profiles at X = 30 mm, 60 mm, and 120 mm for HM1, 3% O2 and HM3, 9% O2.

Validation – RANS – Naples Cyclone burner

(Energy & Fuel 32, 2018, 10256-10265)

[Diagram showing burner setup with thermocouples labeled central and lateral.

Graphs showing temperature (K) profiles for CL-1, CS-1, and CR-1 at different x [m] values.

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Summary & Conclusion

- MILD combustion involves complex interactions among auto-ignition fronts, premixed and non-premixed flames.
- Thus, it shares some commonality with conventional combustion while having its distinctive attributes.
- S-shaped curve – need revision for MILD condition.
- Rxn zones have pancake like structures with typical thickness of about $\delta_{th}/10$.

Summary & Conclusion

- Standard surface based combustion modelling is inadequate.
- Reactor based modelling approach seems to be suited well.
- Validated this for RANS.
- Tested for LES (a priori), further work is on-going.
- Need to be careful while interpreting LIF images of MILD conditions.
Questions?