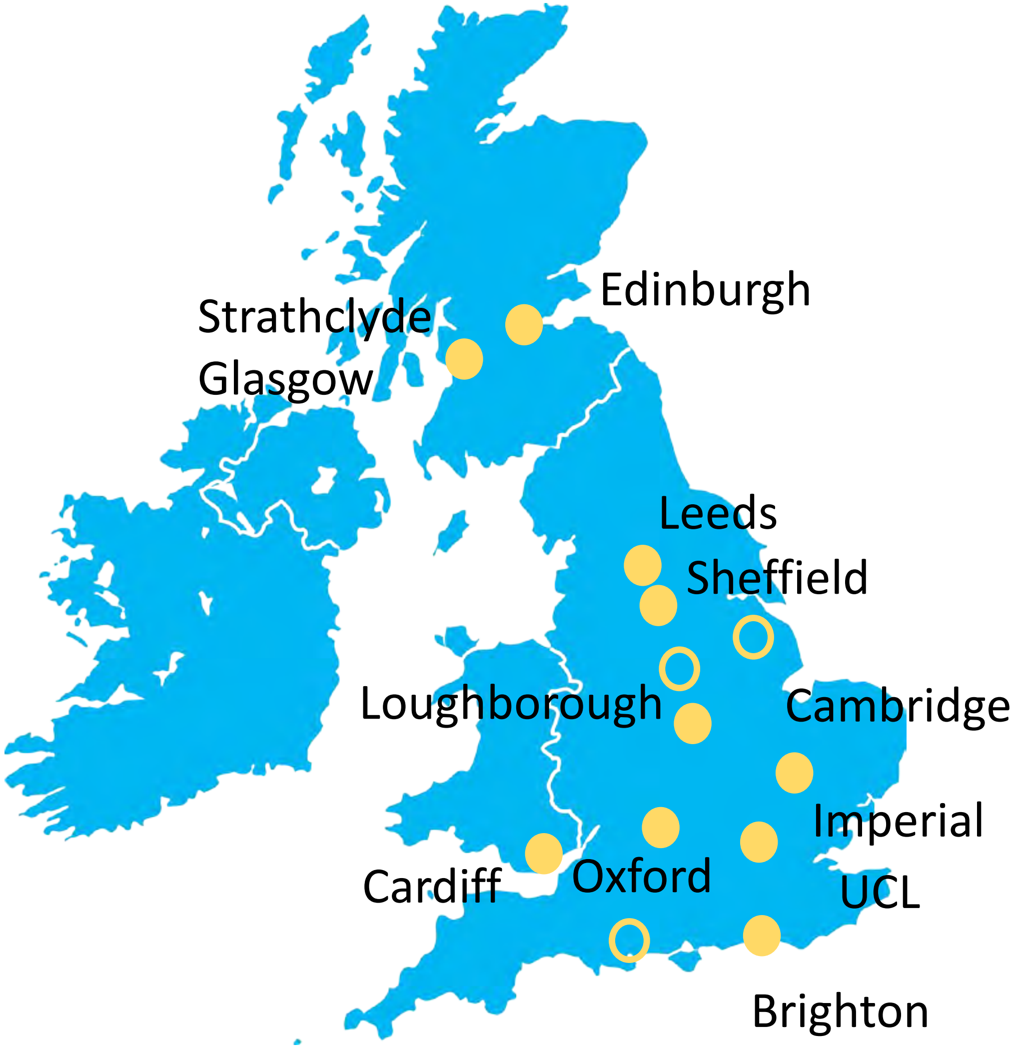
UK Fluids Network

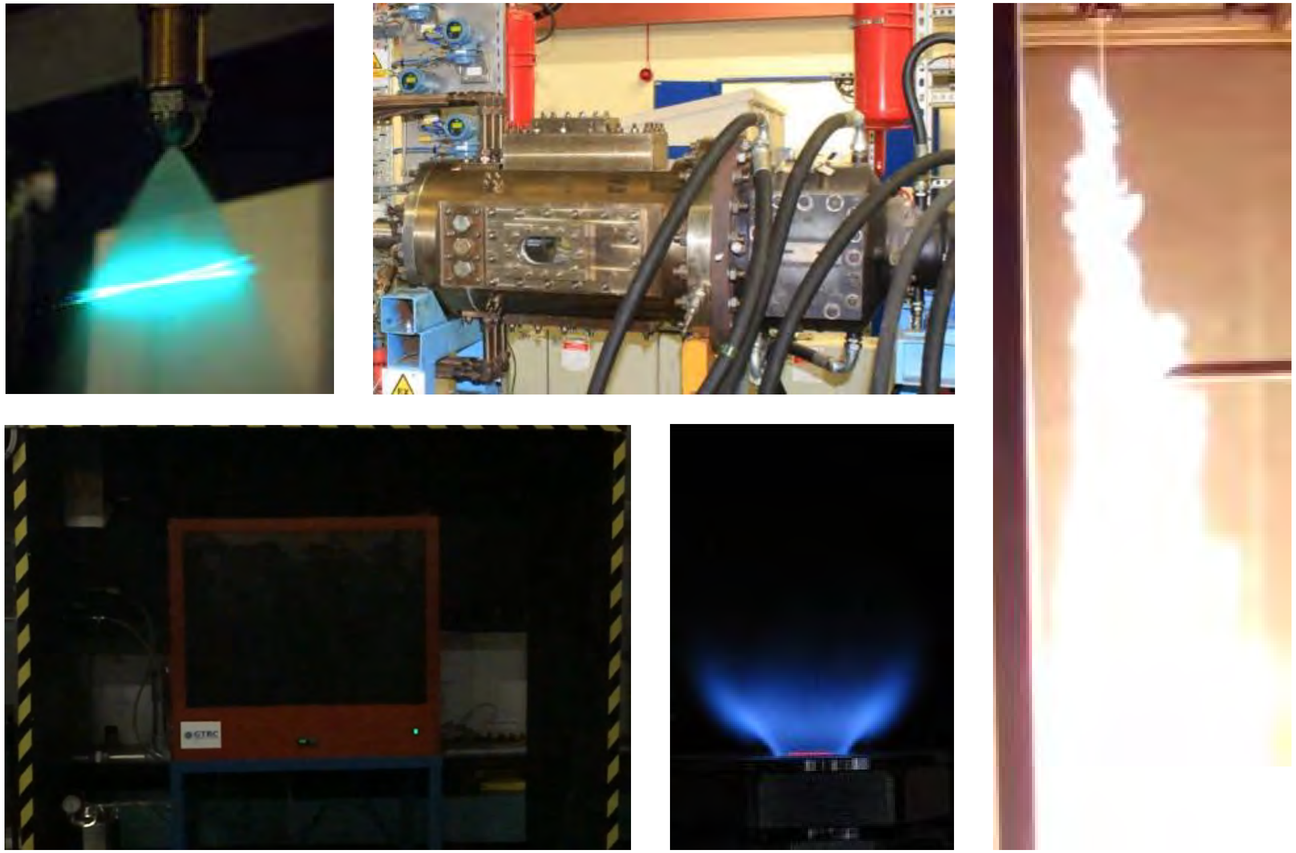
Experimental Combustion/UK
SIG Combustion 28 Sep 2017

Simone Hochgreb, University of Cambridge

Experimental combustion research UK



GTRC EXPERIMENTAL COMBUSTION



Dan Pugh

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

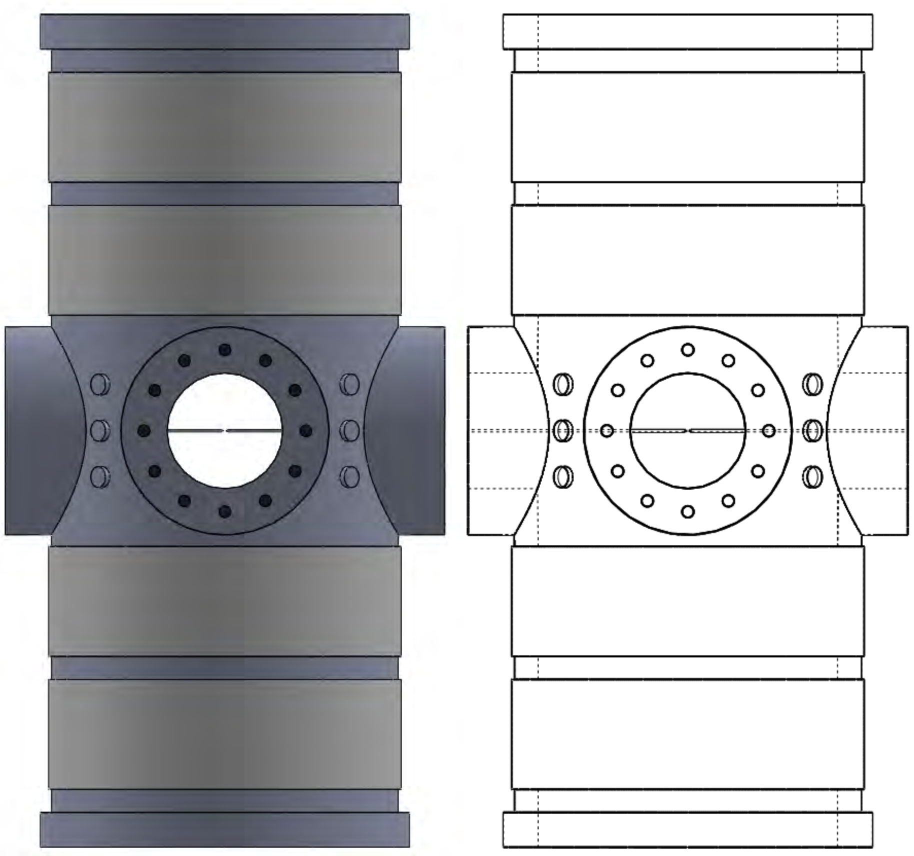
26th July 2017

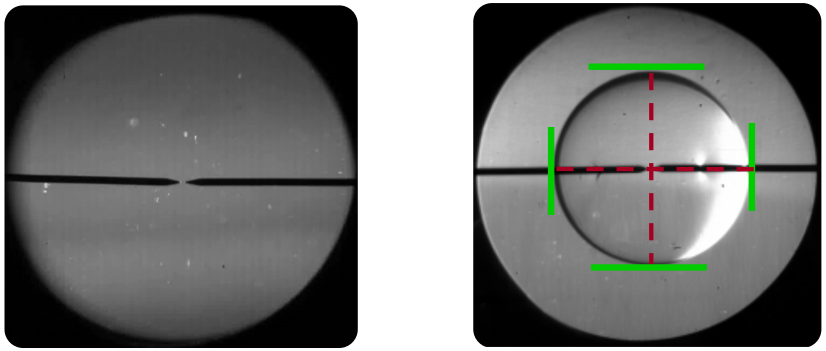
pughdg@Cardiff.ac.uk

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.





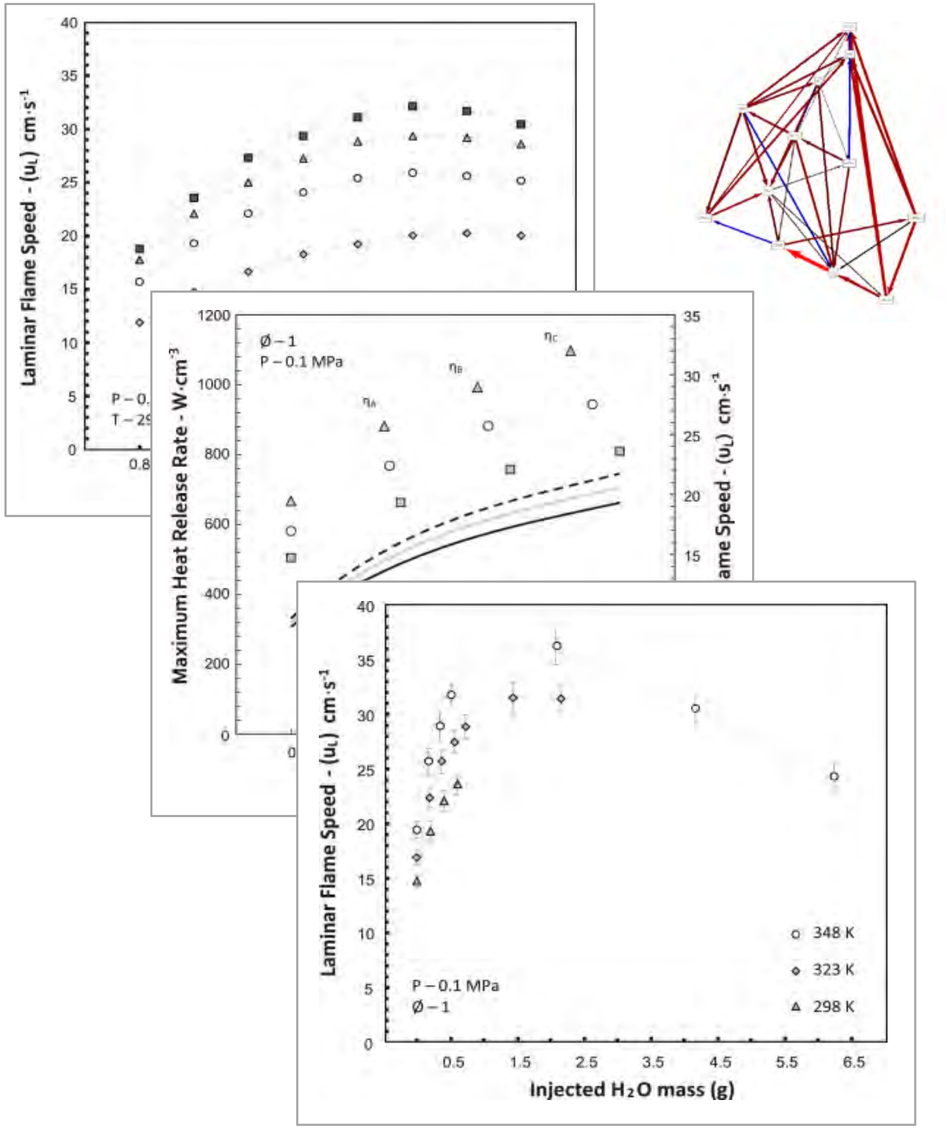
Constant volume bomb

Work Areas

- Natural Gas / CH_4.
- Alternative fuels – syngases, biogas, industrial by-product gases.
- 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.



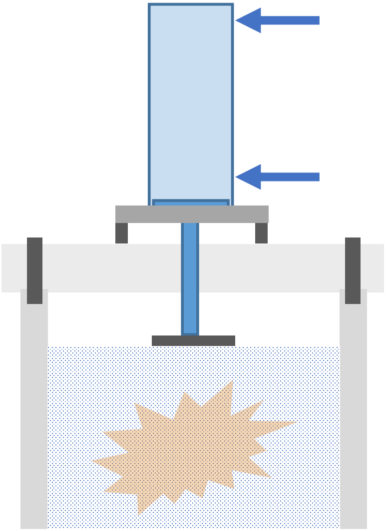
D G. Pugh, A P. Crayford, P J. Bowen, M Al-Naama, Parametric investigation of water loading on heavily carbonaceous syngases, Comb. & Flame, Vol 164, 2016, Pages 126-136,

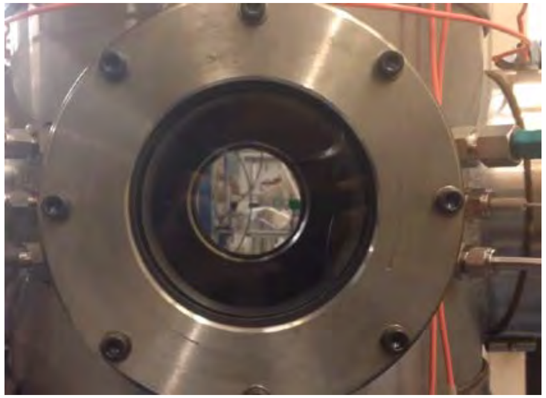
http://dx.doi.org/10.1016/j.combustflame.2015.11.009

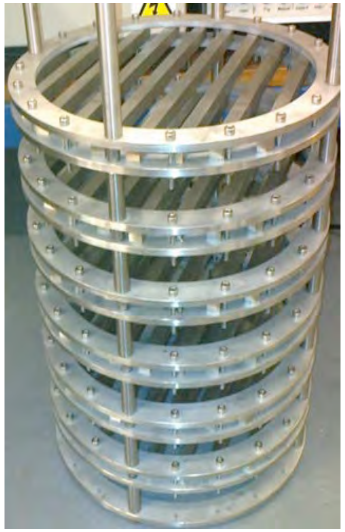
Dynamic Volume Bomb

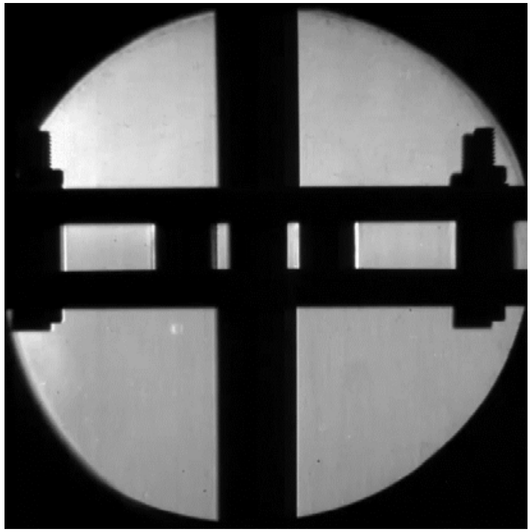
Experimental Facility Modification

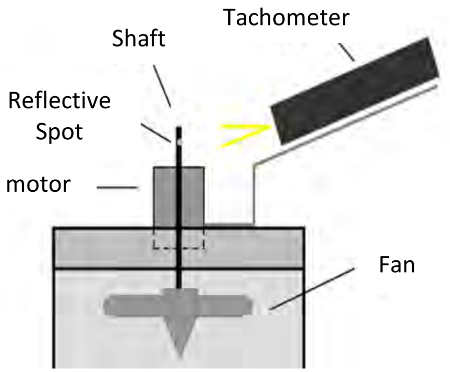
- Inject and vaporise liquid fuel, then charge air and over-pressurise the system.
- Rapid decompression from internal piston forms quasi-homogenous mist, droplets characterised with laser diffraction system.
- Quantify the influence of obstacle induced turbulence, with mixture ignited from top.
- Optical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

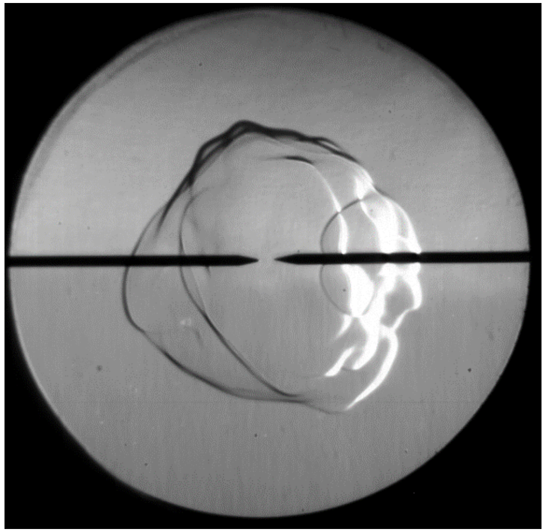












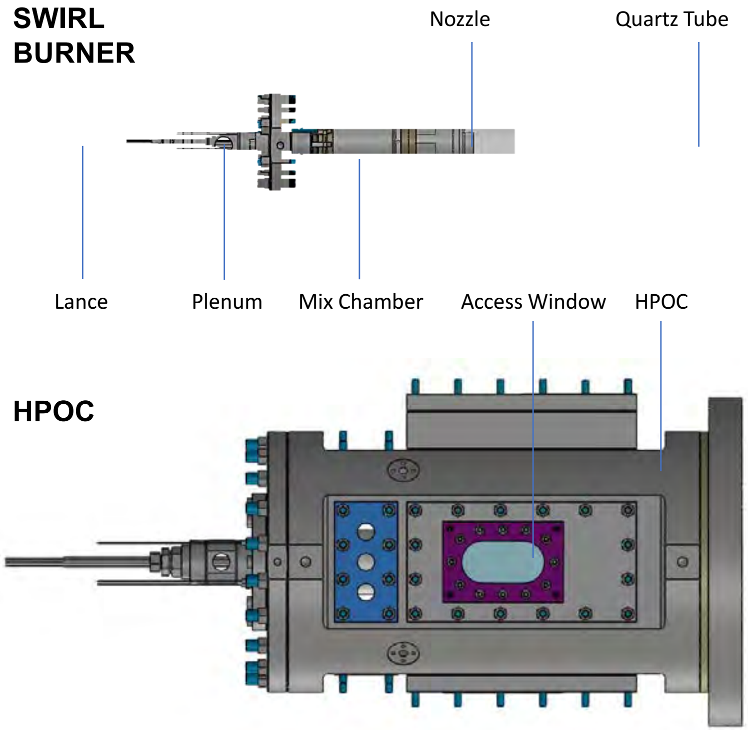
HPOC – Swirl Burner

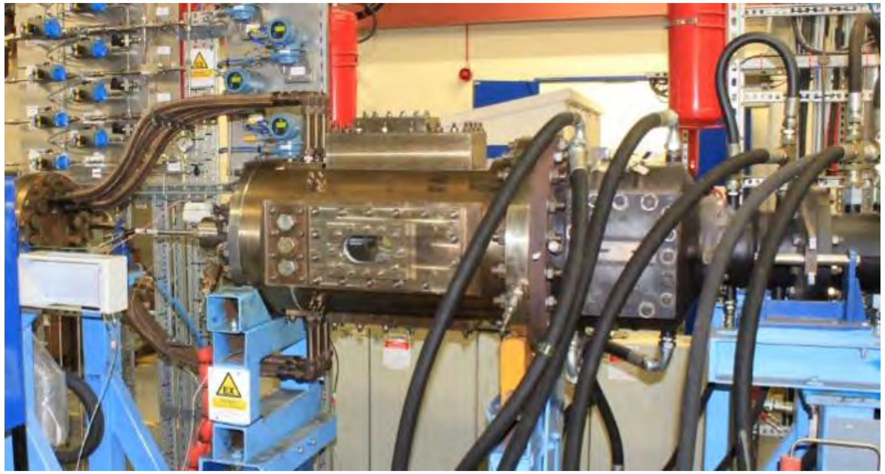
System Capability

- 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, CO_2, NO, NO_2, (Total NO_x), O_2 and unburned hydrocarbons.



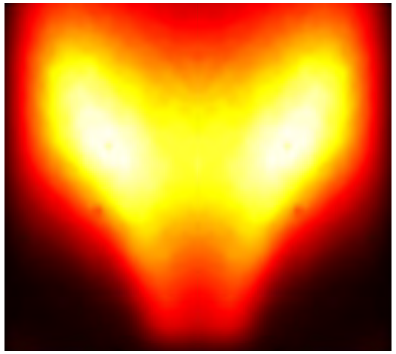


HPOC – Swirl Burner

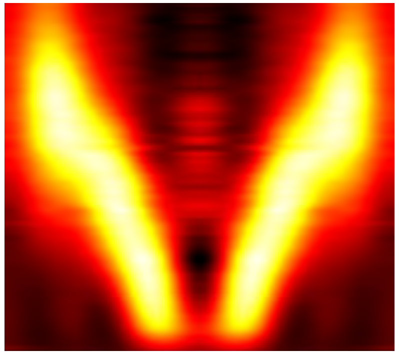
Contemporary Work

- Fuel Flexibility - Investigating changes in natural gas composition, (Gas-to-Power, LNG, H_2, C_xH_y) for changes in flame shape, burner operability, emissions, and thermoacoustic response of the system.
- Carbon Free 'Green' combustion - Stabilising blended H_2 and NH_3 for GT combustors and energy storage applications.
- Exhaust Gas Recirculation - Investigate change in CO_2 reactant fractions on flame operability and produced emissions, and how this may influence downstream CCS technology.
- Humidified combustion - Reducing flame temperatures with H_2O to reduce NO_x emissions. Work presented at ASME Turbo expo 2017.

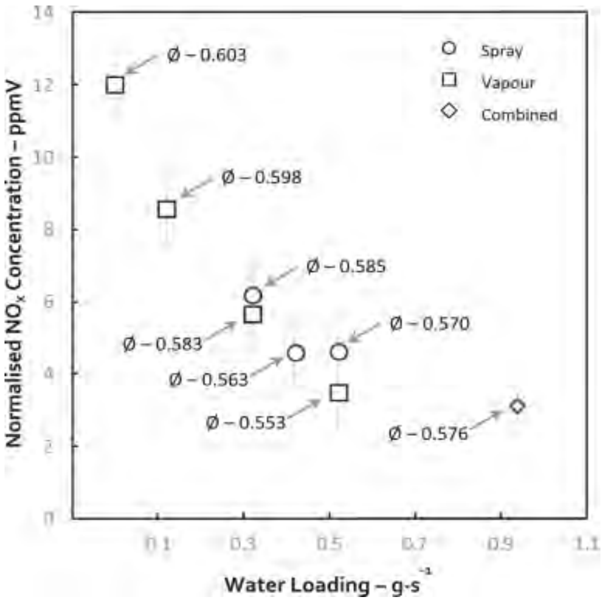
OH* Chemiluminescence



Abel Deconvoluted



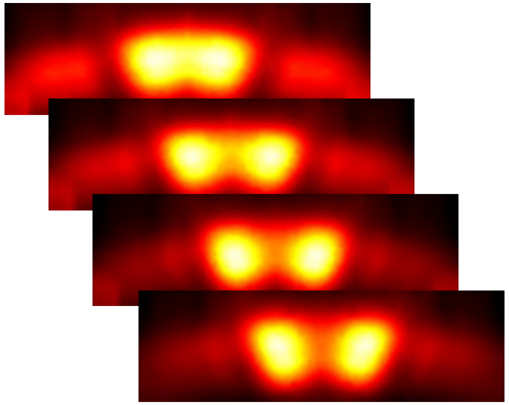
NO_x Emissions



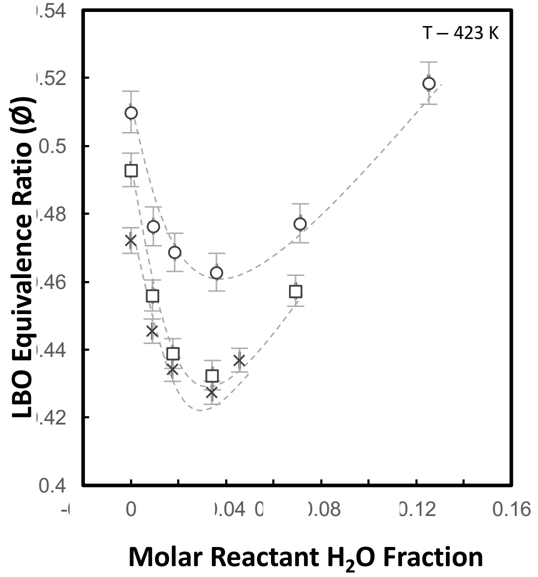
D.G. Pugh, P.J. Bowen, R. Marsh, A.P. Crayford, J. Runyon, S. Morris, A. Valera-Medina, A. Giles, Dissociative influence of H_2O vapour/spray on lean blowoff and NOx reduction for heavily carbonaceous syngas swirling flames, Comb. and Flame, Vol. 177 Pages 37-48

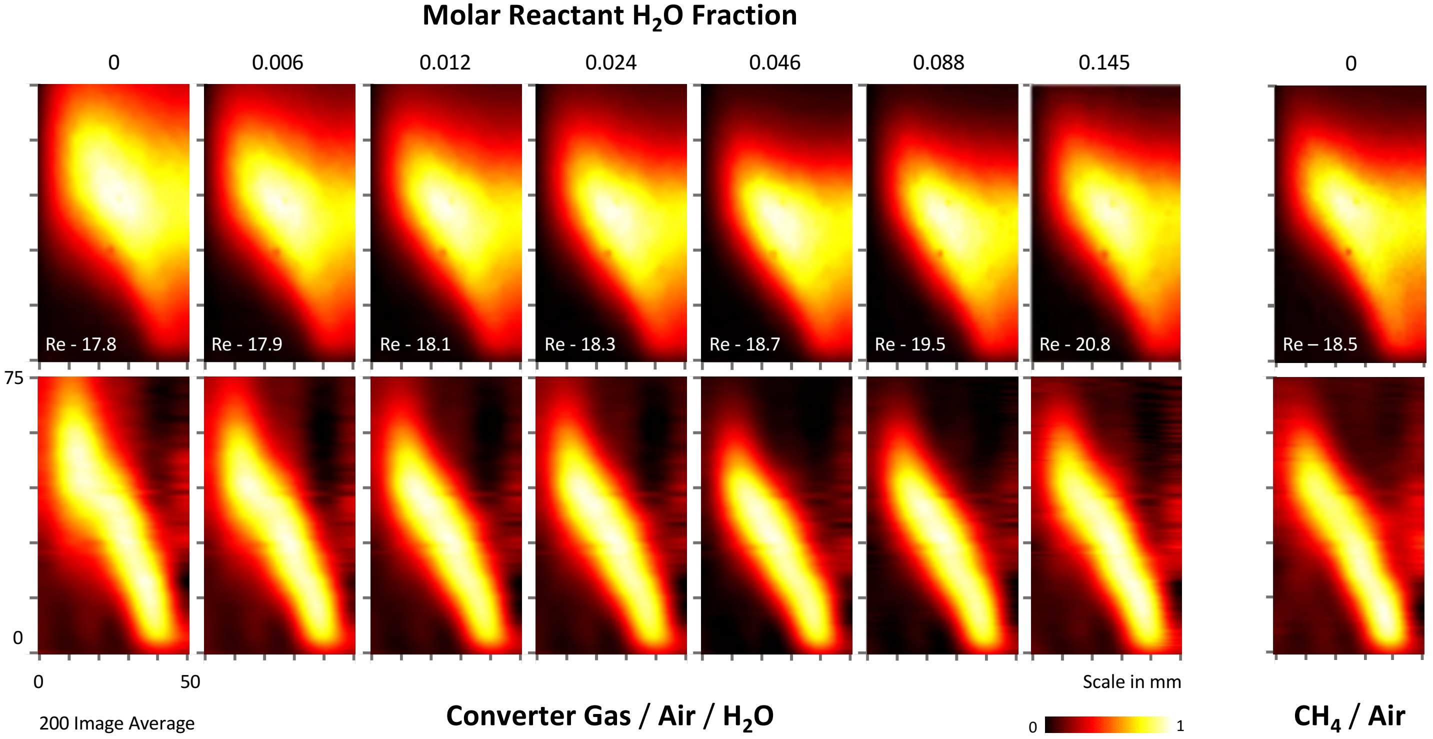
2017http://dx.doi.org/10.1016/j.combustflame.2016.11.010.

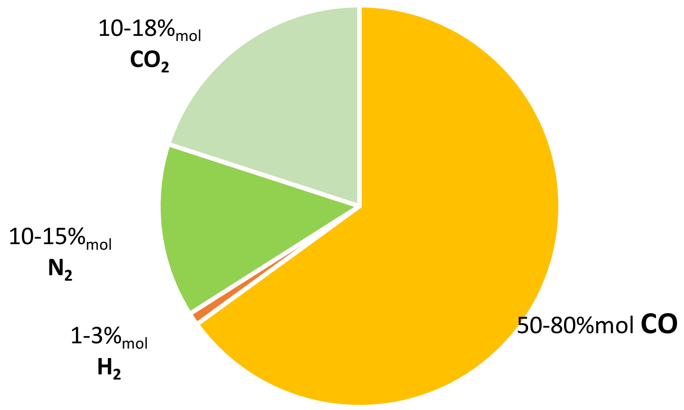
OH PLIF

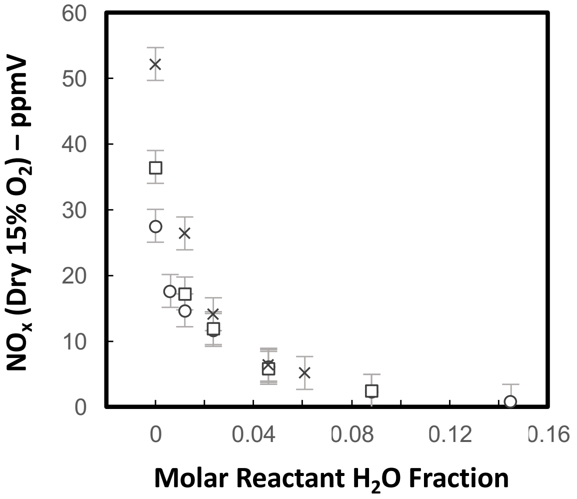


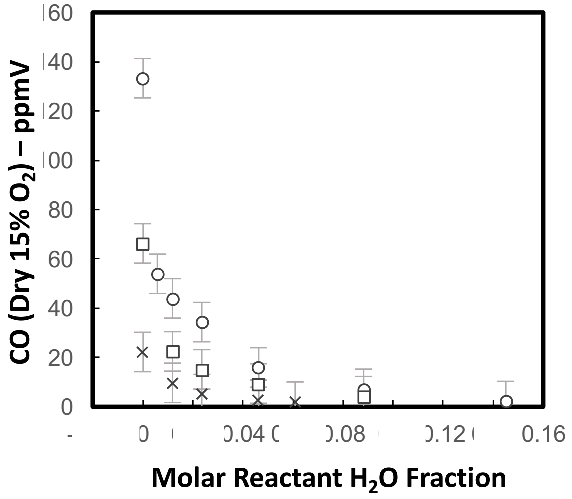
Humidified CO Work







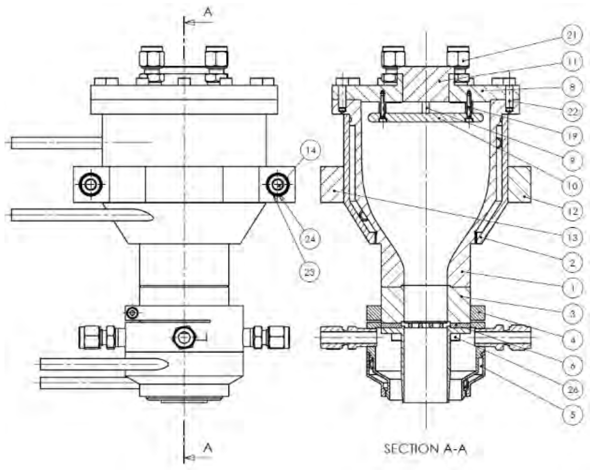


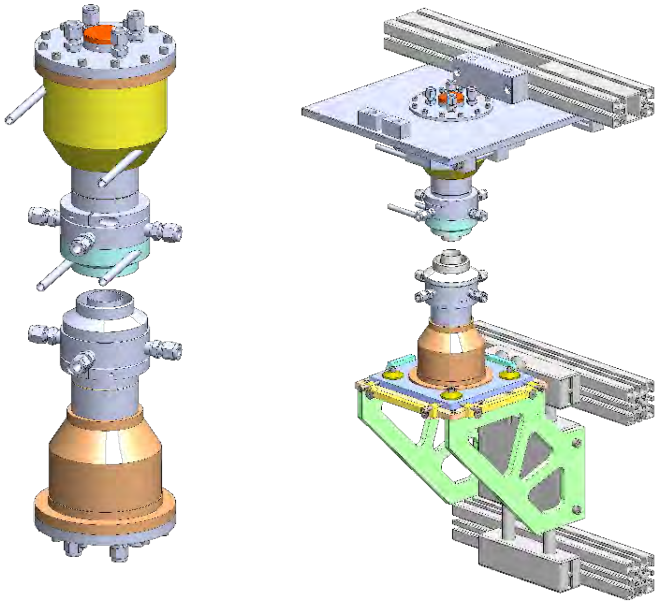


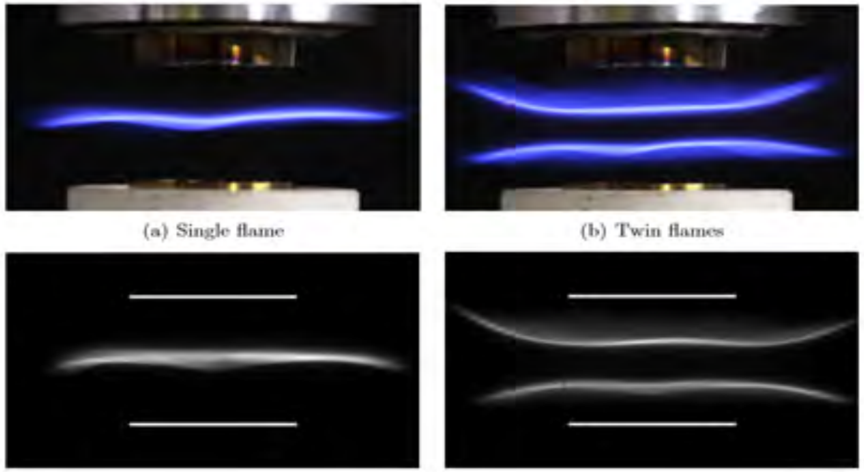
Counterflow Burner

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.





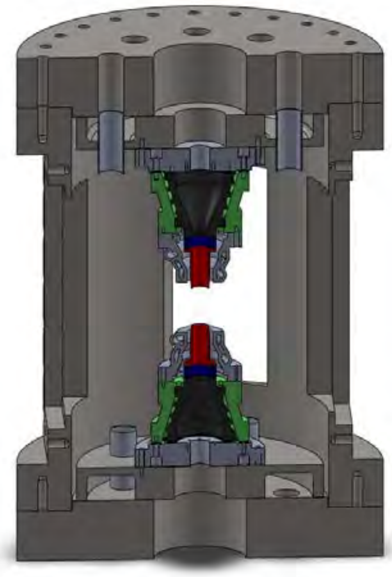

(a) Single flame

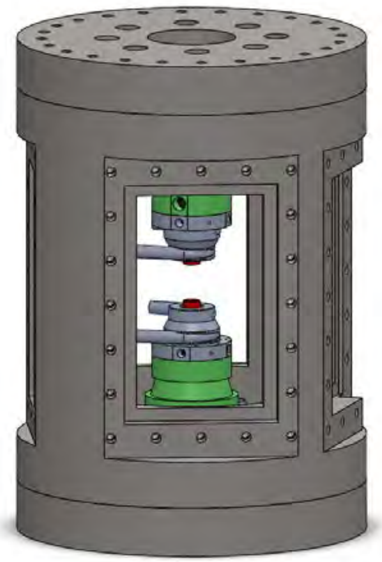
(b) Twin flames

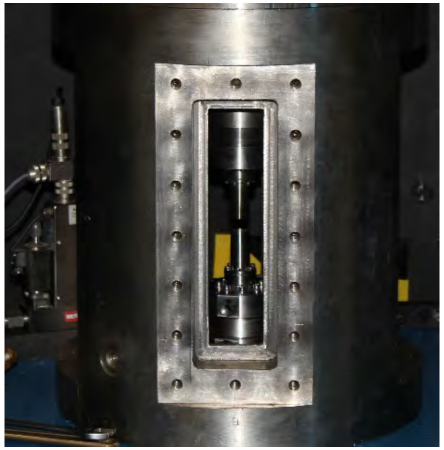
Counterflow Burner

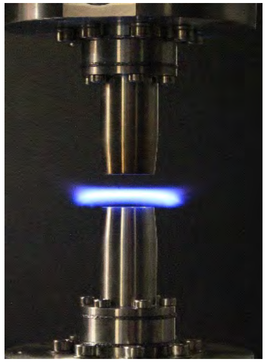
Development of the Cardiff Facility

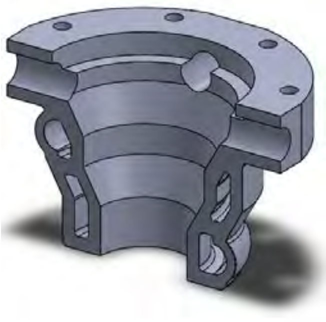
- Imperial design modified to operate at elevated temperature (473 K) and pressure (10 bar).
- Reactant preheat will facilitate combustion of prevaporised liquid fuels, and humidified combustion.
- Diametric quartz windows will allow for the application of optical diagnostic techniques.
- Design has 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.

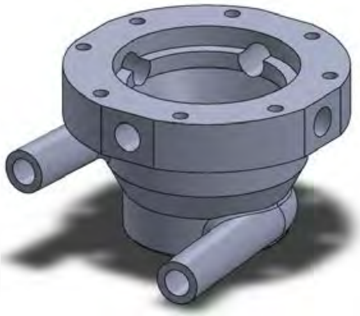


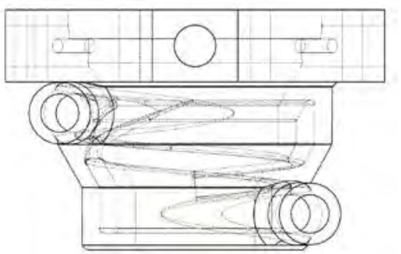






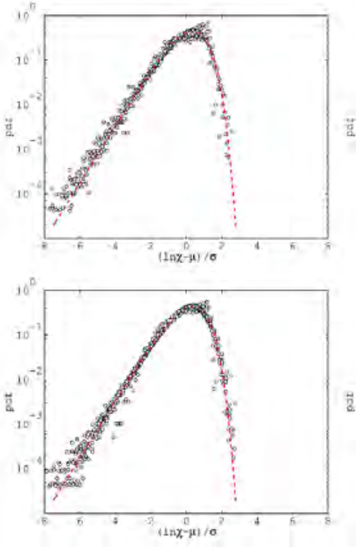


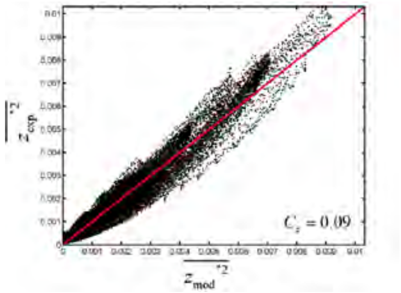




Turbulent flows

- **Scalar / Thermal Dissipation rate conditional on mixture fraction ir swirling flows with and without reaction**
  - Development of scalar dissipation rate measurements for non-reacting and reacting flows - Experiments in Fluids 55, (2014)
  - Measurements of Scalar Dissipation rate in unsteady gas jets, simulating automotive injectors – Physics of Fluids 27, (2015)
  - Measurements of scalar dissipation rate in non-reacting Swirl burners. Experimental evaluation of SGS models for LES and quantification of the behaviour in the flows – Physics of Fluids 27, (2015), and Physics of Fluids 28, (2016)
  - 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**
  - Simultaneous multiple plane measurements of reaction zone and flow velocity field [with emphasis on fractal grid flames]. [Fluid Dyn. Res. 45, (2013); Proc. Comb Inst. 35, (2015) & Combustion and Flame 162, (2015); publication in preparation]
  - 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]

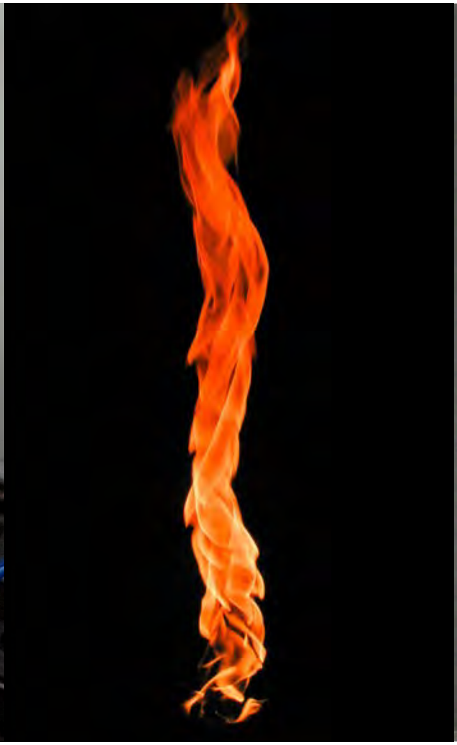
Combustion SIG – Oxford capabilities

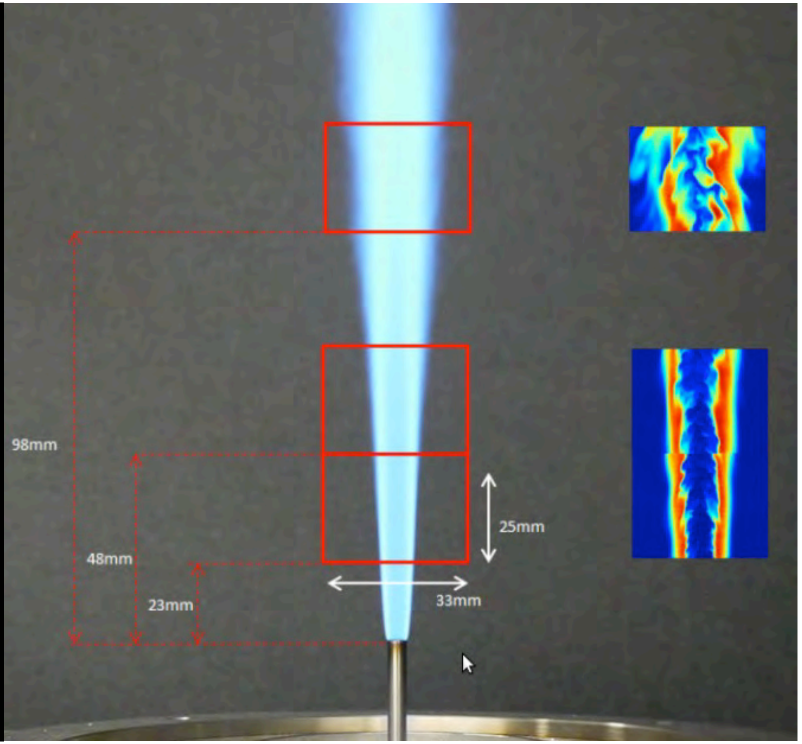
Ben Williams, Martin Davy and Richard Stone

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, CH_2O, CN…
- Localised extinction; heat release imaging
- Particle Image Velocimetry, ~10 Hz and 8 kHz

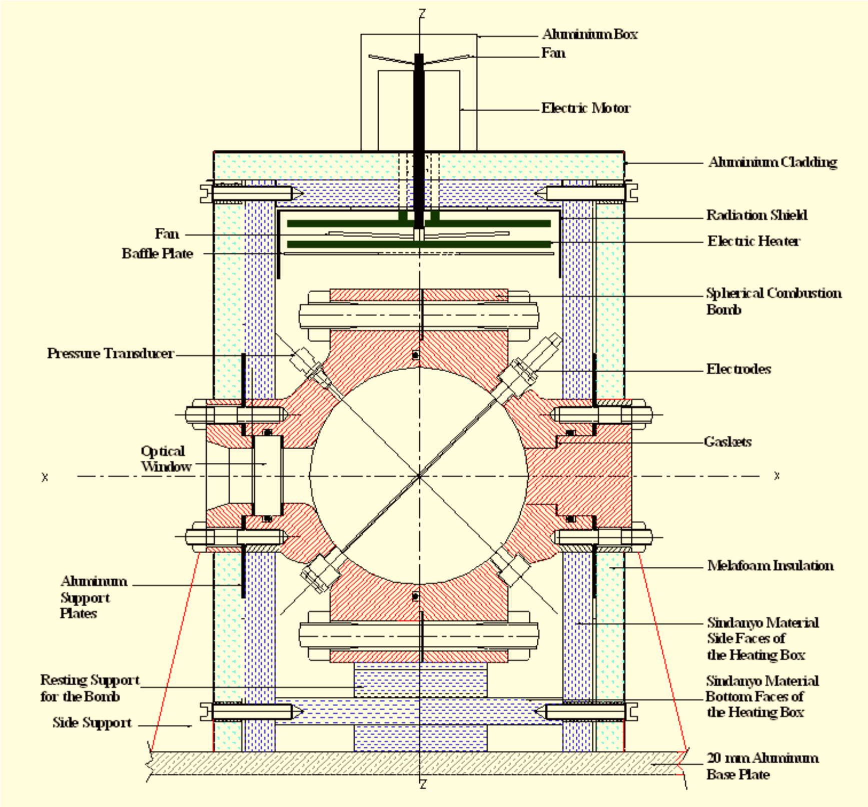
- New laser diagnostics labs in build now

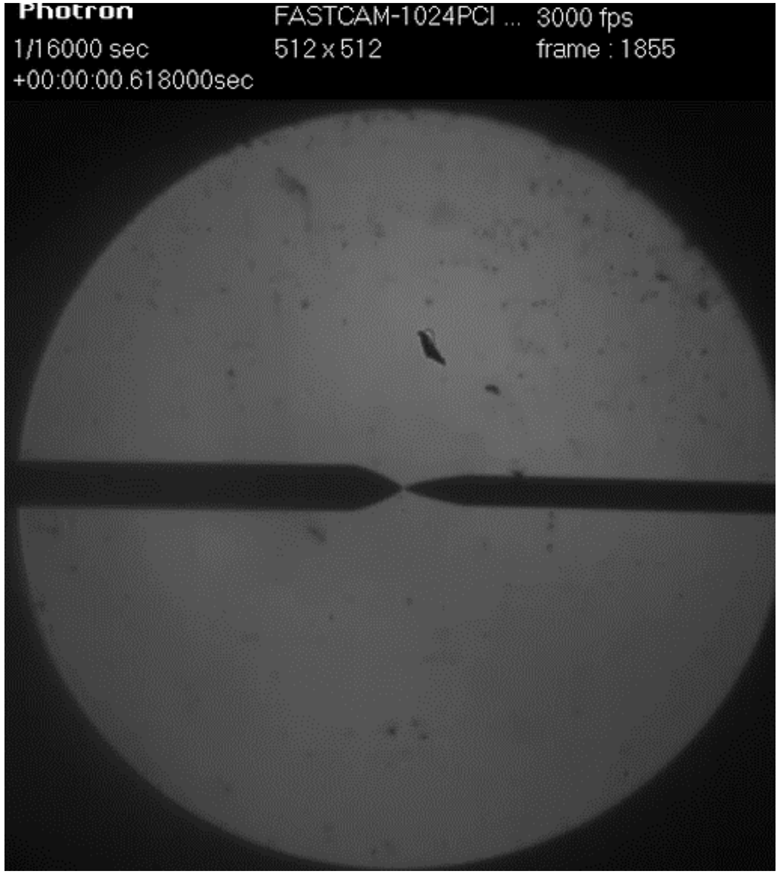
Other methods/comments

- **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

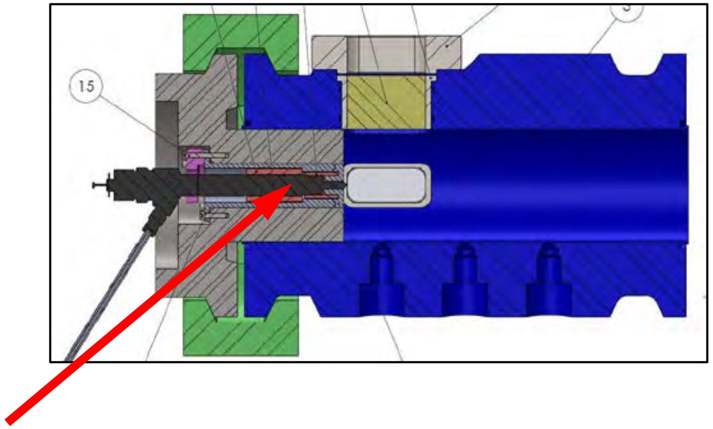




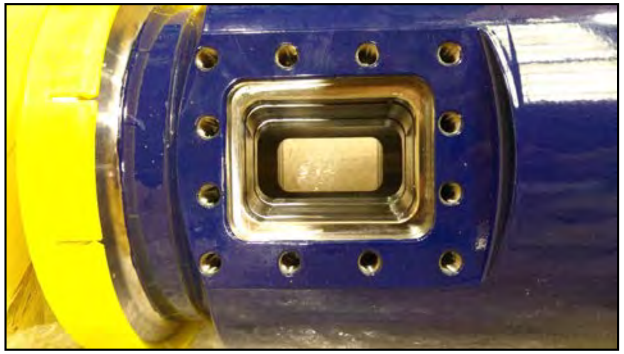
- Controlled environment
- Laminar burning velocity
- Schlieren, chemiluminescence

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

Condition	Pressure (bar)	Temperature (K)	Test duration (air driven, ms)	Test duration (He driven, ms)
Low Condition	50	500	5	14
Design – ECN ‘Spray A’	60	900	3	10
High condition	120	1500	-	8

- 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

University of Strathclyde
Dr Iain Burns

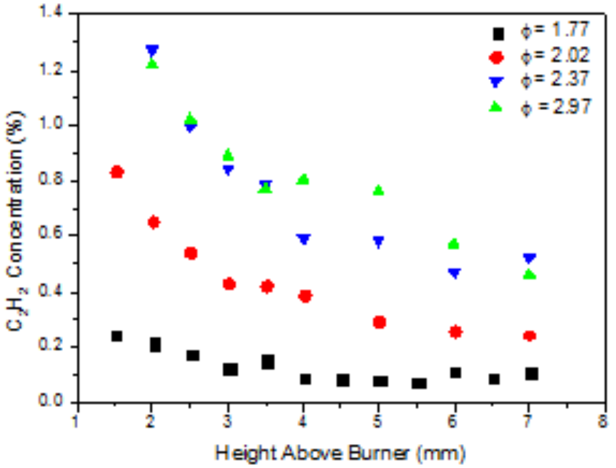
Measurement techniques:

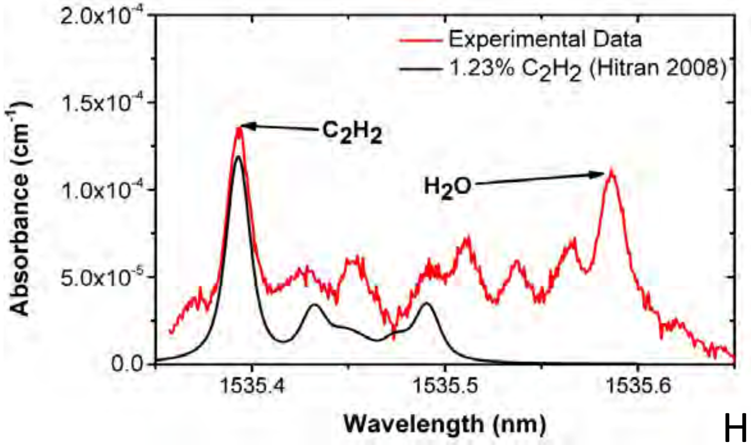
- Flame studies based on laser-induced fluorescence (LII) and laser-induced incandescence (LIF):
  - Polycyclic aromatic hydrocarbons (PAH)
  - Nanoparticulates / soot
  - Intermediates: OH, CH
  - Temperature

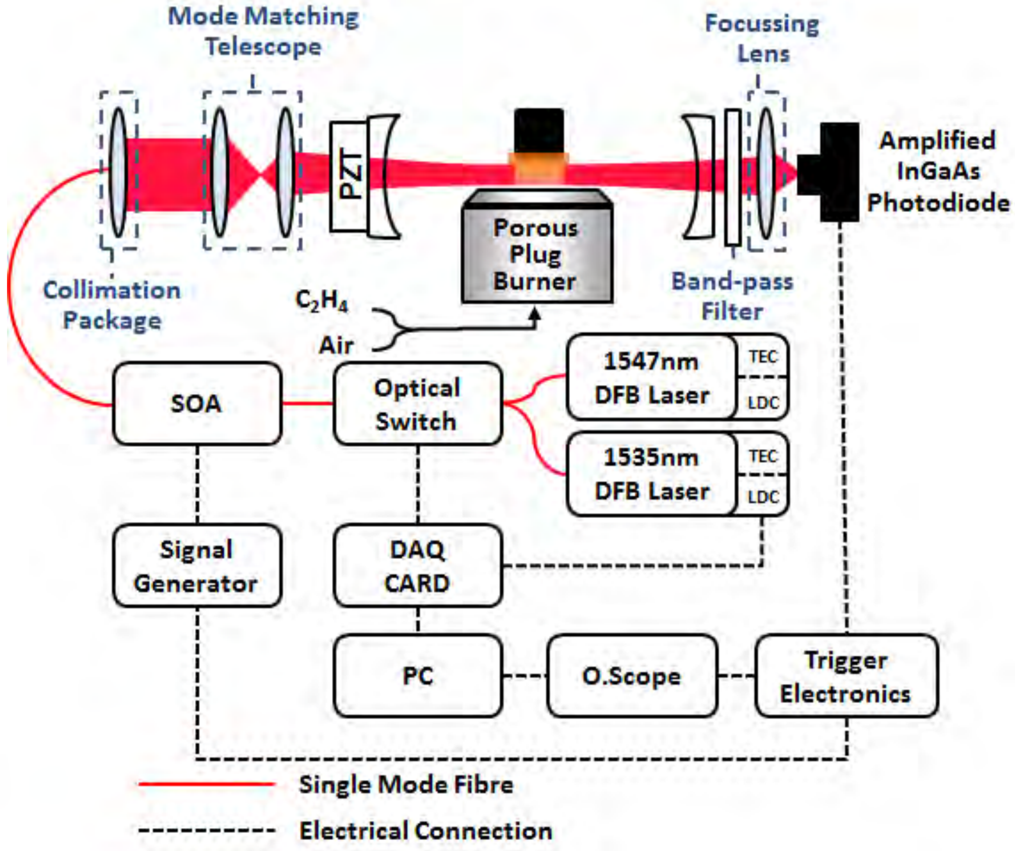
- Cavity-ring down and cavity-enhanced absorption spectroscopy:
  - Sensitive concentration measurements
    Intermediates:
    OH, $^1CH_2$, HCO, C_2H_2

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



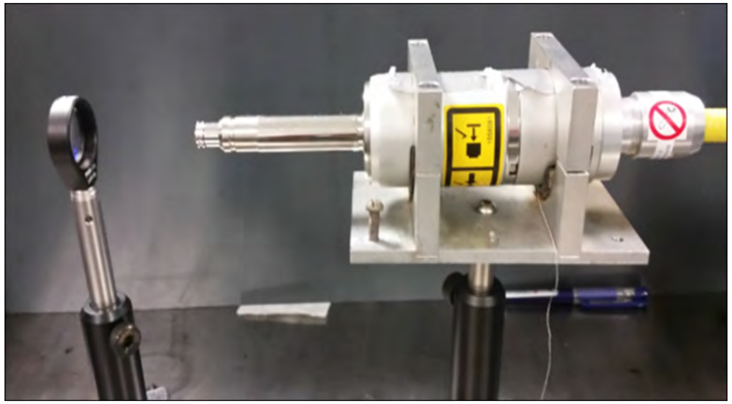


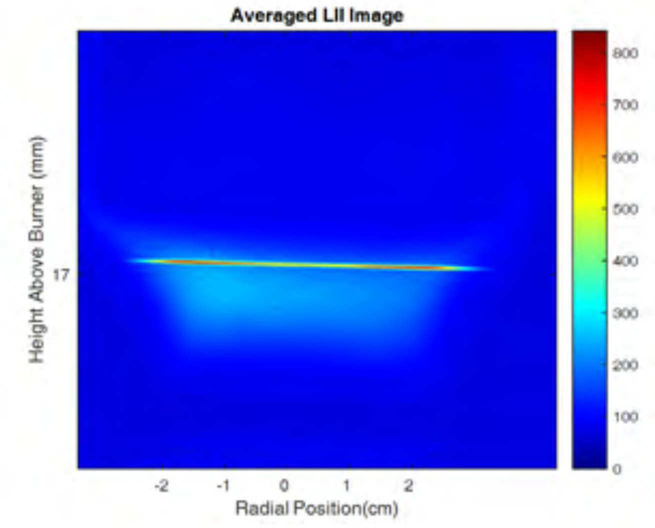


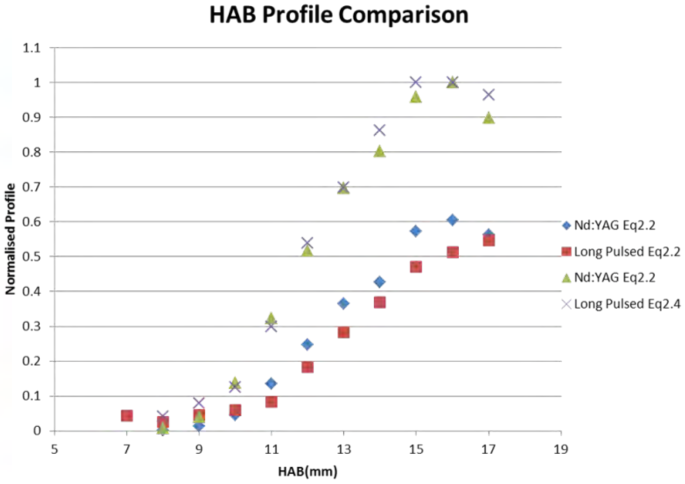
Humphries, G. S. et al. (2016). *IEEE Phot. J., 8*(1), 3900110

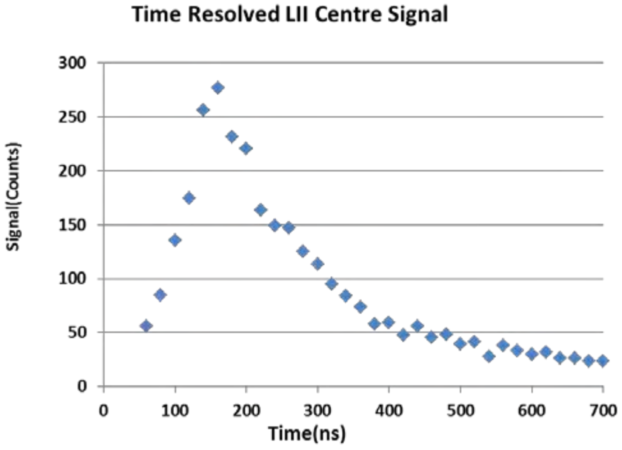
LII using a Long-Pulsed Fibre Laser

- 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









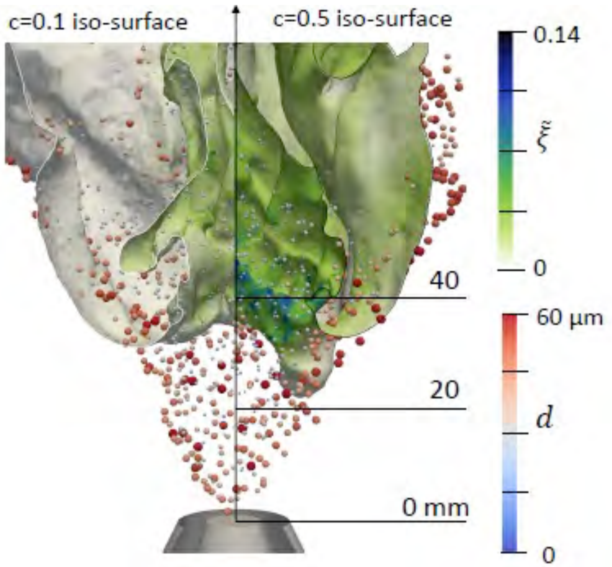
Robert Roy has a poster

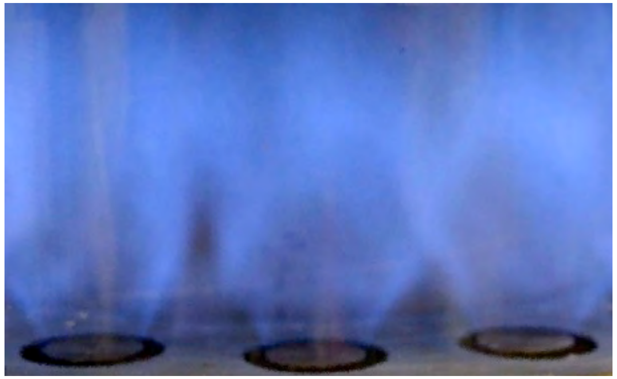
UNIVERSITY OF
CAMBRIDGE

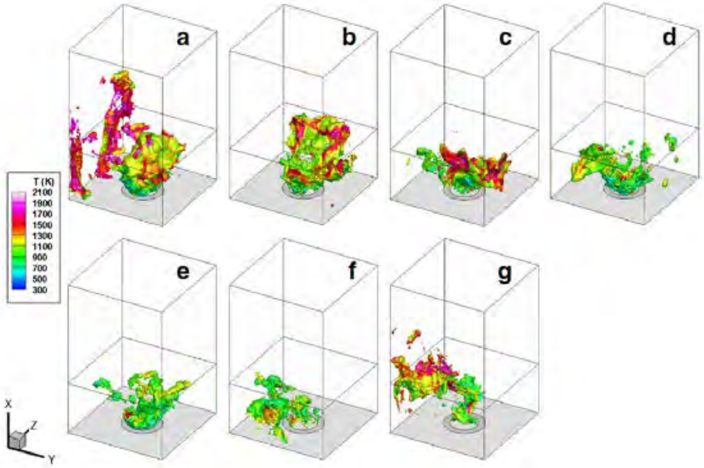
Mastorakos

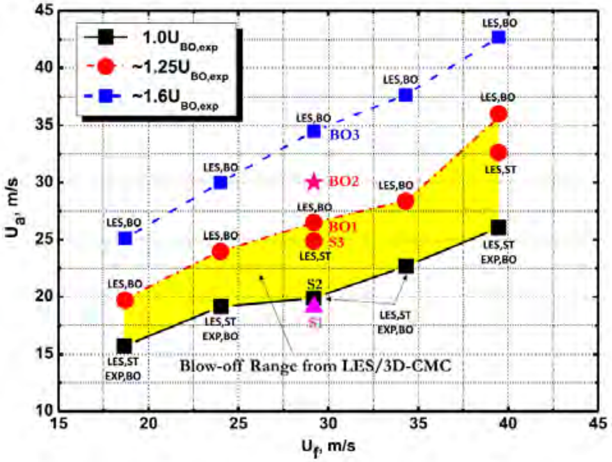
- **EXPERIMENTAL**
- Swirl flames: extinction, ignition, flame transfer functions
- Annular combustor: flame transfer functions, light-round
- Diagnostics: 10 kHz OH-PLIF, 10 Hz OH-PLIF, 10 Hz CH2O-PLIF, LIBS

- **COMPUTATIONAL**
- LES with Conditional Moment Closure: ignition, blow-off, emissions

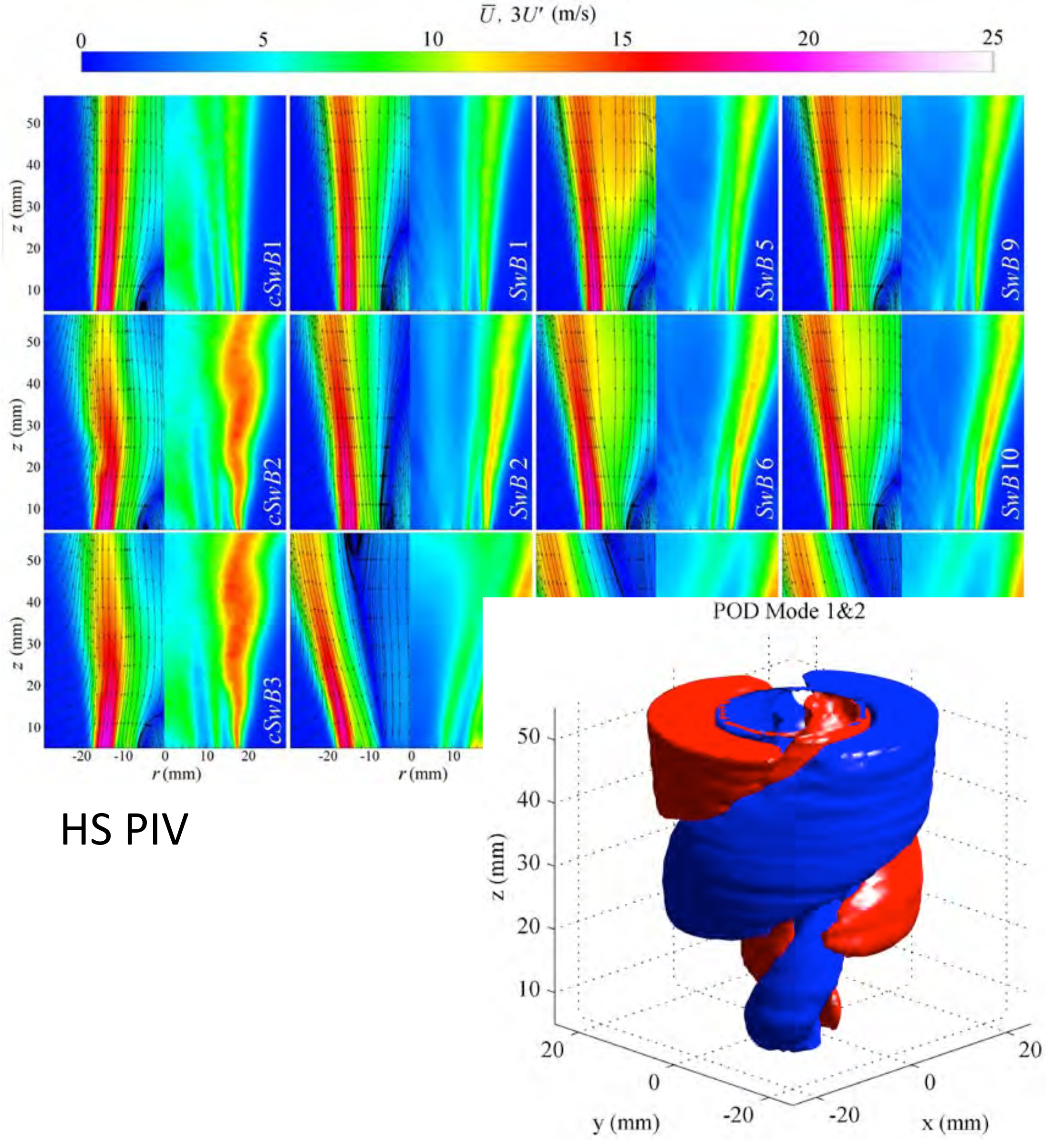




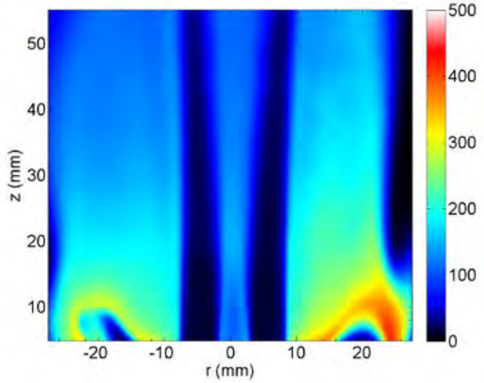




Hochgreb
Turbulent flames & sprays

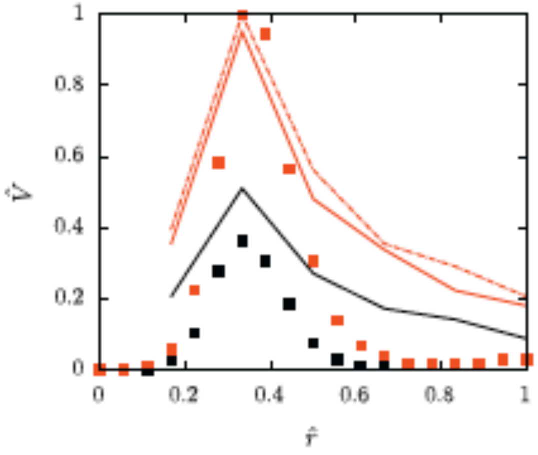


HS PIV



OH PLIF

droplet flux - PDA



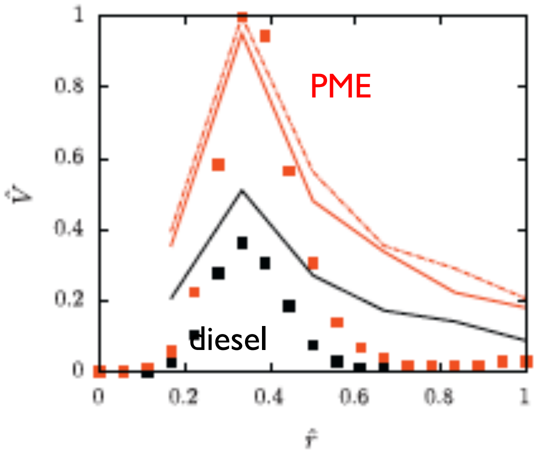
(b) $\hat{F}$, z = 15mm

Spray combustion

Chong, C.T., S. Hochgreb, Spray flame structure of rapeseed biodiesel and Jet-A1 fuel, Fuel. 115 (2014) 551–558 doi:10.1016/j.fuel.2013.07.059.

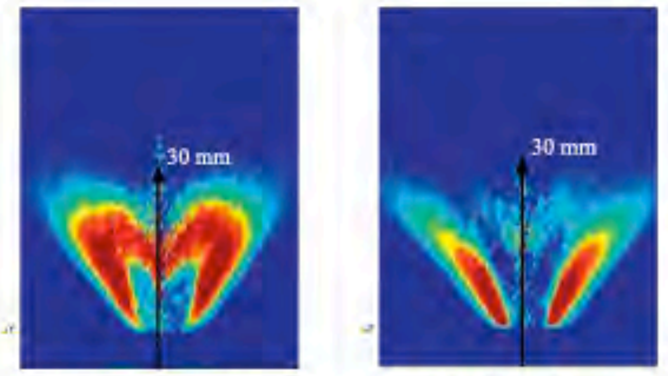
Mohd Yasin, M. F ., Cant, R.S., Chong, C.T., Hochgreb, S. Discrete multicomponent model for biodiesel spray combustion simulation, Fuel. 126 (2014) 44–54 doi:10.1016/j.fuel.2014.02.020.

droplet flux



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

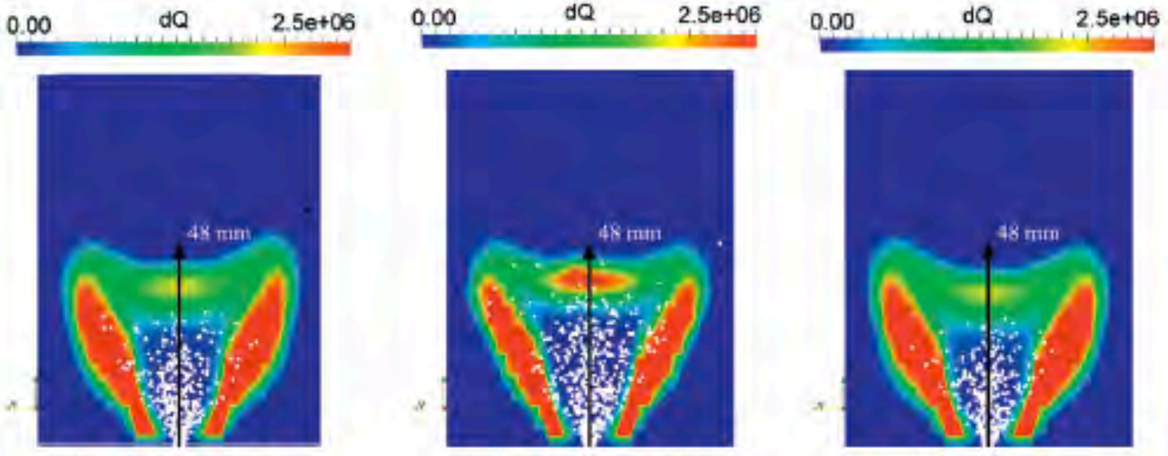
experiments



(a) biodiesel [1] (b) diesel [1]

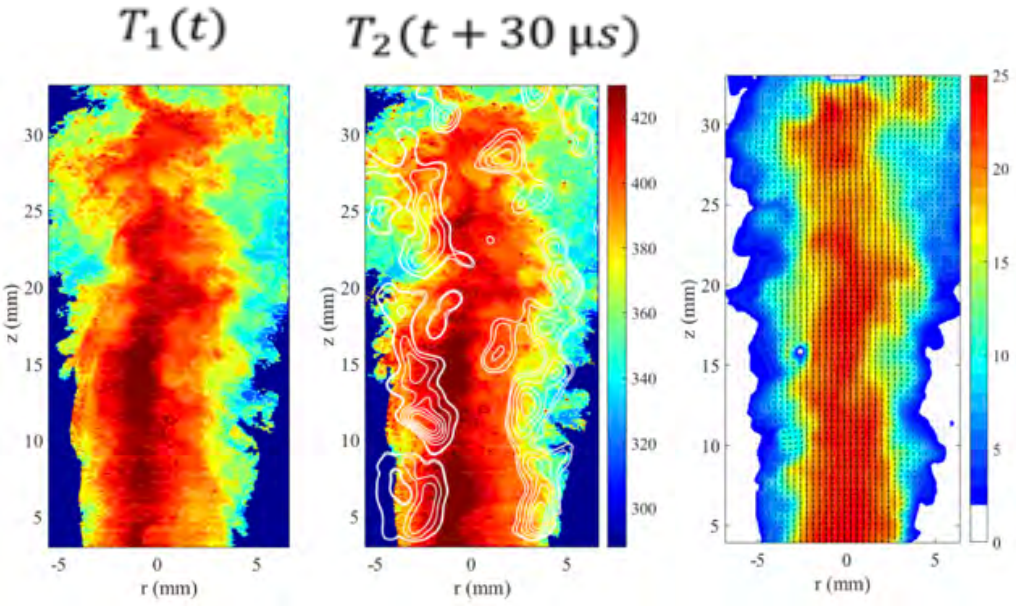
OH*

model



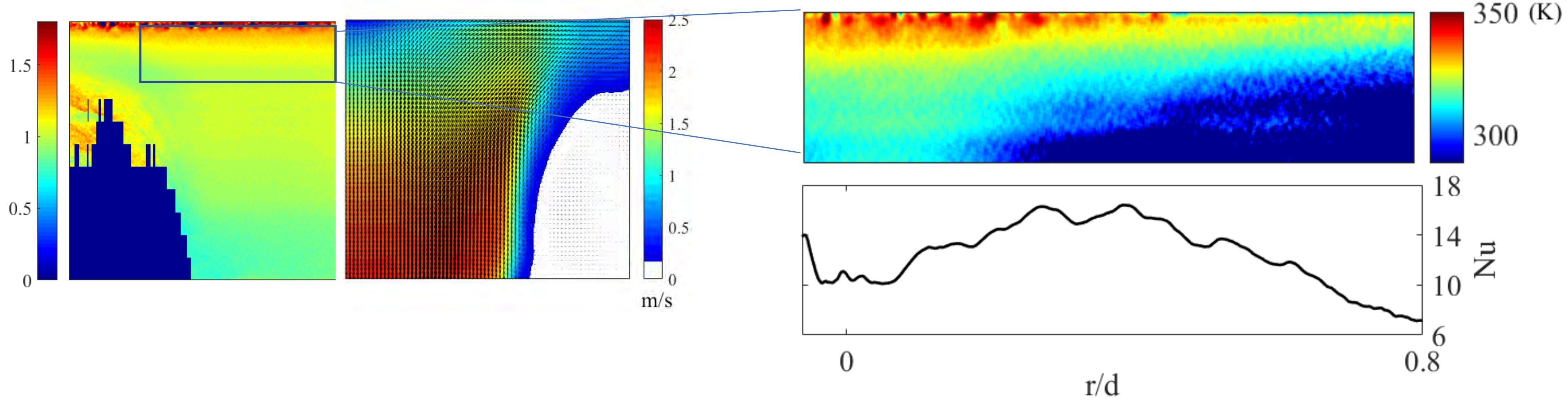
(c) PME-CTM (d) PME-DM (e) IDEA

Thermographic PIV



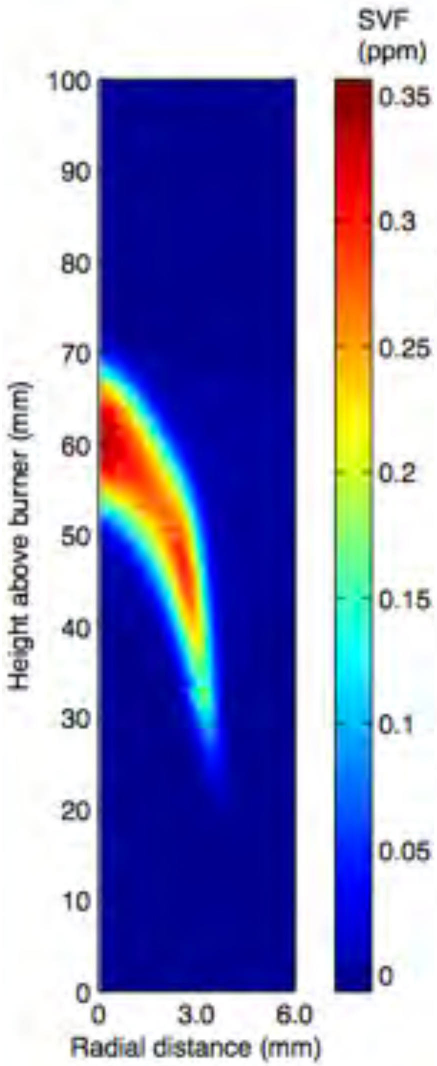
Fan, L., Gao, Y., Hayakawa, A., Hochgreb, S., 2017. Exp. Fluids 58, 34.DOI: [10.1007/s00348-017-2313-2](https://doi.org/10.1007/s00348-017-2313-2)

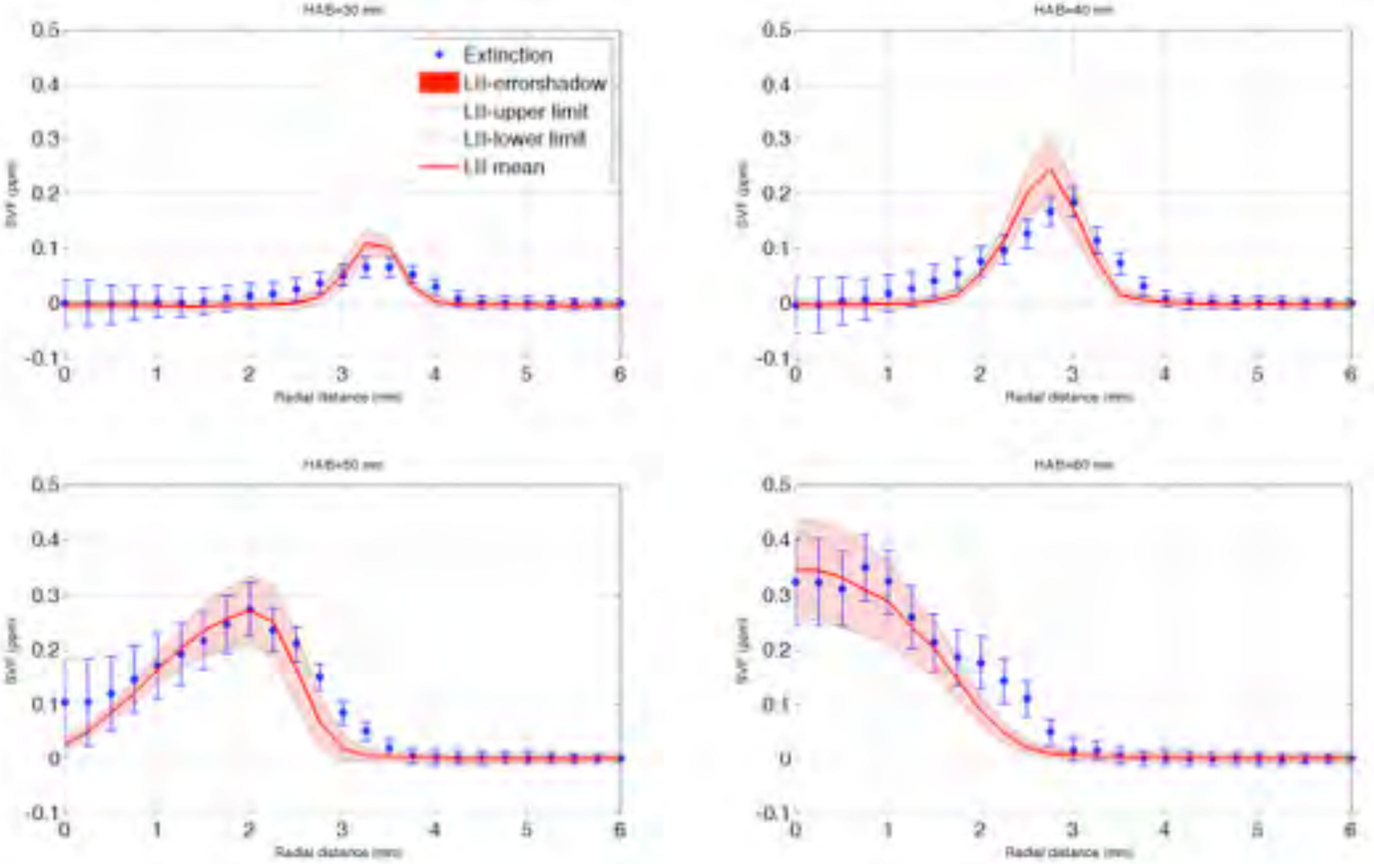
- Extensions: higher T
- Heat transfer
- LDA (Heyes/Strathclyde)



High resolution soot volume fraction via cavity extinction and LII

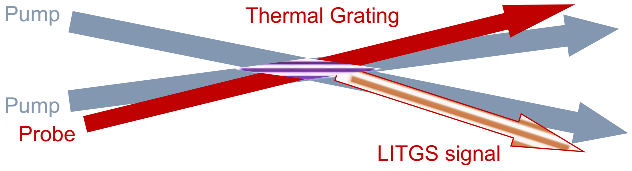
- extension: liquid fuels
- carbon nanotubes
- nano oxides



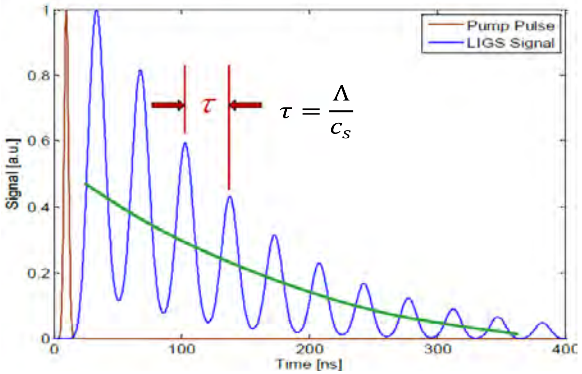


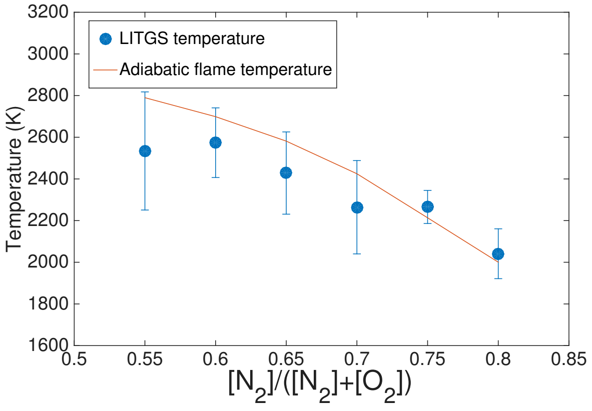
Tian, B., Gao, Y., Balusamy, S., Hochgreb, S., 2015. Appl. Phys. B 120, 469–487. DOI: 10.1007/s00340-015-6156-3

Laser-Induced Thermal Grating Spectroscopy (LITGS)



measure *c*





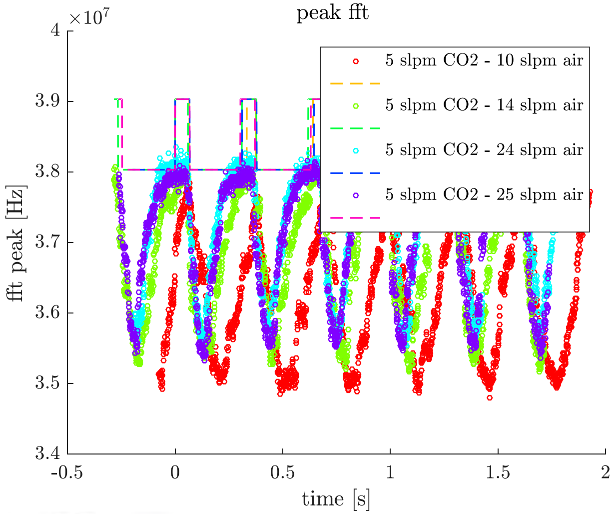
Hayakawa, A., et al., 2016. Japanese Symposium on Combustion , November 23-25, Sendai, Japan. p. P102.

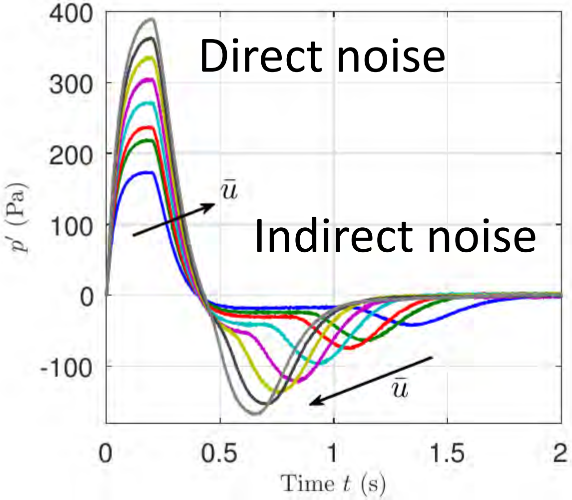
OH/5 bar CH4 flame

Extension:

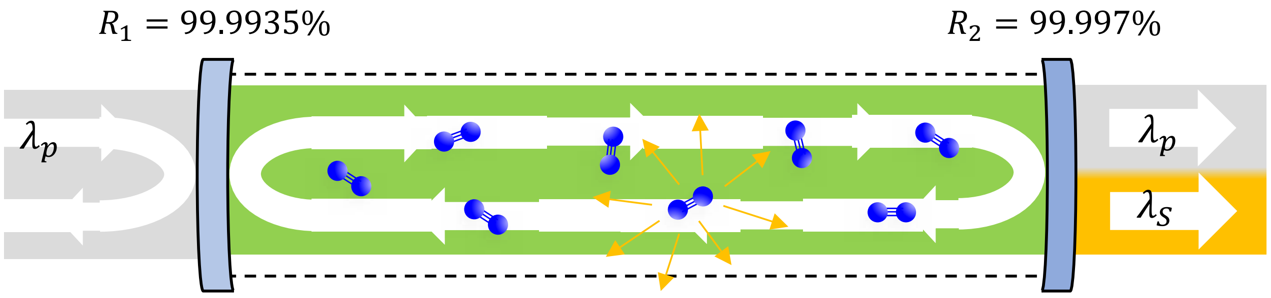
- 1 kHz *c* measurements entropy spots @ 355 nm (thermoacoustics)

DeDomenico/Fan/Williams /Shah/ Hochgreb



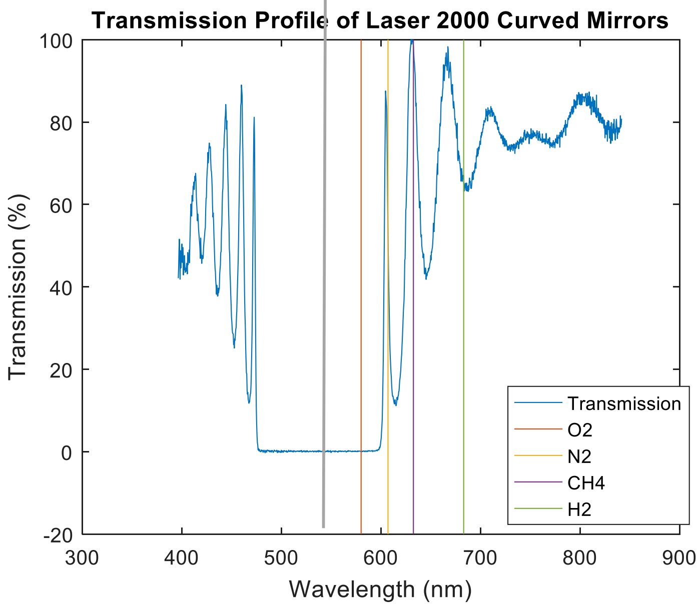


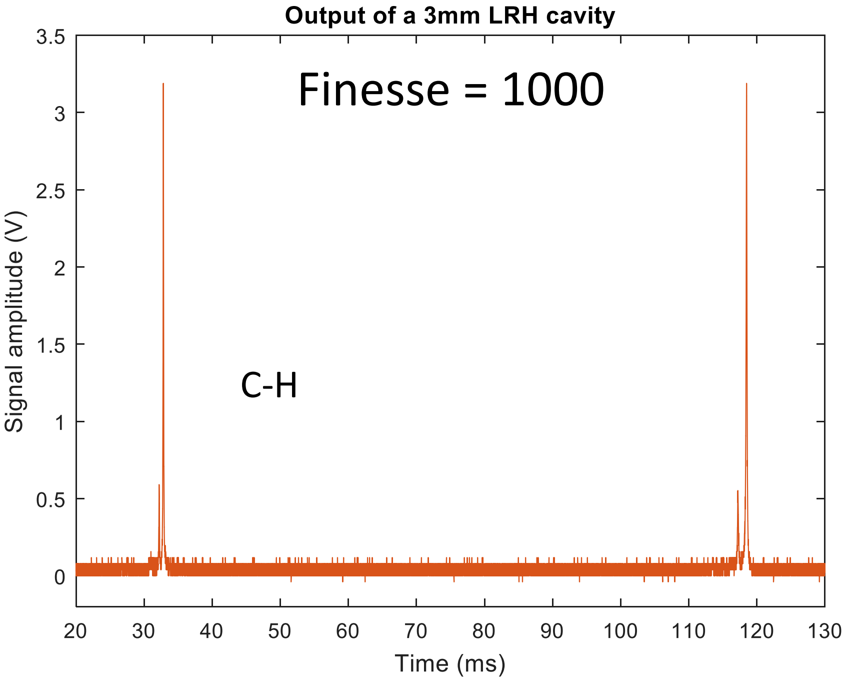
CERS – Cavity enhanced Raman spectroscopy



$$Finesse = \frac{FSR}{FWHM}$$

$\lambda_p = 532\text{mm}$


Transmission Profile of Laser 2000 Curved Mirrors


Output of a 3mm LRH cavity

Further afield

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

Loughborough (Carrotte):
- High pressure combustion facility

UCL:
- Heat release imaging

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

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

Summary

	CAM	CARD	IMP	OXF	STR	OTHER
Comb. Bomb		x		x		
Lam flame	x	x	x	x	x	
Shock tube				x		
Turb. Flame Imaging	x		x	x		EDIN UCL
Sprays	x	x	x	x		EDIN BRI
High pressure		x		x		EDIN
Diag. develop.	x			x	x	

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…