TECC-AE, Task 2.1

Spray ignition limitations and sub grid model for CFD for lean extinction and spark ignition

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Speaker’s role within the project: Task leader
Outline

- Introduction – scientific background
- Work achieved
- Exploitation and future work
- Conclusions
Introduction

- High-altitude relight is very important from a safety point of view.
- Lean-burn gas turbine combustors are tougher to ignite.
- Dearth of knowledge apart from empirical data from 70’s.
- EU Project TIMECOP: UCAM performed new experiments, focusing on the turbulent behaviour, stochastic aspects, and recirculating flow. Little work on sprays.
- Project TECC: focus on spark ignition experiments and modelling for high swirl, high velocity conditions; model and study blow-off.
Introduction

Why this shape? What factors determine the distance between loops? How are flame patterns related to this curve? Can we predict it?

Knowledge on extinction is useful to understand ignition and vice versa.

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EXPERIMENTS
Experimental arrangement

- Square section: 95mm x 95mm x 150mm
- Ignition by laser (Nd:YAG laser at 1064 nm (dichroic mirrors to purify I), f=10Hz, f_l=150 mm converging lens, E ∈ [40;370] mJ/pulse.
- Heptane fuel, ambient conditions

All dimensions in mm.
**Ignition behaviour - 1**

- Timescales extracted from the evolution of the OH* chemiluminescence in time

- **Extinction:**
  - Time for which the curve of intensity goes down to zero and stays equal to that value for at least 15 ms
  - 3 orders of magnitude (see below). Short failure mode = flame never anchored on the bluff-body, mainly spark in B.

*Long* failure mode: Hundreds of ms

*Intermediate* mode: A few tens of ms

*Short* failure mode: From a few µs to a few ms
OH* movie from intermediate failure mode at 5 kHz
Full ignition probability high in centre of burner, decreases to zero as we go downstream. Kernel probability decreases as U increases, higher than full ignition probability.
Stable flame structure and blow-off behaviour

DATA AVAILABLE:

- Reaction zone shape and thickness
- Extinction time
- Location of blow-off events identified
- Statistical data on lift-off velocity (cold flow)

**OH**$^*$ chemiluminescence

Average of **OH**$^*$ time series for individual blow-off events

**OH-PLIF**
LES-CMC simulations

LES-CMC modelling of spray combustion:

- flame is initiated by a ‘spark’ modelled imposing a burning flamelet in selected cells
- simple chemistry with single step reaction, modified to give correct SL.
- CMC code: new sub-models in TECC; core engine from TIMECOP project (and older NICE project on diesel engines).

LES code:

- PRECISE-LES from Rolls-Royce
- Block-structured, ca. 3 M cells.
- Validation for Sandia D-F & TECC-AE swirl spray experiment.
Scalar dissipation rate models as for gaseous flow:

\[ \frac{\partial Q_\alpha}{\partial t} + u_j \frac{\partial Q_\alpha}{\partial x_j} = -\frac{1}{\rho \bar{P} \eta} \frac{\partial Q_\alpha}{\partial x_j} \left[ \bar{\rho} \bar{P} \eta \left( u_j Y_\alpha \eta - u_j \eta Q_\alpha \right) \right] + \bar{N} \eta \frac{\partial^2 Q_\alpha}{\partial \eta^2} + \bar{w} \eta \]

\[ \bar{S}|\eta = \int_{V_{CMC}} \frac{\tilde{S} \cdot \delta(\eta - \xi)}{\bar{P}(\eta)} dV + \bar{S}|\eta + \bar{S}|\eta Q_\alpha - (1 - \eta) \bar{S}|\eta \frac{\partial Q_\alpha}{\partial \eta} \]

Source terms from spray with:

\[ \tilde{S} = \frac{1}{\rho V} \sum_{i=1}^{N} \tilde{m}_i \]

Borghesi G. et al., Comb. Th. Modelling, 2011

Scalar dissipation rate models as for gaseous flow:

\[ \bar{N}|\eta = \text{AMC model applied on CFD grid and then integrated over the CMC cell} \]

\[ \bar{N} = \bar{N}_{res} + \bar{N}_{sgs} = D \left( \frac{\partial \tilde{\xi}}{\partial x_j} \right)^2 + C_N \frac{\nu_t}{\Delta} \tilde{\xi}^{n2} \]

\[ \tilde{\xi}^{n2} = C_V \Delta^2 \frac{\partial \tilde{\xi}}{\partial x_j} \frac{\partial \tilde{\xi}}{\partial x_j} + \frac{\Delta^2}{\mu_t} \tilde{\xi}'' \tilde{S}'' \]

most often neglected

OR with

\[ \tilde{\xi}'' \tilde{S}'' = \tilde{\xi} \tilde{S} - \tilde{\xi} \tilde{S} = \tilde{\xi}_s \tilde{S} - \tilde{\xi} \tilde{S} \]
LES of cold flow: SWH1 conditions

Mean and RMS velocity profiles

Spectra of axial velocity at point: y=-8mm, x=16mm
LES of ignition: SWH1 conditions
LES of ignition: SWH1 conditions

Probability of ignition: reasonable agreement with experimental trend (Pign decreases as we go downstream and outwards in the radial direction). LES based on 16 simulations with spark at each of 20 points.

Pign calculated explicitly by LES for the first time.
LES of blow-off: SWH1 and SWH3

Conditional T [K] at stoich. m.f.

Localized extinction & re-ignition

Localized extinction & no re-ignition
LES of blow-off: SWH1 (stable)

Isosurface of the stoich. m.f. colored by the temperature

(T>400K, i.e. holes mean cold flow - local extinction)
LES of blow-off: SWH3 (blow-off event)

Isosurface of the stoich mixture fraction coloured by the temperature

(T>400K, i.e. holes mean cold flow - local extinction)

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Low-order model for ignition (~ 25% by TECC)

Optimum design process: take decisions on ignitability early on.
New designs (lean, new fuels, mixing patterns) put “existing wisdom” and empirical correlations in question.

Our approach:

- Distill fundamental knowledge from experiments, DNS & LES
- Simple to use, quick
- “Interrogate” a CFD solution of the inert (un-ignited) flow to provide an educated guess about success

Code SPINTHIR: Stochastic Particle INTEGRator for High-altitude Relight. (“Spinthir” means “spark” in Ancient Greek.)

(Neophytou et al, Comb. Flame 159 (2012) 1503-1522)
1. Track virtual “flame elements” using a random walk with mean & stochastic velocity component from the CFD solution.
2. If local Karlovitz number < critical value, particle remains alive and new particle is launched from this position. (Ka depends on local $\xi$.)
3. For sprays, laminar burning velocities for \textit{sprays at relight conditions} is used (Neophytou & Mastorakos, Comb. Flame 156 (2009) 1627–1640).
4. If local Ka > critical value, forget this particle.
5. Count volume of combustion visited by flame: this is the “ignition progress factor” $\pi_{\text{ign}}$.
6. Continue for a long time
7. Repeat for many times to compile statistics (sample space: individual spark events)
Results from SPINTHIR

MODEL

EXPERIMENT

"Failed" event: flame did not grow

"Successful" event: flame grew

Ignition model on TIMECOP burner

Ignition model on TECC burner

"Successful” event: flame grew

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Qualitatively OK with experimental trends; fuel placement in CFD critical to capture exactly the location of reduction of Pign as we go downstream.
Results from SPINTHIR

Builds insight on ignitability of combustor as a function of flow pattern, size of spark, variability between spark events etc.

Neophytou et al., Mediterranean Combustion Symp. Sept 2011
CFD solution from S. Stow, RR

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Results from SPINTHIR

Statistics of $\pi_{\text{ign}}$: assist designer decide spark location and shape
JOURNAL:

CONFERENCE:
Conclusions

- Spark ignition: experiment and simulation provide insights into failure modes and data for model validation.
- Blow-off: experiment provide insights on flame structure and timescales.
- LES/CMC: has been developed for both spark ignition and lean extinction; good agreement with experiment. Captures ignition probability and blow-off velocity.
- Low-order model for spark ignition provides useful design tool.
- Codes have been delivered to industrial partner.