Measurements in thermoacoustic oscillations :
(ii) chemiluminescence and imaging

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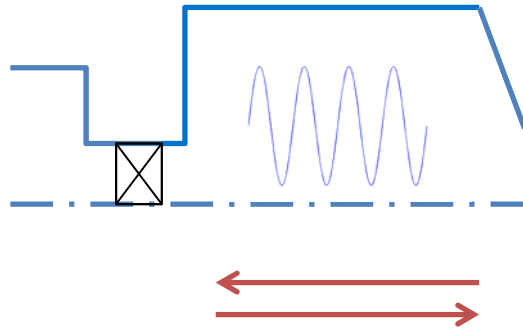
Tango Workshop

IIT Madras, 4-7 Feb, 2014

Outline

- ## Measurement of heat release rates
  - Direct method
  - Chemiluminescence
  - Pressure method

- ## Imaging measurements
  - Chemiluminescence
  - OH PLIF
  - High speed measurements
  - Phase-reconstructed measurements

Outline

- **Measurement of heat release rates**
  - Direct method
  - Chemiluminescence
  - Pressure method

- Imaging measurements
  - Chemiluminescence
  - OH PLIF
  - High speed measurements
  - Phase-reconstructed measurements

Take div (momentum) + D/Dt (thermodyn)

$$\frac{D^2 p'}{Dt^2} - c^2 \frac{\partial^2 p'}{\partial x^2} = \frac{\gamma - 1}{\gamma} \frac{p}{\mathcal{R}} \frac{D^2 s'}{Dt^2}$$

heat release rate/volume

Usual assumption:

$$\frac{Ds'}{Dt} = \frac{q'}{\rho T} = q' \frac{\mathcal{R}}{p}$$
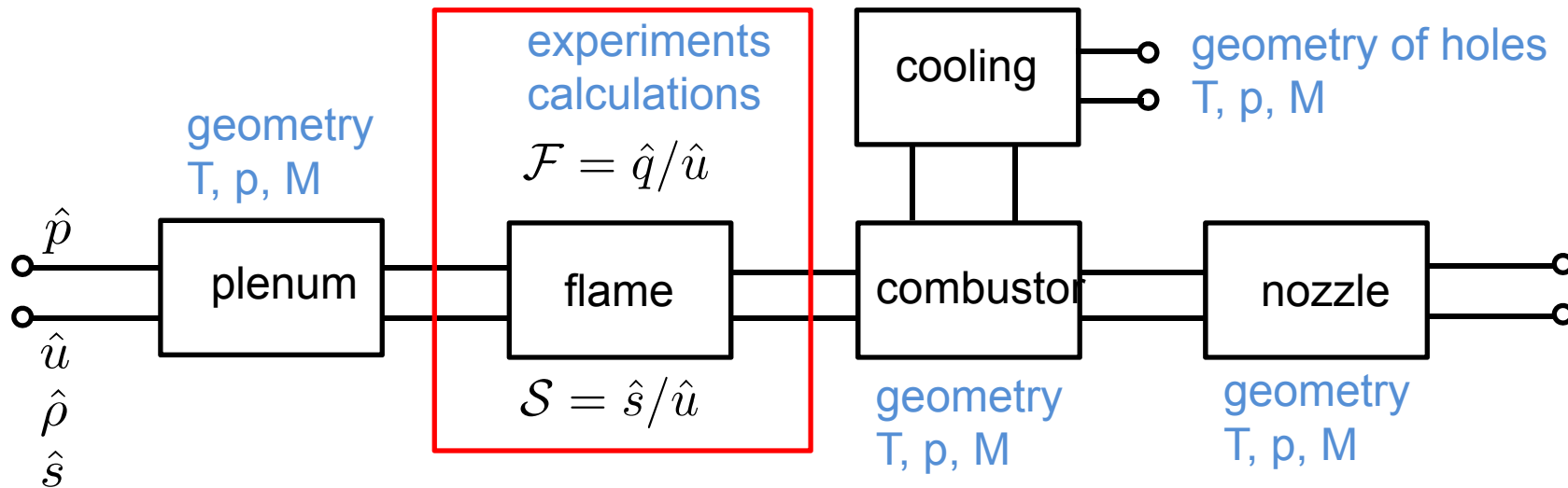
Connect q' to p' or u'

So that:

$$\frac{D^2 p'}{Dt^2} - c^2 \frac{\partial^2 p'}{\partial x^2} = \frac{\gamma - 1}{\gamma} \boxed{\frac{Dq'}{Dt}}$$

wave equation   source term

geometry
T, p, M

experiments
calculations

$$\mathcal{F} = \hat{q}/\hat{u}$$

cooling

geometry of holes
T, p, M

$\hat{p}$

$\hat{u}$

$\hat{\rho}$

$\hat{s}$

plenum

flame

combustor

nozzle

$$\mathcal{S} = \hat{s}/\hat{u}$$

geometry
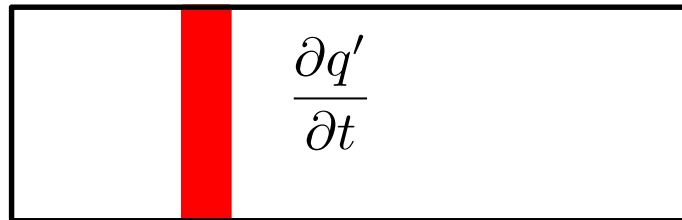T, p, M

geometry
T, p, M

Transfer function between boxes
Coupling between state variables

Allows de-coupling between different elements
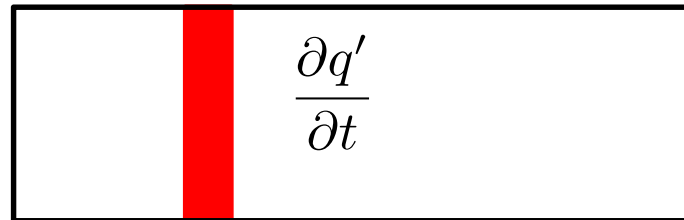Individual model for each sub-system

Largely most used and very successful model

Measurement of heat release rate fluctuation
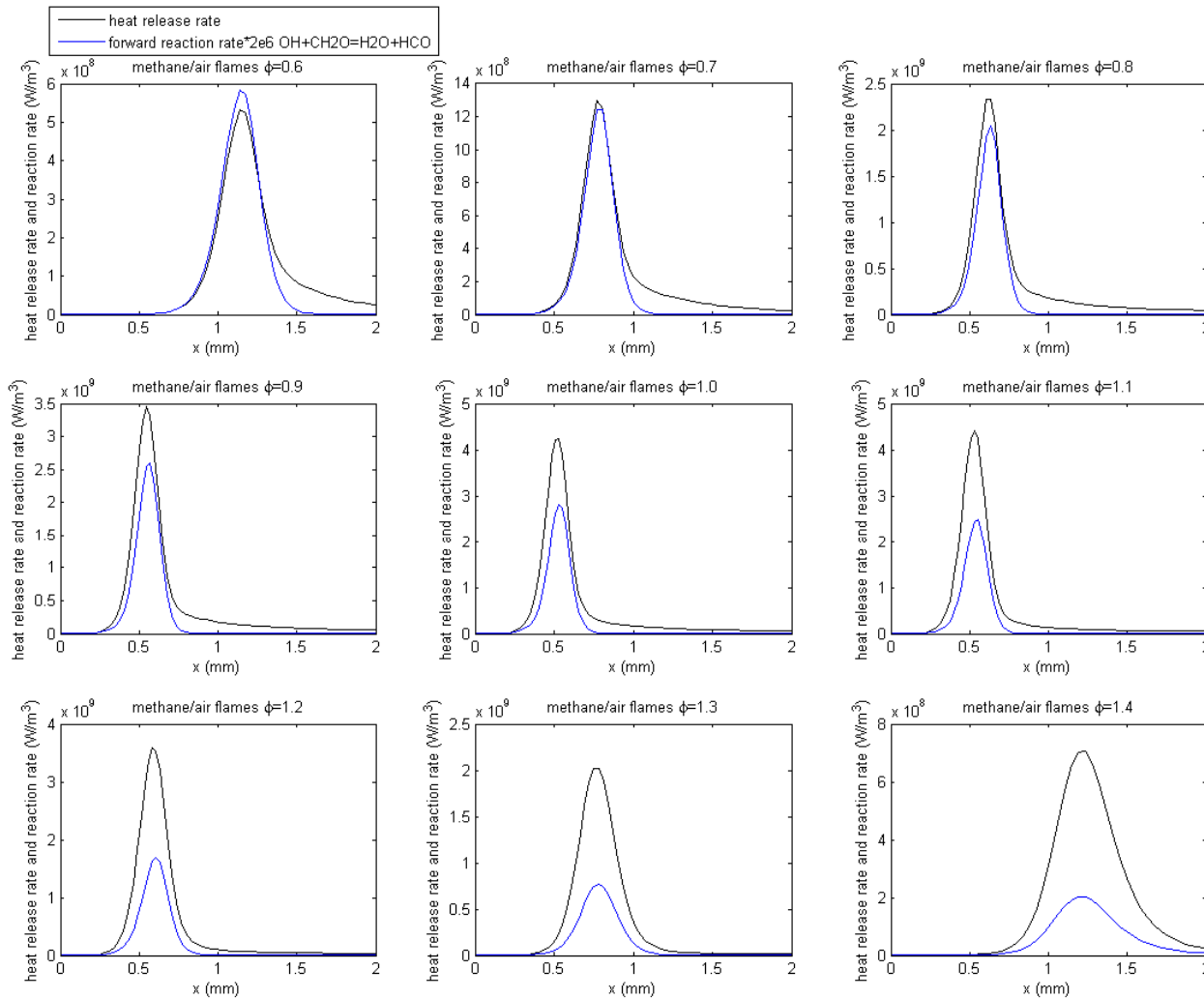
$$\frac{\partial q'}{\partial t}$$

- Direct
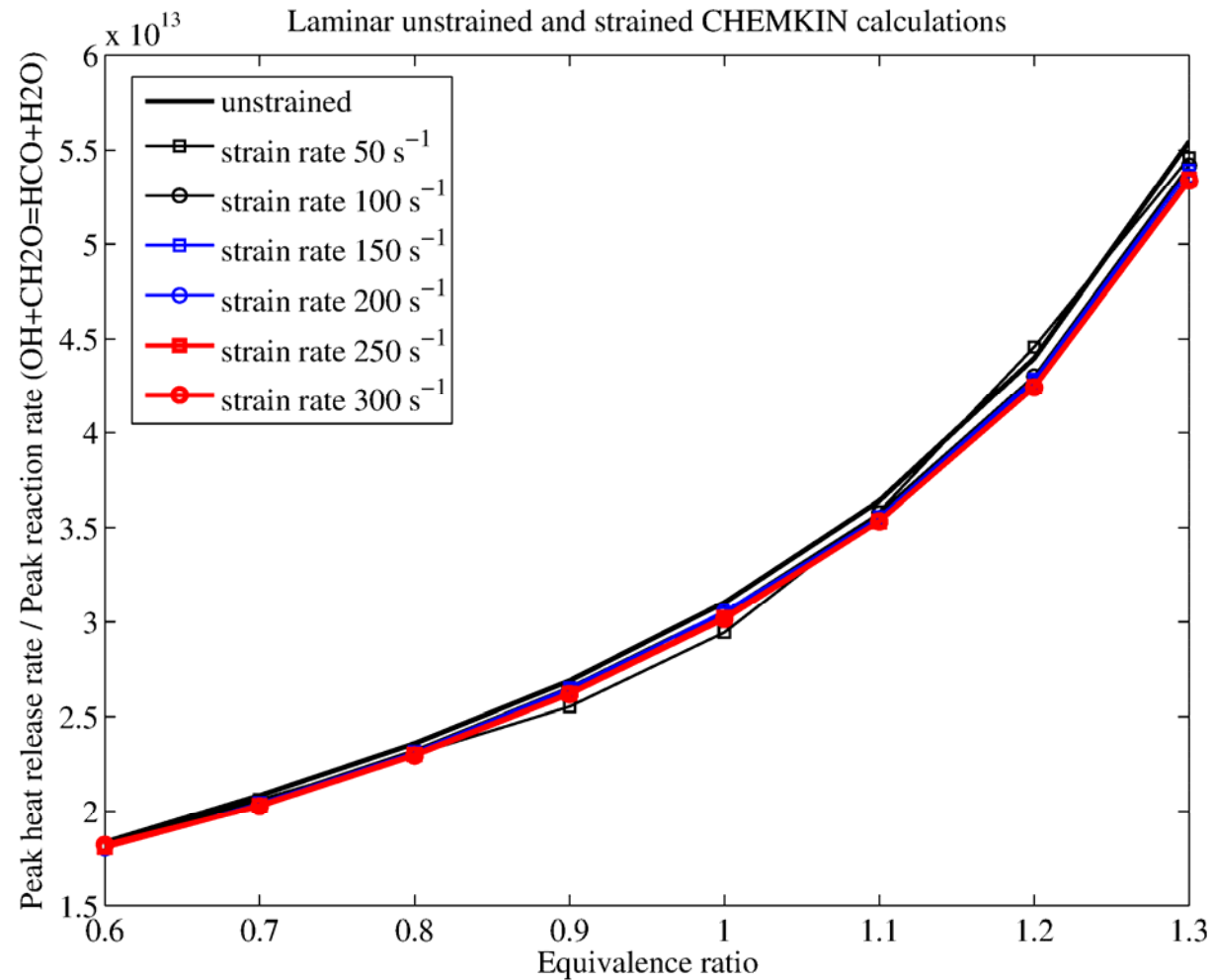- Chemiluminescence
- Pressure

Measurement of heat release rate fluctuation

$$\frac{\partial q'}{\partial t}$$

- Direct
- Chemiluminescence
- Pressure

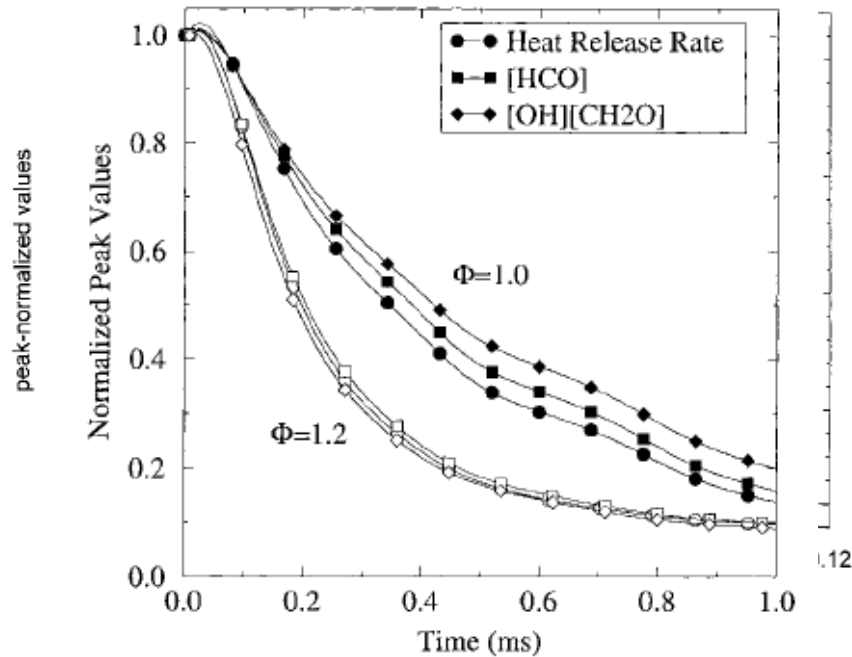# Heat release rate in methane flames

Heat release rate fluctuation

FIG. 1. Time variation of peak heat release rate, HCO concentration, and the product of OH and CH_2O concentrations. Taken on the centerline from a computed [4] 2-D counter-rotating vortex-pair colliding with a laminar pre-mixed flame (CH_4–air, ϕ = 1 and 1.2, 20% N_2 dilution). Values normalized to the values in the undisturbed flame.

Paul, P. H. and Najm, H. N. Proc. Comb. Inst. 27 (1998)

q'~ [OH][CH2O]
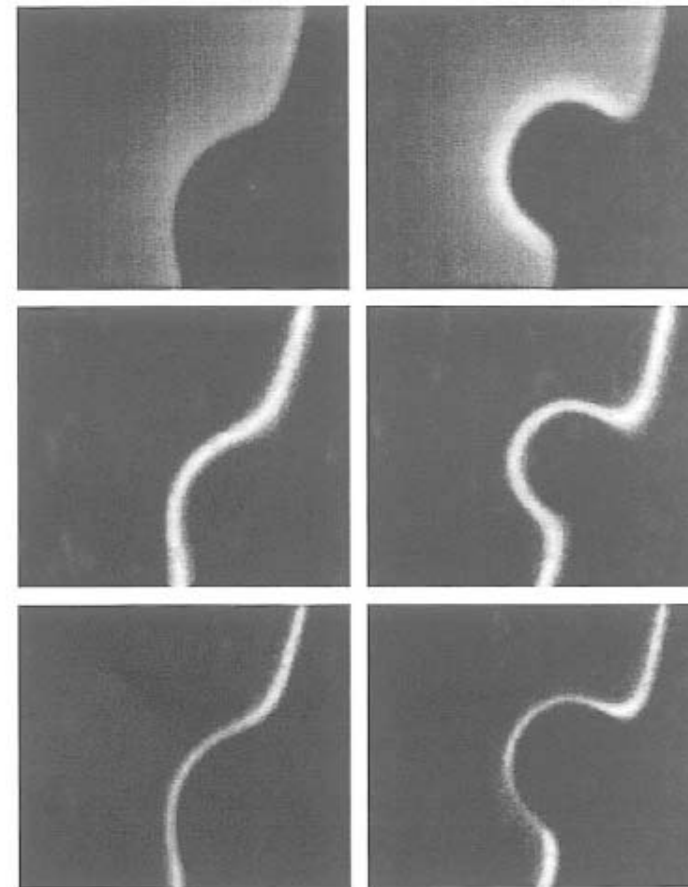Use excitation lines with low T dependence

FIG. 3. PLIF images of OH (*top*), CH_2O (*middle*), and the product (*bottom*) taken at 2 ms (*left*) and 6 ms (*right*) into the interaction of a line-vortex pair with a laminar V-flame. Field of view 20 by 17 mm. The color table is linear running from black (low) to white (high signal).
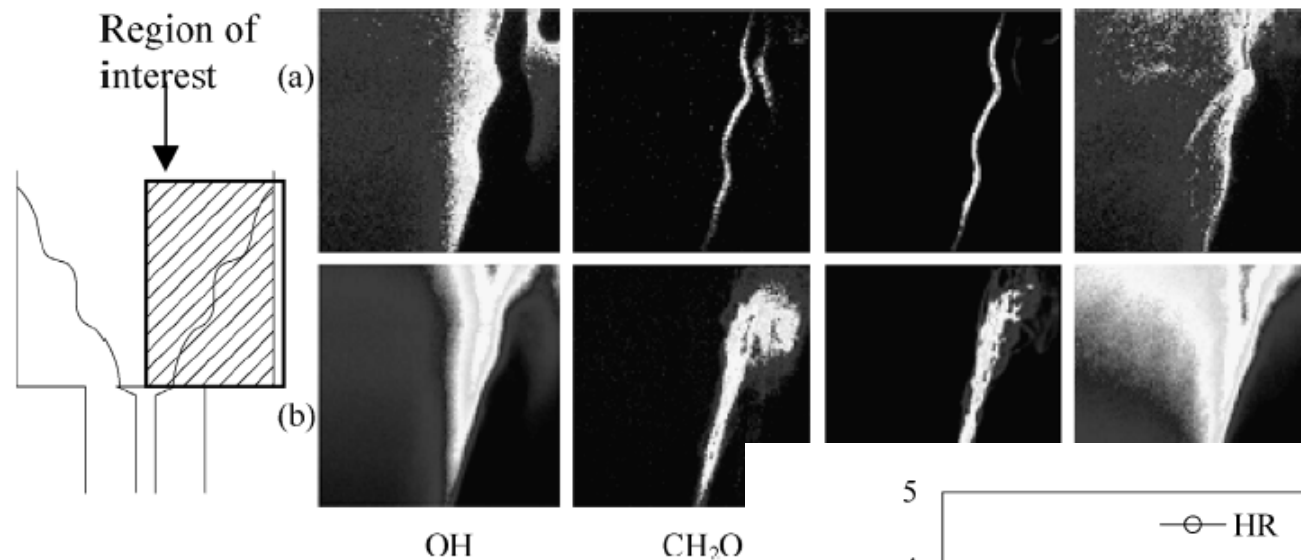
Region of interest

(a)

(b)

OH   CH₂O

Fig. 9. (a) Images of OH PLIF, CH₂O PLIF, and corresponding HR and
stabilized flame at $\phi = 0.6$. (b) Averaged OH PLIF, CH₂O PLIF, HR,

Ayoola et al, Combustion and Flame 144 (2006) 1–16

Quantitative measurements
Low sensitivity to strain
Requires substantial effort
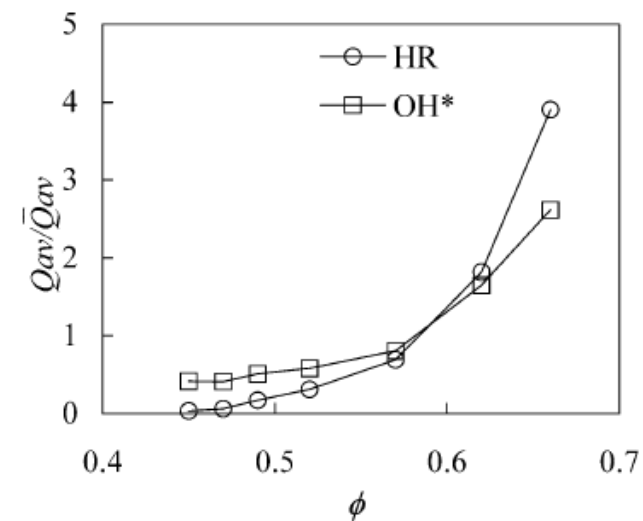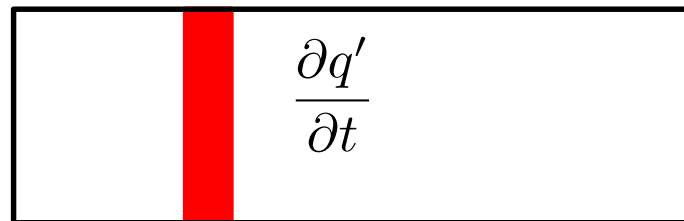Sensitive to equivalence ratio fluctuations

Fig. 10. Profiles of normalized HR and OH* in a bluff-body
stabilized flame at different equivalence ratios.

1

Measurement of heat release rate fluctuation

$$\frac{\partial q'}{\partial t}$$

- Direct

- Chemiluminescence
  - Premixed flames
  - ϕ oscillations
  - ϕ imaging

- Pressure

Spectroscopic studies of low-pressure flames; temperature measurements in acetylene flames

By A. G. GAYDON AND H. G. WOLFHARD, *Imperial College, London*

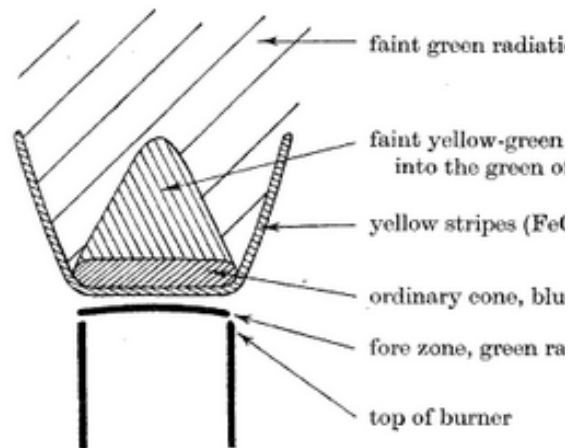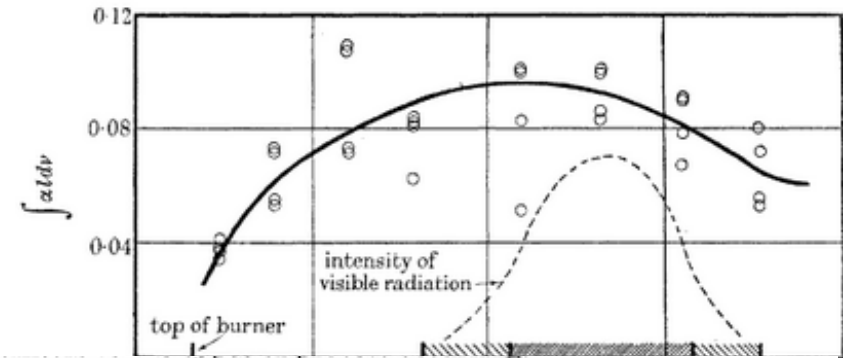(*Communicated by Sir Alfred Egerton, F.R.S.—Received 9 January* 1948)

faint green radiati

faint yellow-green into the green o

yellow stripes (Fe(

ordinary cone, blu

fore zone, green ra

top of burner

FIGURE 1. Flame coloured with
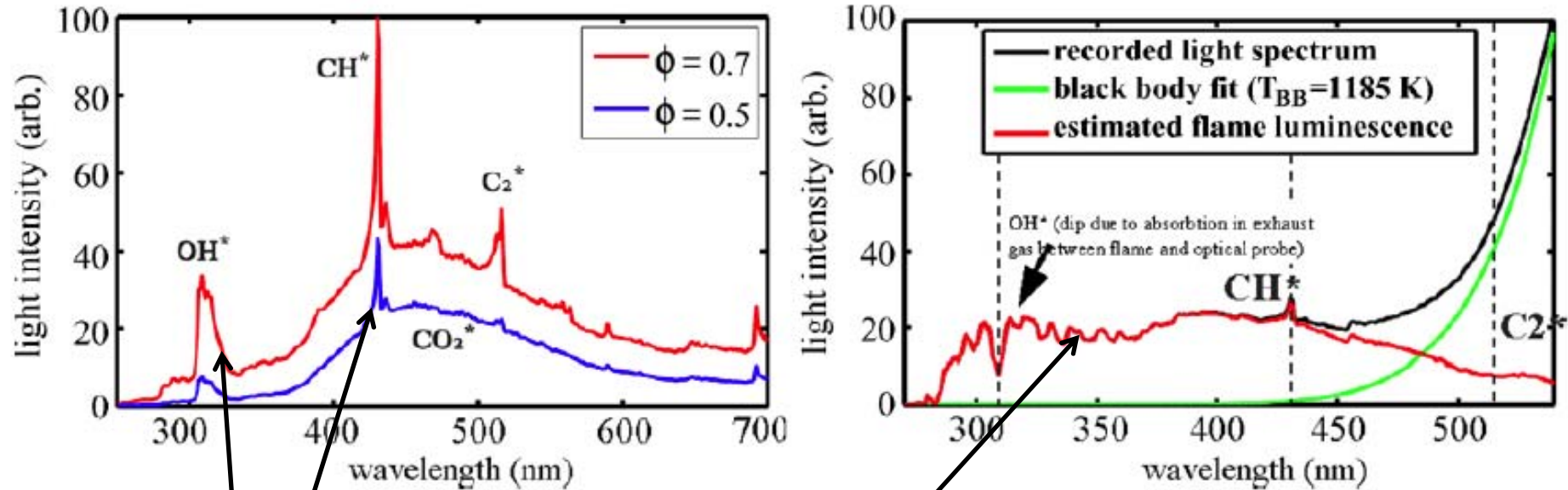
The experimental arrange:

All these spectroscopic methods of measuring the temperature appear to give values which are much too high. This might appear to indicate that the flame contains some active species, such as for example an abnormally high concentration of fast electrons, which cause strong excitation of all substances in the flame. However, this is not supported by the observation that all the Fe lines do not reverse at the same temperature, or the fact that the rotational temperatures are in general higher than the excitation temperatures. Thus in the low-pressure flame of acetylene with air we have,

Theoretical flame temperature	2400° K
Excitation temperature by Fe lines	3500° K
Excitation temperature of OH	< 3800° K
Rotational temperature excited OH	5700° K

On the other hand, the temperature of the unexcited OH radicals (observed by absorption) probably does not differ much from the theoretical equilibrium value. It seems fairly certain that in these flames with acetylene the excitation of the OH is due to chemiluminescence. This is shown by the great strength of the OH radiation from these flames; it is around 500 times greater than from an oxy-hydrogen flame which has a comparable temperature and OH concentration. Also the OH radiation is vastly stronger in the reaction zone than just above, where the radiation is no doubt mainly thermal in origin.

Guethe, F., D. Guyot, G. Singla, N. Noiray, B. Schuermans, Chemiluminescence as diagnostic tool in the development of gas turbines, **Appl. Phys. B Lasers Opt**. **(2012)** 1–18.

Distinct lines

Lines subsumed by luminescence

Fig. 1 Chemiluminescence spectra of swirl stabilised premix lab burners at atmospheric (*left*) and elevated gas turbine (>15 bar) pressure (*right*) [32]
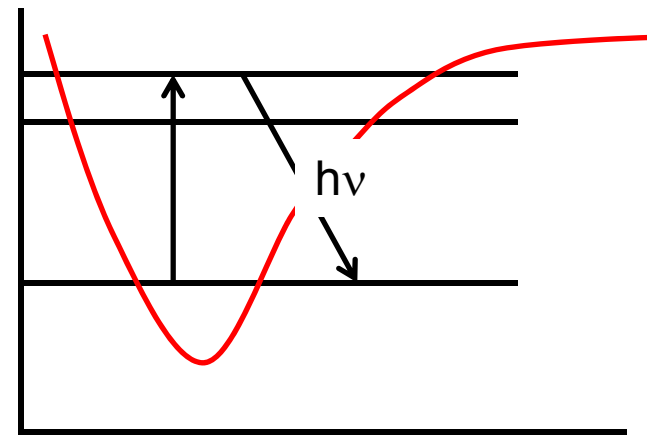
Chemiluminescence mechanisms

CH*:

C2 + OH → CH* + CO

C2H + O2 → CH* + CO2

C2H + O → CH* + CO

Small molecules
→ energy does not accommodate in bonds
→ energy levels compatible with visible range

OH*:

CH* + O2 → OH* +CO

HCO+O → CO + OH*

CO2*:

HCO+O → CO2* + H

CH2 + O2 → CO2* + H + H

$h\nu$

CH*/OH* ratio, stoichiometry and power

Fig. 3. Dependence of CH*/OH* on equivalence ratio for various inlet axial Re in the swirl combustor (solid line: 4th order least-square fit, dashed: 95% confidence).

Muruganandam, T.M., B.-H. Kim, M.R. Morrell, V. Nori, M. Patel, B.W. Romig, et al., Optical equivalence ratio sensors for gas turbine combustors, Proc. Combust. Inst. 30 (2005) 1601–1609.
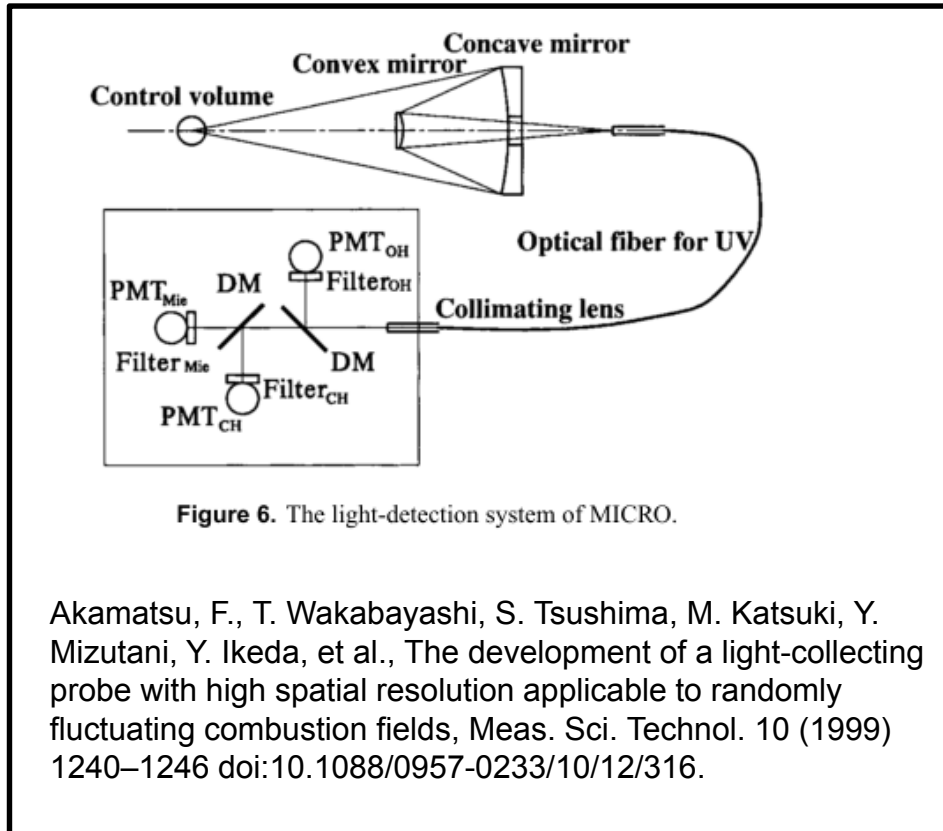

Fig. 6. Volume integrated chemiluminescence in the liquid fuel combustor (n-heptane) ($f = \phi$ varied by adjusting fuel, a = air adjusted).

- Premixed flames: CH*/OH* ratio scales with ϕ
- Total CH*, OH* chemiluminescence scales with power
- Partially mixed flames: ?

Figure 6. The light-detection system of MICRO.

Akamatsu, F., T. Wakabayashi, S. Tsushima, M. Katsuki, Y. Mizutani, Y. Ikeda, et al., The development of a light-collecting probe with high spatial resolution applicable to randomly fluctuating combustion fields, Meas. Sci. Technol. 10 (1999) 1240–1246 doi:10.1088/0957-0233/10/12/316.

Hardalupas, Y., M. Orain, C. S. Panoutsos, a. M.K.. Taylor, J. Olofsson, H. Seyfried, et al., Chemiluminescence sensor for local equivalence ratio of reacting mixtures of fuel and air (FLAMESEEK), Appl. Therm. Eng. 24 (2004) 1619–1632 doi:10.1016/j.applthermaleng.2003.10.028.

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Fig. 1 Recreation of chemiluminescence spectrum showing the broad band background of the hydrocarbon chemiluminescence from CO_2^*, HCO^*, and CH_2O^*, based on work from [2, 3, 5, 6, 14]. Note that this portion does not cover the entire range of CO_2^* emission as suggested by [14]

Kopp, M., M. Brower, O. Mathieu, E. Petersen, F. Güthe, CO2* chemiluminescence study at low and elevated pressures, **Appl. Phys. B Lasers Opt. 1-10 (2012)**DOI 10.1007/s00340-012-5051-4.
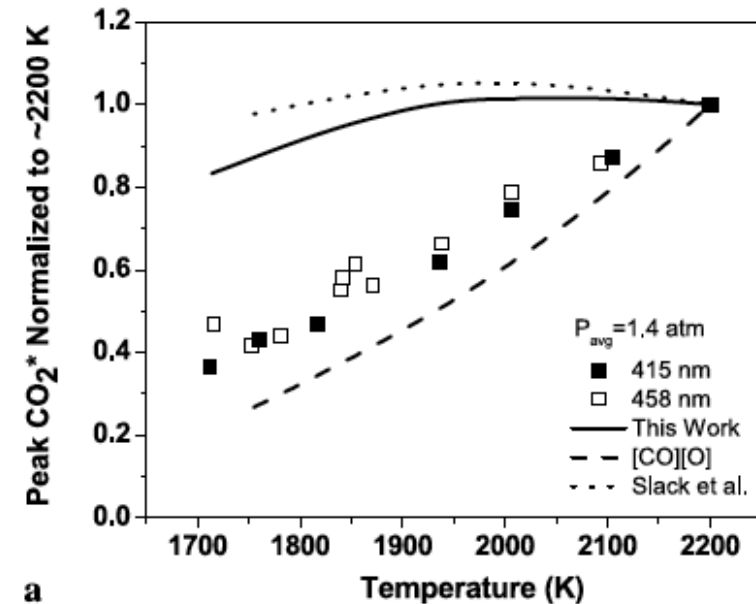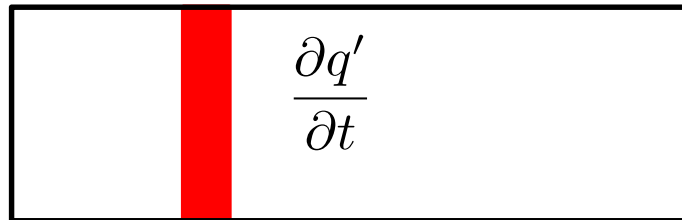

Fig. 10 Alternate peak CO_2^* predictions from another rate in the literature experimental results from this work for average pressures of (a) 1.4 atm a

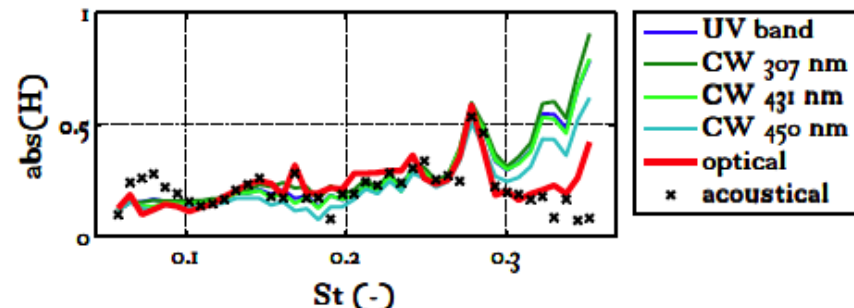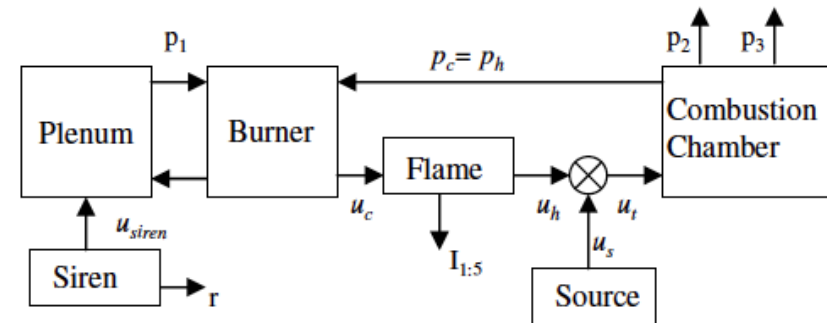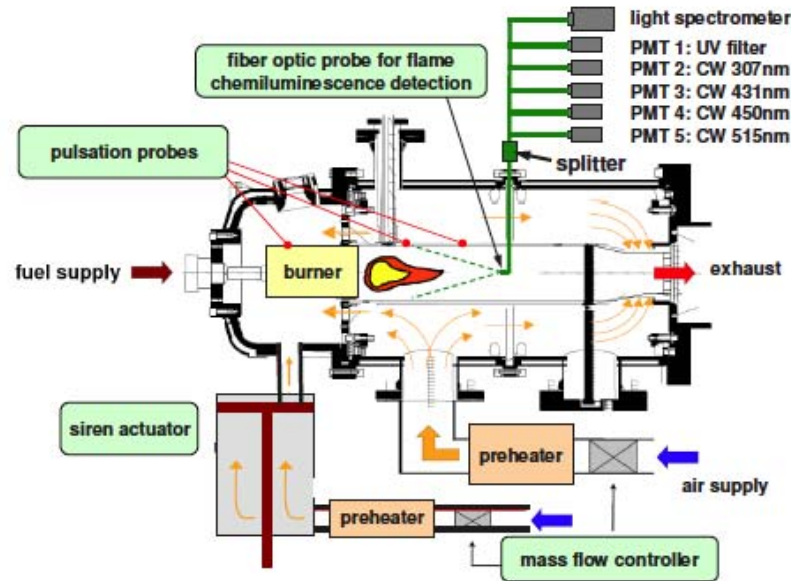Mechanisms for CO2* can yield good relative results for background

Correction for CO2* especially important for CH* measurements

$$\frac{\partial q'}{\partial t}$$

- Direct
- Chemiluminescence
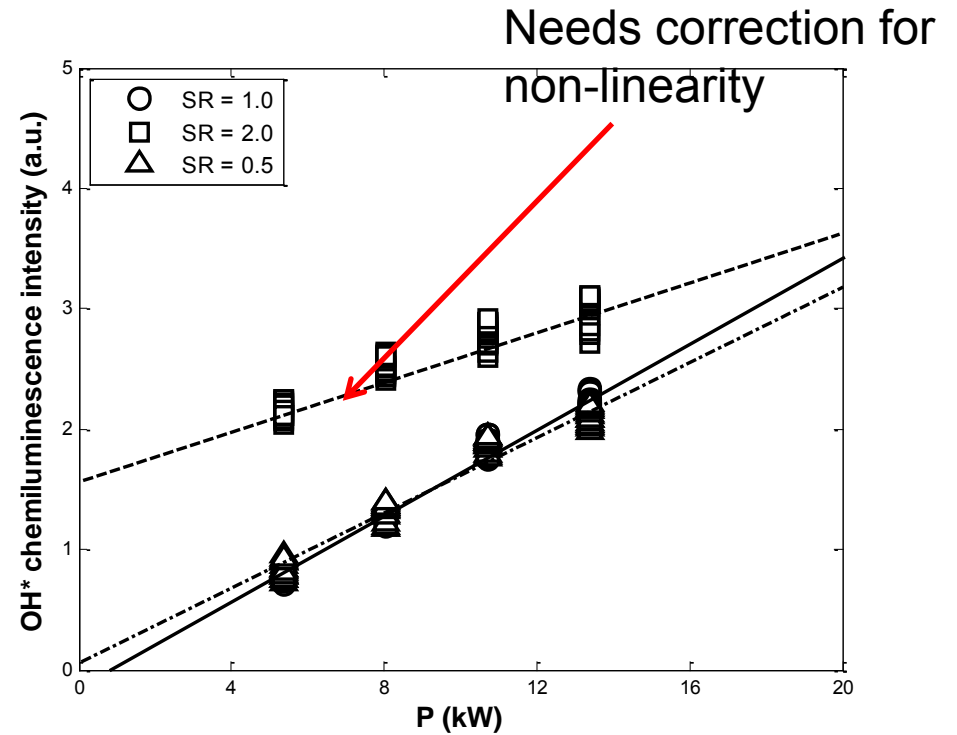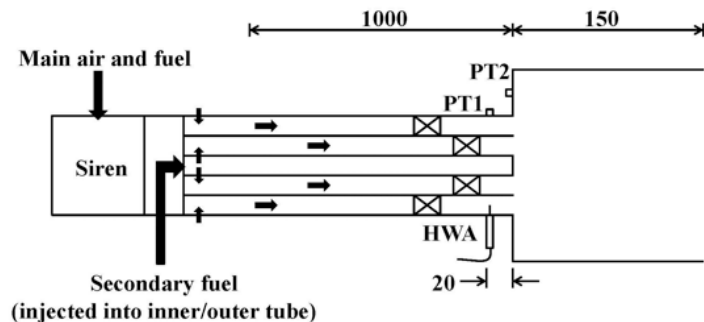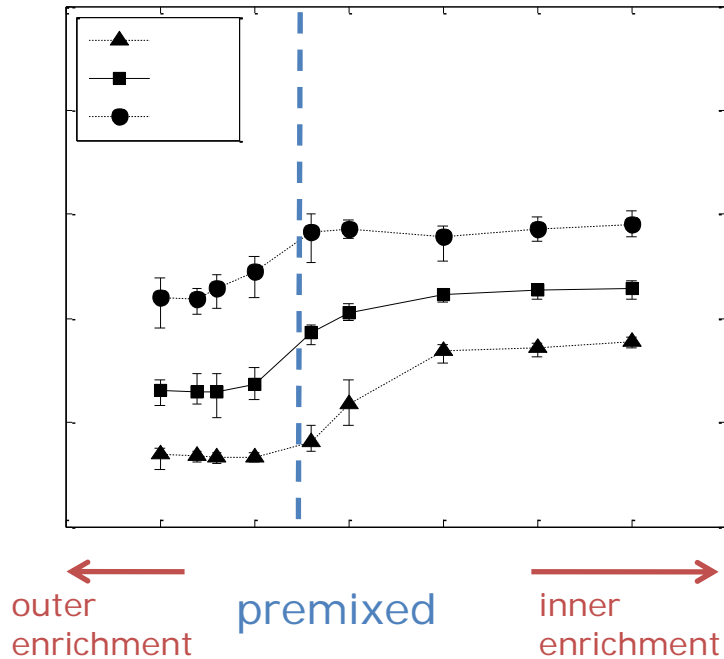- **Pressure**

Pressure vs. optical

Schuermans, B., F. Guethe, D. Pennel, D. Guyot, Paschereit, O. Thermoacoustic modeling of a gas turbine using transfer functions measured at full engine pressures, in: Am. Soc. Mec Eng. Int. Gas Turbine Institute, Turbo Expo IGTI, 2009: pp. GT2009–59605.

Schuermans, B., F. Guethe, W. Mohr, Optical Transfer Function Measurements for Technically Premixed Flames, J. Eng. Gas Turbines Power. 132 (2010) 081501 doi:10.1115/1.3124663.

Non-uniform equivalence ratio

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Han & Hochgreb, ECM 2013

Needs correction for non-linearity

Legend (left plot): ▲, ■, ●

outer enrichment ← **premixed** → inner enrichment

Legend (right plot):
- ○ SR = 1.0
- □ SR = 2.0
- △ SR = 0.5

OH* chemiluminescence intensity (a.u.) vs P (kW)

Main air and fuel

1000   150

PT2
PT1

Siren

HWA

Secondary fuel
(injected into inner/outer tube)

20

Mean CH*, OH* varies with power
Slope varies with power
Ideally: calibration at fixed p, T, AFR, split

Fig. 2 Schematic of a swirl-stabilized, lean-premixed, gas turbine combustor. Dimensions in millimeters. (a) Side view (mixing section and quartz combustor section), (b) schematic drawing of experimental setup for equivalence ratio measurements.
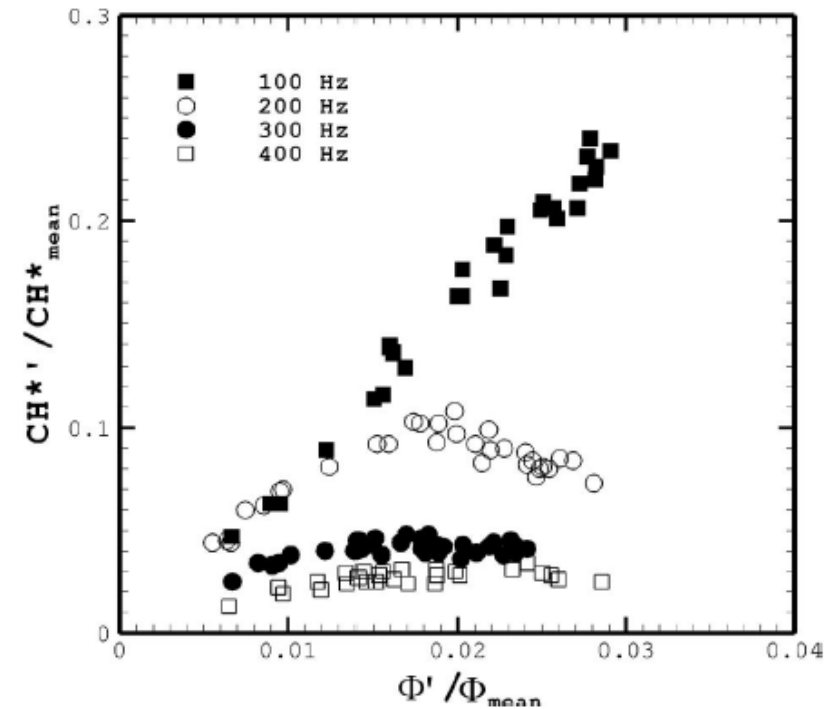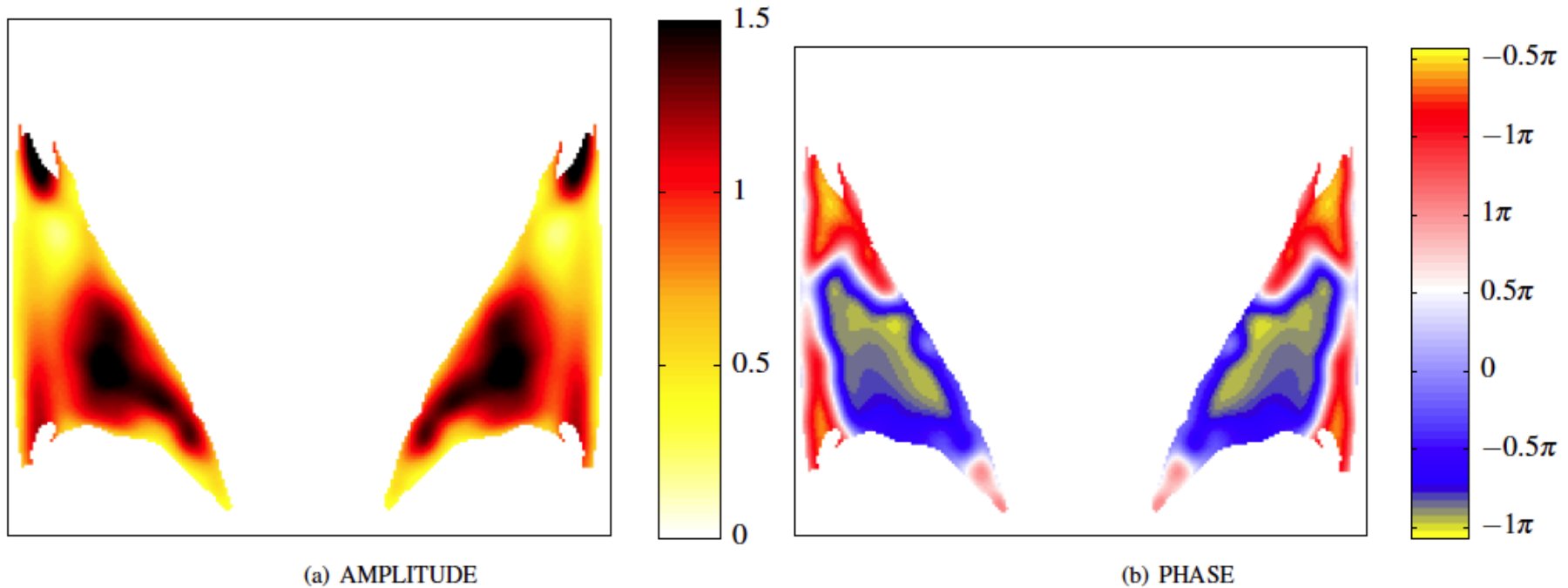

Fig. 6 Dependence of the normalized CH* chemiluminescence intensity fluctuation on the modulation frequency. Inlet conditions: $T_{in} = 200°C$, $V_{mean} = 60$ m/s, and $\Phi_{mean} = 0.60$.

Kim, K.T., J.G. Lee, B.D. Quay, D. Santavicca, Experimental Investigation of the Nonlinear Response of Swirl-Stabilized Flames to Equivalence Ratio Oscillations, J. Eng. Gas Turbines Power. 133 (2011) 021502 doi:10.1115/1.4001999.

Φ from absorption measurements

CH*/CO2* ratio

(a) AMPLITUDE

(b) PHASE

Bobusch, B., Cosic, B., J.P. Moeck, C.O. Paschereit, Optical measurement of local and global transfer functions for equivalence ratio fluctuations in a turbulent swirl flame, in: Proc. ASME Turbo Expo 2013 Turbine Tech. Conf. Expo. GT2013 June 3-7, 2013, San Antonio, Texas, USA, 2013: pp. GT2013–95649.

Under lean conditions:
CH*/CO2* ~ C/O2

Single camera method

Non-uniform flames: very much a project in development

Outline

- Measurement of heat release rates
  - Direct method
  - Chemiluminescence
  - Pressure method

- Imaging measurements
  - Chemiluminescence
  - OH PLIF
  - High speed measurements
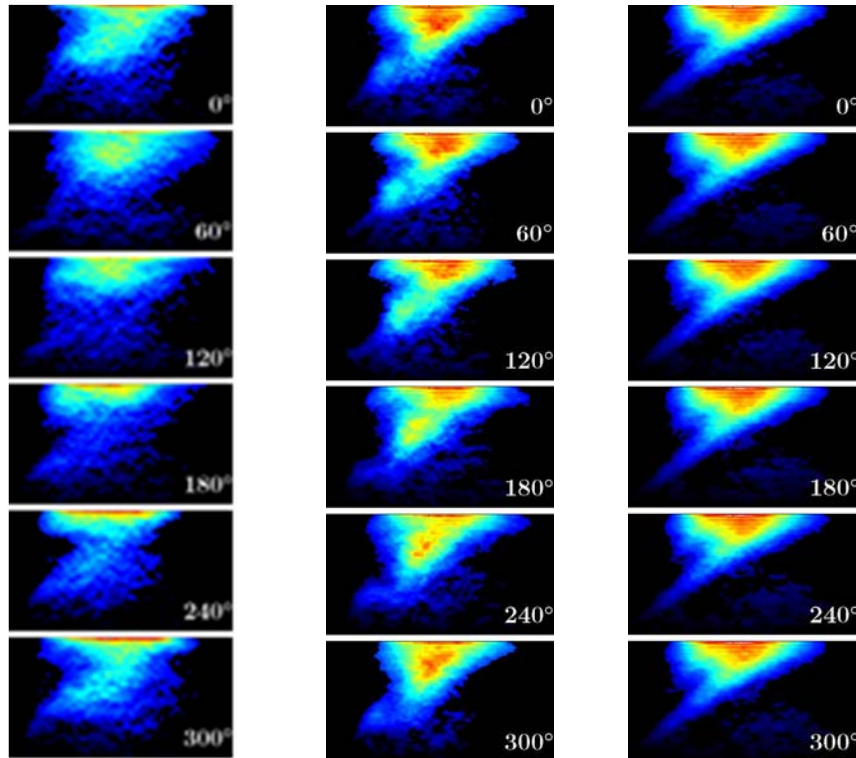 - Phase-reconstructed measurements

Measurable imaging dynamic quantities for instabilities

- OH*, CH*, CO2*
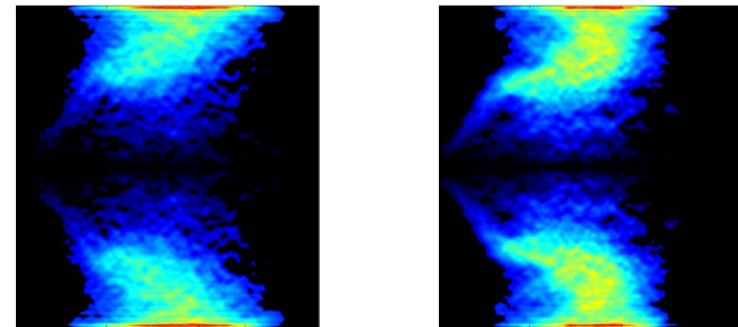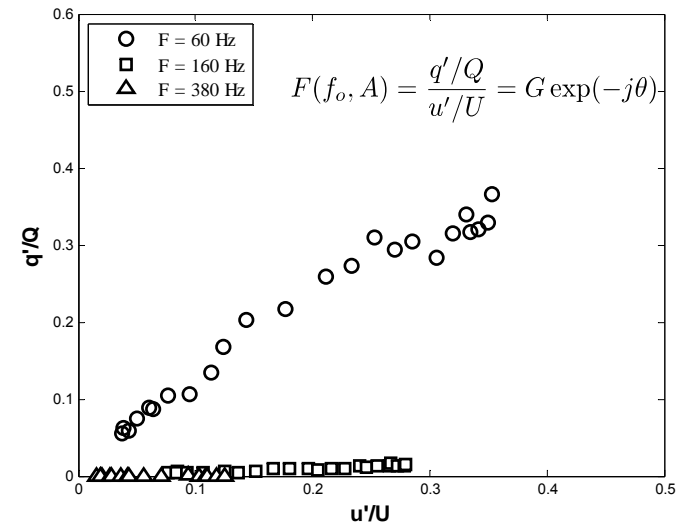
- Velocity (2D and 3D)

- OH (HS-PLIF)

- T (Rayleigh)

- HS CH, CH2O PLIF feasible, but too low signal for current technologies

Flame behaviour - premixed

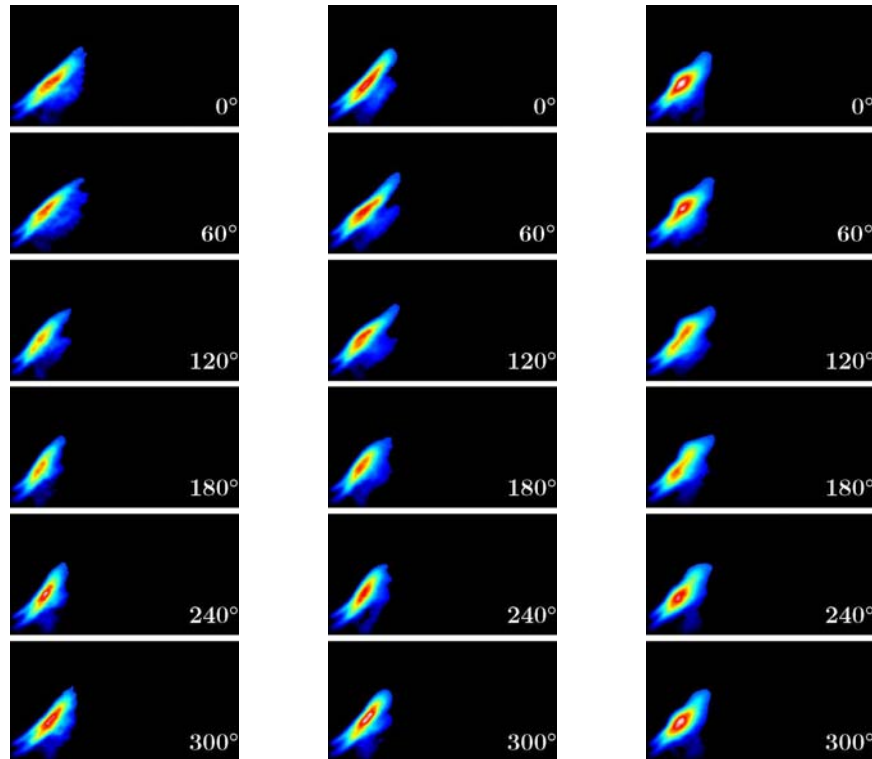- Φ_g = 0.60, U = 5 m/s, SR = 1.0
  f_0 = 60, 160 and 380 Hz

$$F(f_o, A) = \frac{q'/Q}{u'/U} = G\exp(-j\theta)$$

(a) f_0 = 60 Hz   (b) f_0 = 160 Hz   (c) f_0 = 380 Hz

(1) u'/U= 0.1   (2) u'/U= 0.2
f_0 = 60 Hz

Han & Hochgreb, ECM 2013

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- Φ_g = 0.60, U = 5 m/s, SR = 2.0
  f_0 = 60, 160 and 380 Hz

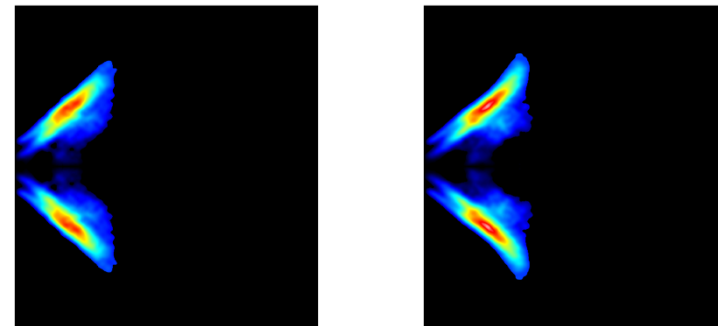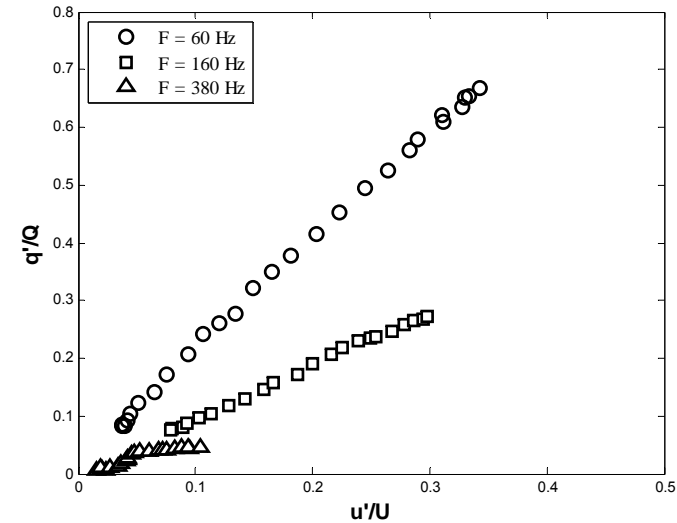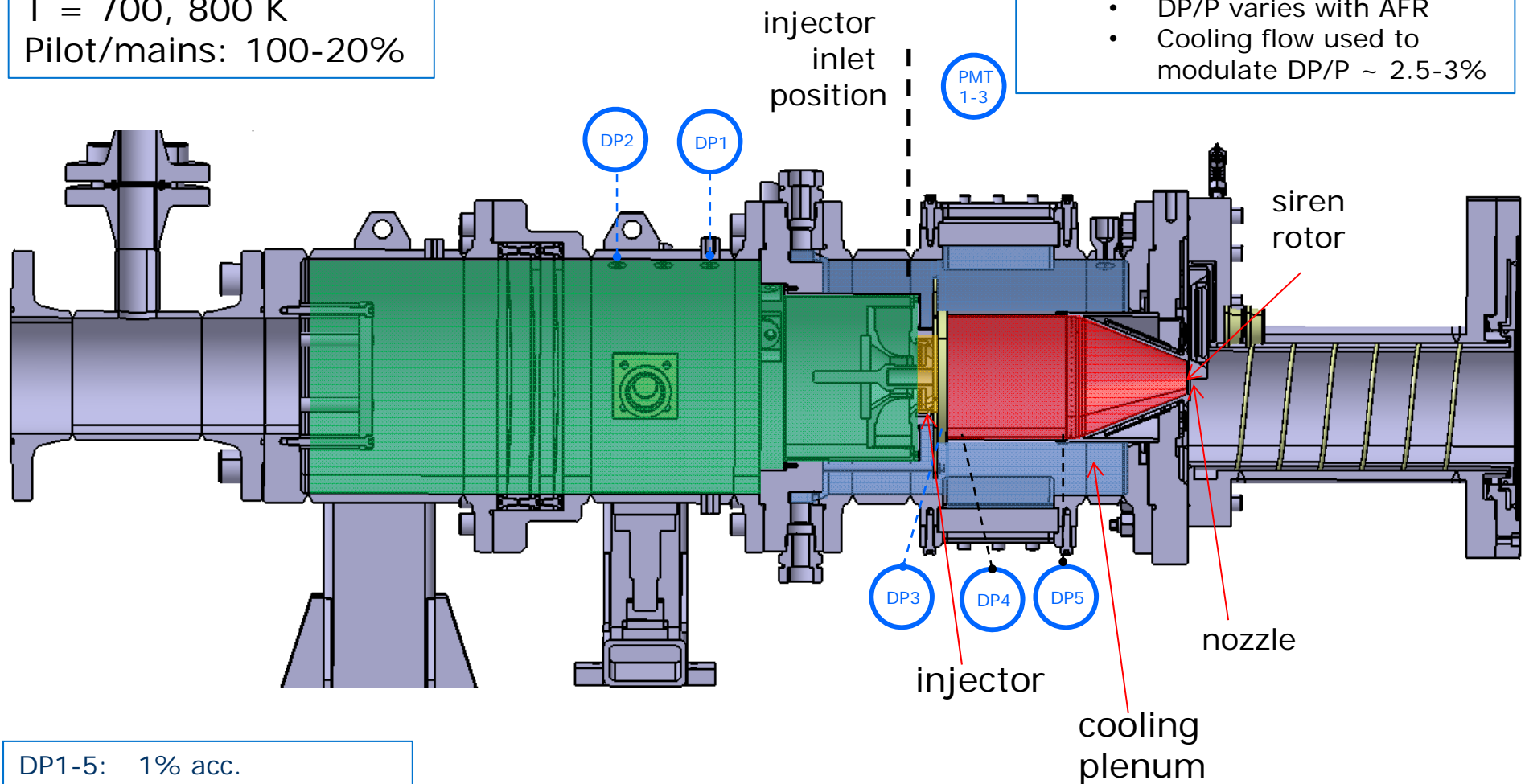(a) f_0 = 60 Hz   (b) f_0 = 160 Hz   (c) f_0 = 380 Hz

(1) u'/U = 0.1   (2) u'/U = 0.2
f_0 = 60 Hz

CIPCF with siren

P = 5.7 bar
T = 700, 800 K
Pilot/mains: 100-20%

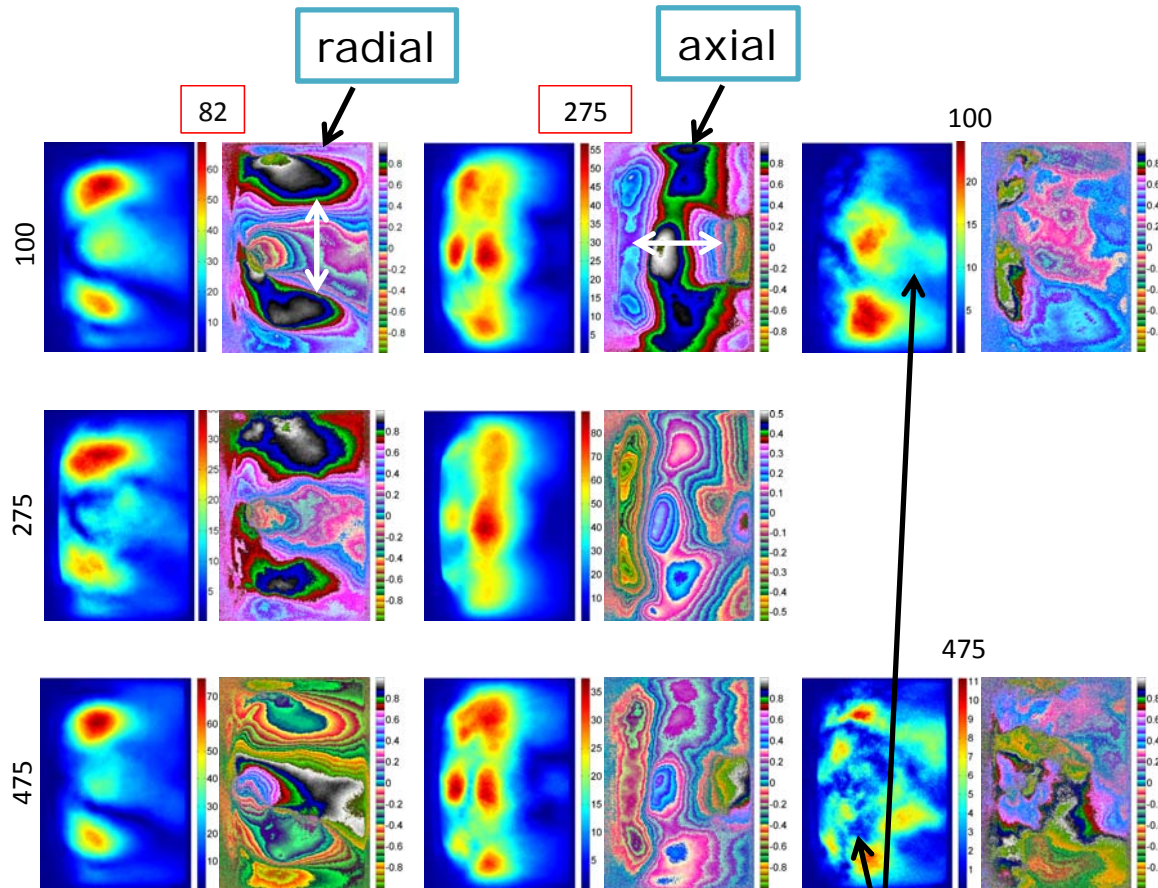+/- 15% area fluctuation
Fixed mean choked area
- DP/P varies with AFR
- Cooling flow used to modulate DP/P ~ 2.5-3%

injector inlet position

PMT 1-3

DP2   DP1

siren rotor

DP3   DP4   DP5

injector

nozzle

cooling plenum

DP1-5:   1% acc.
DP7,8:   15% acc. (vibration)
PMTs: OH*, CH*, CO2*

S. Hochgreb - ASME GT-2013-95311

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HS OH* imaging: FFT amplitude and phase

radial

axial

82

275

100

100

275

475

TP7
Kerosene
5.2 bar, 800 K
AFR 29
Split 20:80

Low coherence

Very coherent
Mains action

Hochgreb, S, Dennis, D., Ayranci, I., Bainbridge, W. and Cant, R. S., ASME GT-2013-95311

TARS injector

Two main modes separated by a phase difference

a
PLIF Camera
PIV Cameras
PIV Sheet
Dye Laser
523 nm
283 nm
PIV Laser
Pump Laser
532 nm
Burner
PLIF Sheet Optics

3.8 mJ/pulse
5 kHz

b
85 mm
85 mm
110 mm
CH4
15 mm
25 mm
15 mm
Swirler
Air
Plenum
Side view
Air
CH4
Z
X
Laser sheet
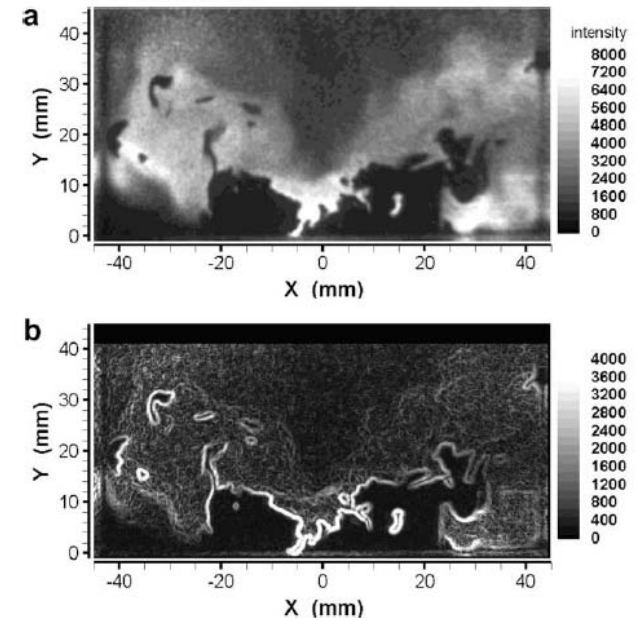Top view

Fig. 1. (a) Experiment configuration. (b) Dual-swirl GTMC burner.
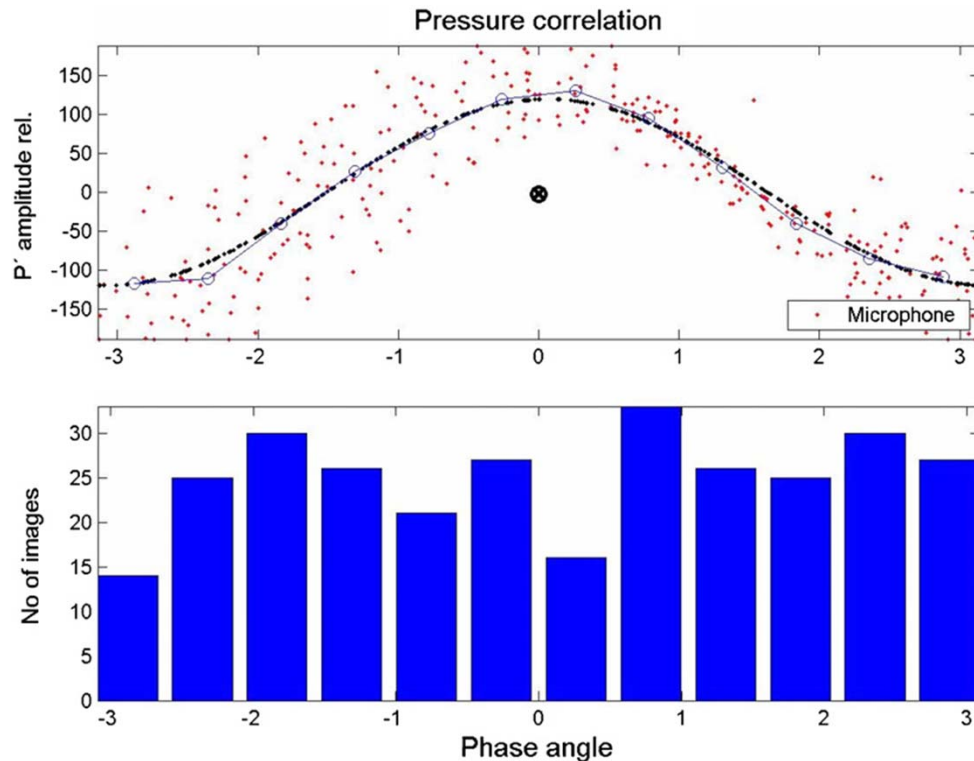
Fig. 3. (a) Sample OH-PLIF image. (b) OH gradient magnitude.

PIV POD 1st mode power spectrum

I. Boxx et al., Combust. Flame (2010),
doi:10.1016/j.combustflame.2009.12.015

I. Boxx et al., Combust. Flame (2010),
doi:10.1016/j.combustflame.2009.12.015

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Pressure correlation

Figure 10. Rayleigh plot from filtered pressure function locked to frequency Sr = 0.16 (left) and Sr = 1.8 (right).

Figure 11. Rayleigh plot from phase averaged images locked to the frequency Sr = 0.16 (left) and Sr = 1.8 (right) using an idealized cosine function for the pressure.

Hilbert transform

$$C(t_p) = \mathcal{F}^{-1} \left[\mathcal{F}[p(t_p)] H(f_{qN} - f_q) \right]$$

Equivalent to a narrow local f filter

Güthe, F., B. Schuermans, Phase-locking in post-processing for pulsating flames, Meas. Sci. Technol. 18 (2007) 3036–3042 doi:10.1088/0957-0233/18/9/039.
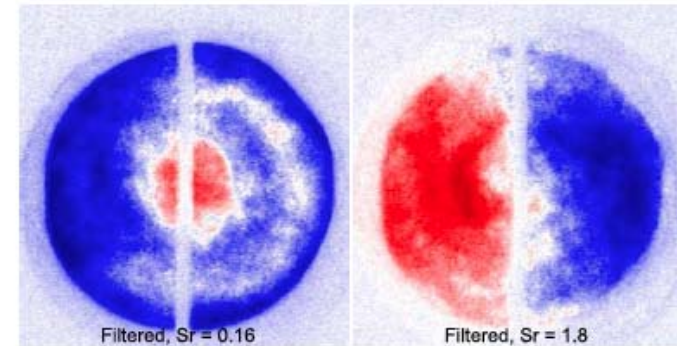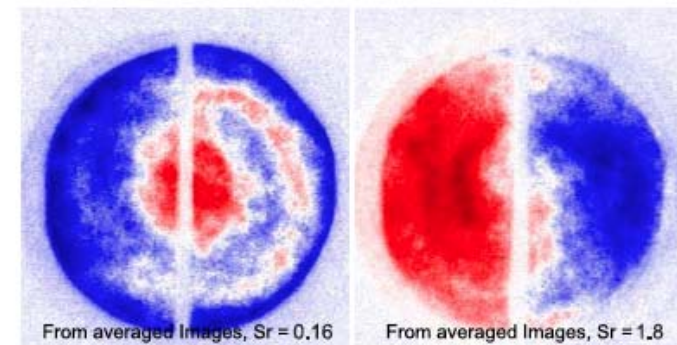
Summary

- Chemiluminescence:
  - Simple, inexpensive and fast
  - Quantitative (with appropriate calibration)
  - Questionable for partially mixed systems

- Imaging
  - High speed dynamic PIV, OH PLIF possible, additional insight: but cumbersome, expensive.
  - Low speed phase reconstruction possible via Hilbert transforms: high quality imaging and phase discrimination, but more labor intensive
  - Interpretation of large quantities of information still difficult: low order reduction techniques (POD, DMD) evolving and important → experimenters learning from computational researchers