UK Fluids Network

Experimental Combustion/UK
SIG Combustion 28 Sep 2017

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Experimental combustion research UK
GTRC EXPERIMENTAL COMBUSTION

Dan Pugh

Constant Volume Bomb
HPOC/Swirl Burner
EPSRC - AGT
Counterflow Burner

26th July 2017
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Constant volume bomb

Study Laminar Flame Propagation

- Schlieren optical technique employed to measure laminar flame speed.
- Facilitates parametric evaluation of temperature, pressure, reactant mixture and humidity.
- Characterise flame stretch and influence on propagation using Markstein length.
- Mass flow control to regulate gaseous or vaporised fuel and equivalence ratio.
Constant volume bomb

Work Areas

- Natural Gas / CH₄.
- Parametric changes in temperature and pressure, deriving power law correlations.
- Reaction mechanism optimisation, and development.
- Contemporary work investigating catalytic enhancement of heavily carbonaceous fuels with water addition.

Upcoming Work

- Influence of higher hydrocarbon addition to natural gas (LNG), and change in thermo-diffusive influence.
- Correlating results against behaviour witnessed in generic GT representative swirl burner.

Dynamic Volume Bomb

Experimental Facility Modification

- Inject and vaporise liquid fuel, then charge air and over-pressurise the system.
- Rapid decompression from internal piston forms quasi-homogenous mist, droplets characterised with laser diffraction system.
- Quantify the influence of obstacle induced turbulence, with mixture ignited from top.
- Optical tachometers provide scalable rotational speed to induce turbulence into the system.
HPOC – Swirl Burner

System Capability

- Casing rated to 900 K, 16 bar.
- Axial and tangential optical access.
- Liquid or gaseous fuel supply, with combustors operated in premixed or diffusion configurations.
- Five lines allow for fuel/oxidant mixture blending, with precise mass flow control.
- Convergent quartz tubes facilitate optical access, with representative combustor geometry.
- Pressurised steam supply to facilitate humidified combustion.

Analytical Diagnostic Tools

- Optical techniques including; high speed filming, Schlieren, Chemiluminescence, Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF). High frequency pressure transducers give acoustic output of the system.
- Online gas analysis for real time measurement of exhaust emissions, including; CO, CO₂, NO, NO₂, (Total NOₓ), O₂ and unburned hydrocarbons.
Contemporary Work

- Fuel Flexibility - Investigating changes in natural gas composition, (Gas-to-Power, LNG, H₂, CₓHᵧ) for changes in flame shape, burner operability, emissions, and thermoacoustic response of the system.

- Carbon Free ‘Green’ combustion - Stabilising blended H₂ and NH₃ for GT combustors and energy storage applications.

- Exhaust Gas Recirculation - Investigate change in CO₂ reactant fractions on flame operability and produced emissions, and how this may influence downstream CCS technology.


Humidified CO Work

Molar Reactant H₂O Fraction

Converter Gas / Air / H₂O

Scale in mm

CH₄ / Air

LBO Equivalence Ratio (Ø)

Molar Reactant H₂O Fraction

Re = 17.8
Re = 17.9
Re = 18.1
Re = 18.3
Re = 18.7
Re = 19.5
Re = 20.8
Re = 18.5

200 Image Average

Molar Reactant H₂O Fraction

NOₓ (Dry 15% O₂) – ppmV

CO (Dry 15% O₂) – ppmV

Molar Reactant H₂O Fraction

10-18%mol CO₂
10-15%mol N₂
1-3%mol H₂
50-80%mol CO

10-18%mol CO₂
10-15%mol N₂
1-3%mol H₂
50-80%mol CO

T = 423 K

CO (Dry 15% O₂) – ppmV

Molar Reactant H₂O Fraction

Molar Reactant H₂O Fraction

Converter Gas / Air / H₂O

Scale in mm
Counterflow Burner

Experimental Facility

- Counterflow or opposed flow burners stabilise flames between concentric jets.
- Allowing measurement of laminar flame speed, turbulence, extinction strain rate, chemical speciation and soot formation.
- Reactants shrouded with inert flow to prevent secondary flame formation. Setup can be configured for premixed or diffusion flames.
Counterflow Burner

Development of the Cardiff Facility

- Imperial design modified to operate at elevated temperature (473 K) and pressure (10 bar).
- Reactant preheat will facilitate combustion of prevaporised liquid fuels, and humidified combustion.
- Diametric quartz windows will allow for the application of optical diagnostic techniques.
- Design has allowed for trial of components built using AM or ‘3D printed’ stainless steel technology, with integrated cooling channels.
- Plans to test applied equivalence ratio measurement technique, employing quantified chemiluminescence ratios.
Turbulent flows

• **Scalar / Thermal Dissipation rate conditional on mixture fraction in swirling flows with and without reaction**
  • Development of scalar dissipation rate measurements for non-reacting and reacting flows - *Experiments in Fluids* 55, (2014)
  • Development of thermal dissipation rate measurements in swirl-stabilised burners based on Rayleigh Scattering – publication in preparation
  • Measurements of Velocity, Temperature, Thermal dissipation rate in swirl stabilised burner using PIV and Rayleigh – publication in preparation

• **Flow-Flame interactions**
  • Volumetric measurements in swirl stabilised burner - starting Jan. 2018. This will include flow velocity, reaction zone and fuel concentration
• **Laser Ignition of jets of gas and liquid fuel**
  • Experiments in Homogeneous Isotropic Turbulence without mean flow at various levels of turbulence [Proc. Comb Inst. 36, (2017); ongoing]

• **Development and application of Laser Diagnostics**
  • Development of LIBS for Air-Fuel ratio measurements in flames. Sensors for monitoring fuel variability. Applications in swirl burners and gas turbine combustors [18th Int Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 4-7 July 2016; ECM 2017; ongoing]
  • Flame Chemiluminescence for different fuel blends. Experiments and Detailed chemistry calculations. Sensors for flame monitoring of heat release rate and air-fuel ratio. Application in swirl burners and gas turbine combustors. [AIAA paper 2017-0153; ECM 2017; ongoing]
  • CO Laser Induced Fluorescence in Reacting flows – [ongoing]
  • Development of plenoptic imaging (camera and processing software) [21st ILASS-Japan, Tokyo, Japan, 17-18 December 2012; 18th Int Symp on Applications of Laser Techniques to Fluid Mechanics”, Lisbon, Portugal, 4-7 July 2016; ongoing]
  • Development of novel flow velocimetry and temperature technique that operates without seeding particles [patent pending]
Gas turbine combustion

- **Combustion oscillations and control of emissions**
  - Development of tools for prediction of self-induced combustion oscillations and associated control [ECM 2017; ongoing]
  - Non-linear dynamics of time-dependent pressure, flow velocity and heat release rate with and without oscillations [publication in preparation; ongoing]
  - Time dependent PIV velocity measurements and OH PLIF measurements conditional on pressure under combustion oscillations [partly complete-preparation of publications; ongoing]
  - Effects of Fuel variability and fuel or air dilution by inert gases on combustion [ongoing]
Combustion SIG – Oxford capabilities

Ben Williams, Martin Davy and Richard Stone
28th September 2017
Burner studies

- Laminar flames (Santoro and Gülder, left)
- Firewhirl / fire tornado (centre)
- Turbulent non-premixed burner – oxy-fuel (right)
Optical diagnostics

• Temperature (LITGS, Rayleigh, pyrometry)
• Soot volume fraction (pyrometry, extinction)
• Particle size (static light scattering)
• Tomography
• Radical species by LIF and chemiluminescence
  • OH, CH, CH₂O, CN...
• Localised extinction; heat release imaging
• Particle Image Velocimetry, ~10 Hz and 8 kHz

• New laser diagnostics labs in build now
Other methods/comments

• **Non-optical methods:**
  • Thermophoretic sampling with electron microscopy
  • Fine gauge thermocouple scan
  • Hot wire anemometry

• **Exhaust sampling:**
  • Cambustion Fast-FID
  • Cambustion DMS500

• Laminar burners are quite portable
Combustion bomb

- Controlled environment
- Laminar burning velocity
- Schlieren, chemiluminescence
Oxford Cold Driven Shock Tube

• Transient test facility that can reproduce e.g. diesel combustion conditions
• Optically-accessible test section
• Construction / commissioning in progress

- CENTRALLY MOUNTED SINGLE HOLE DIESEL INJECTOR – ECN ‘SPRAY A’
- HEATED FUEL, 1700 BAR INJECTION PRESSURE

CLOSE UP OF 70 X 30 MM OPTICAL ACCESS WINDOW (x3)
CDST capabilities / diagnostics

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pressure (bar)</th>
<th>Temperature (K)</th>
<th>Test duration (air driven, ms)</th>
<th>Test duration (He driven, ms)</th>
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- Optical diagnostics activity
  - High speed spray combustion imaging: shadowgraphy, schlieren, Mie scattering. LITGS

- Ignition delay
  - Optical techniques or capture pressure rise at sidewall

- Pre-mixed chemical kinetics studies also planned, with or without spray combustion (dual fuelling)
Shock tube installation

DEDICATED LASER-SAFE ROOM AROUND OPTICAL SECTION FOR OPTICAL AND LASER DIAGNOSTICS
Measurement techniques:
• Flame studies based on laser-induced fluorescence (LII) and laser-induced incandescence (LIF):
  • Polycyclic aromatic hydrocarbons (PAH)
  • Nanoparticulates / soot
  • Intermediates: OH, CH
  • Temperature

• Cavity-ring down and cavity-enhanced absorption spectroscopy:
  • Sensitive concentration measurements
  Intermediates:
  OH, \(^1\text{CH}_2\), HCO, C\text{\textsubscript{2}}H\text{\textsubscript{2}}
Diode laser cavity ring-down spectroscopy in flames

- Previous cavity ring-down work in flames had been based on pulsed dye lasers
- Near infrared diode lasers are used here for *in situ* cw-CRDS
- Applied to measure acetylene concentration profiles in rich ethylene-air flames

LII using a Long-Pulsed Fibre Laser

- For reasons of practicality and safety it may be attractive to use pulsed fibre lasers when performing LII in industrial test environments.
- Their optical properties differ from typical Nd:YAG lasers, including much longer pulse length.
- LII with long-pulse fibre lasers has been compared to reference measurements by ‘standard LII’ in a stable flat-flame.

Robert Roy has a poster.
Mastorakos

- **EXPERIMENTAL**
  - Swirl flames: extinction, ignition, flame transfer functions
  - Annular combustor: flame transfer functions, light-round
  - Diagnostics: 10 kHz OH-PLIF, 10 Hz OH-PLIF, 10 Hz CH2O-PLIF, LIBS

- **COMPUTATIONAL**
  - LES with Conditional Moment Closure: ignition, blow-off, emissions
Hochgreb
Turbulent flames & sprays

HS PIV

OH PLIF

droplet flux - PDA

(b) $\hat{F}, z = 15\text{mm}$
Spray combustion


Thermographic PIV

• Extensions: higher T
• Heat transfer
• LDA (Heyes/Strathclyde)

High resolution soot volume fraction via cavity extinction and LII

- extension: liquid fuels
- carbon nanotubes
- nano oxides

Laser-Induced Thermal Grating Spectroscopy (LITGS)

\[ \tau = \frac{\Lambda}{c_s} \]

OH/5 bar CH4 flame

Extension:
- 1 kHz c measurements entropy spots @ 355 nm (thermoacoustics)

DeDomenico/Fan/Williams/Shah/Hochgreb

CERS – Cavity enhanced Raman spectroscopy

\[ \lambda_p = 532 \text{mm} \]

Transmission Profile of Laser 2000 Curved Mirrors

Output of a 3mm LRH cavity

Finesse = 1000

\[ \text{Finesse} = \frac{\text{FSR}}{\text{FWHM}} \]
Further afield

Sheffield (Pourkashanian):
- Downward fired coal
- CCS
- Kinetics of alternative fuels

Leeds (Lawes, Bradley):
- Combustion bomb
- Turbulent combustion
- Blow off/liftoff

Loughborough (Carrotte):
- High pressure combustion facility

Edinburgh (Linne, Peterson):
- Femtosecond diagnostics
- Sprays
- Wall effects in engines

UCL:
- Heat release imaging
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Future opportunities

• Joining existing facilities and diagnostics capabilities for addressing difficult problems (e.g. shock tube + cw laser diagnostics; high pressure facilities + imaging diagnostics, high frequency diagnostics + entropy spots)

• Exchanging experience: training PhD/RAs in a wider range of techniques (e.g. TDLAS, PIV) or in greater depth

• Addressing key problems in modelling (e.g. subgrid assumptions, assumed closure pdfs), and motivate/justify new facilities/projects (e.g. fs-CARS at Edinburgh for detailed work in flames)

• ... and much much more...