BCURA Review, June 2008

BCURA Project: B74

The properties and combustion characteristics of coal-derived fuels for industrial gas turbine applications

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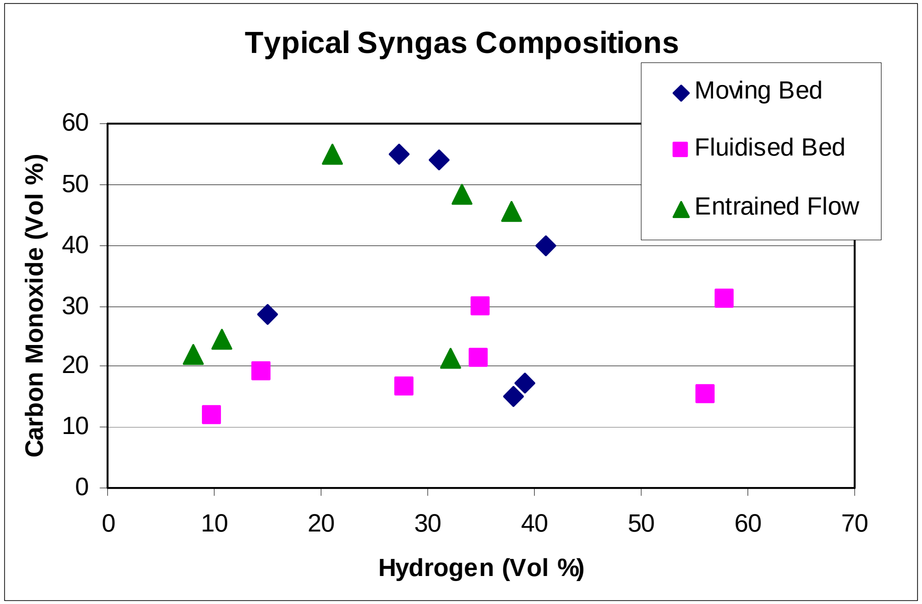
Gasification Technology R&D

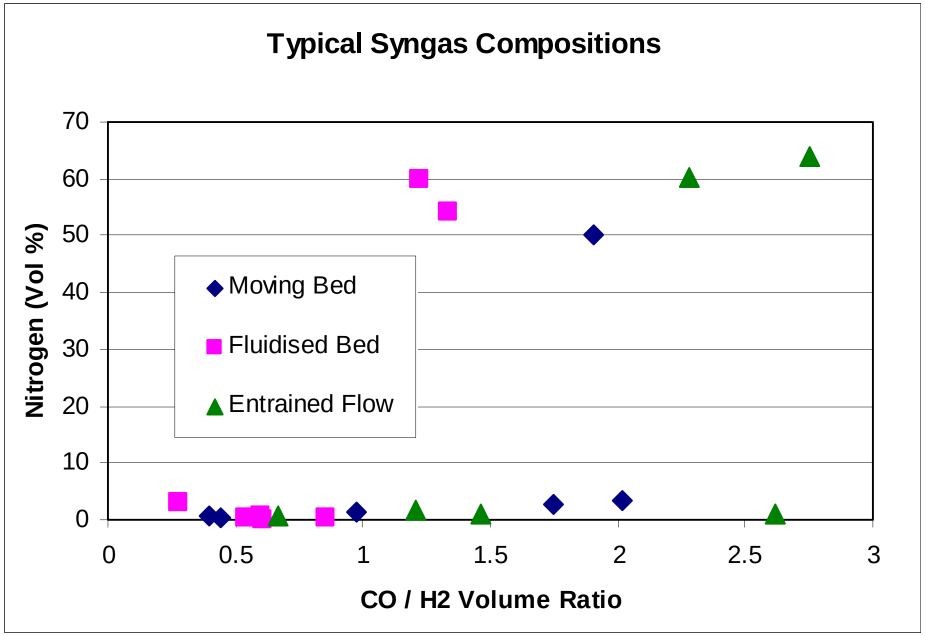
250 MW Polk
Power Station,
Tampa Electric
Company

Program Performance Goal:
By 2010, complete research and development to develop advanced power systems capable of achieving between 45 and 50 percent electrical efficiency at a capital cost of $1000 per kilowatt (in constant 2003 dollars) or less for a coal-based plant.

Typical IGCC power plant syngas compositions

Cranfield UNIVERSITY

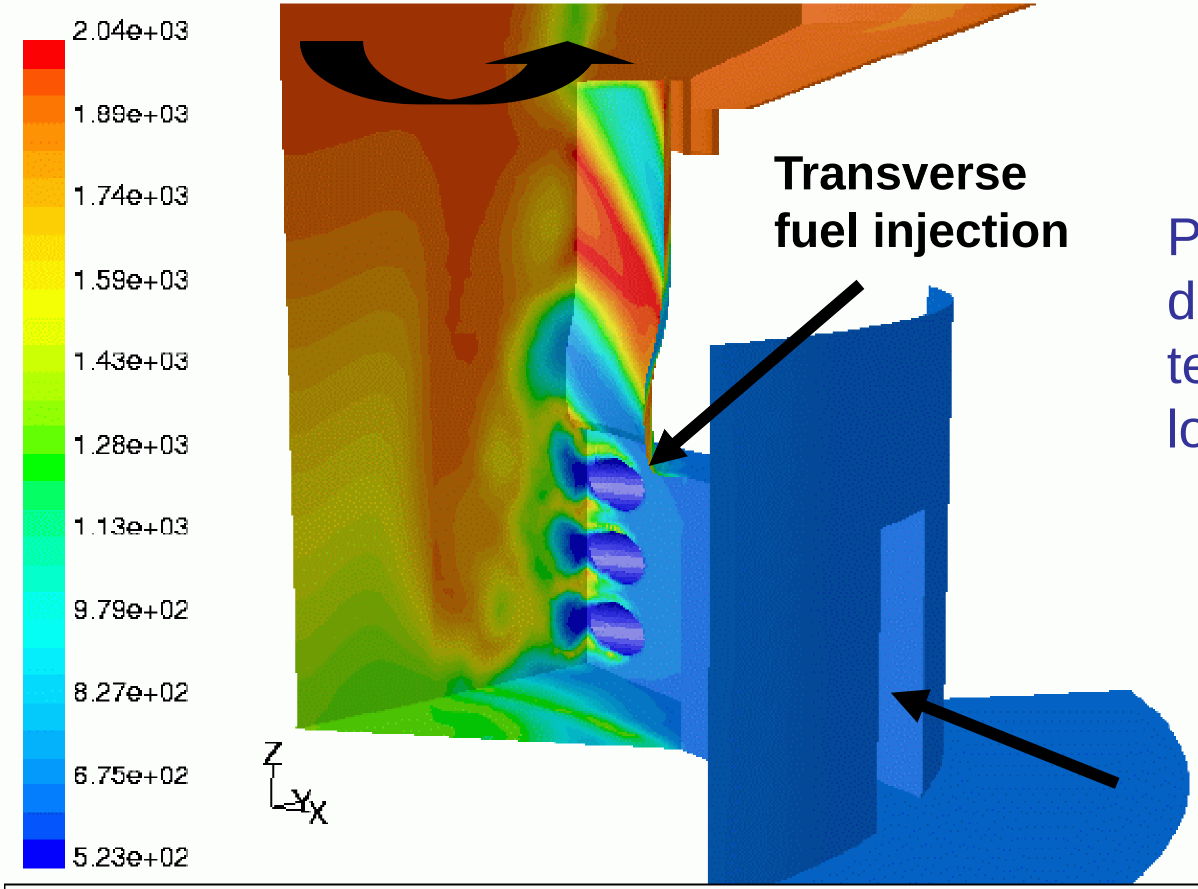




Coal Gasification

Typical syngas compositions - though primarily CO and H_2 (from the water gas reaction) - will vary (amongst other factors) according to :

- ☐ the nature of the coal feed – coal/petroleum coke blends
- ☐ the relative proportions of steam and oxygen or steam and air employed
- ☐ the carrier gas for coal particles
- ☐ the process operating temperatures and pressures



Swirl-stabilised combustion

Transverse fuel injection

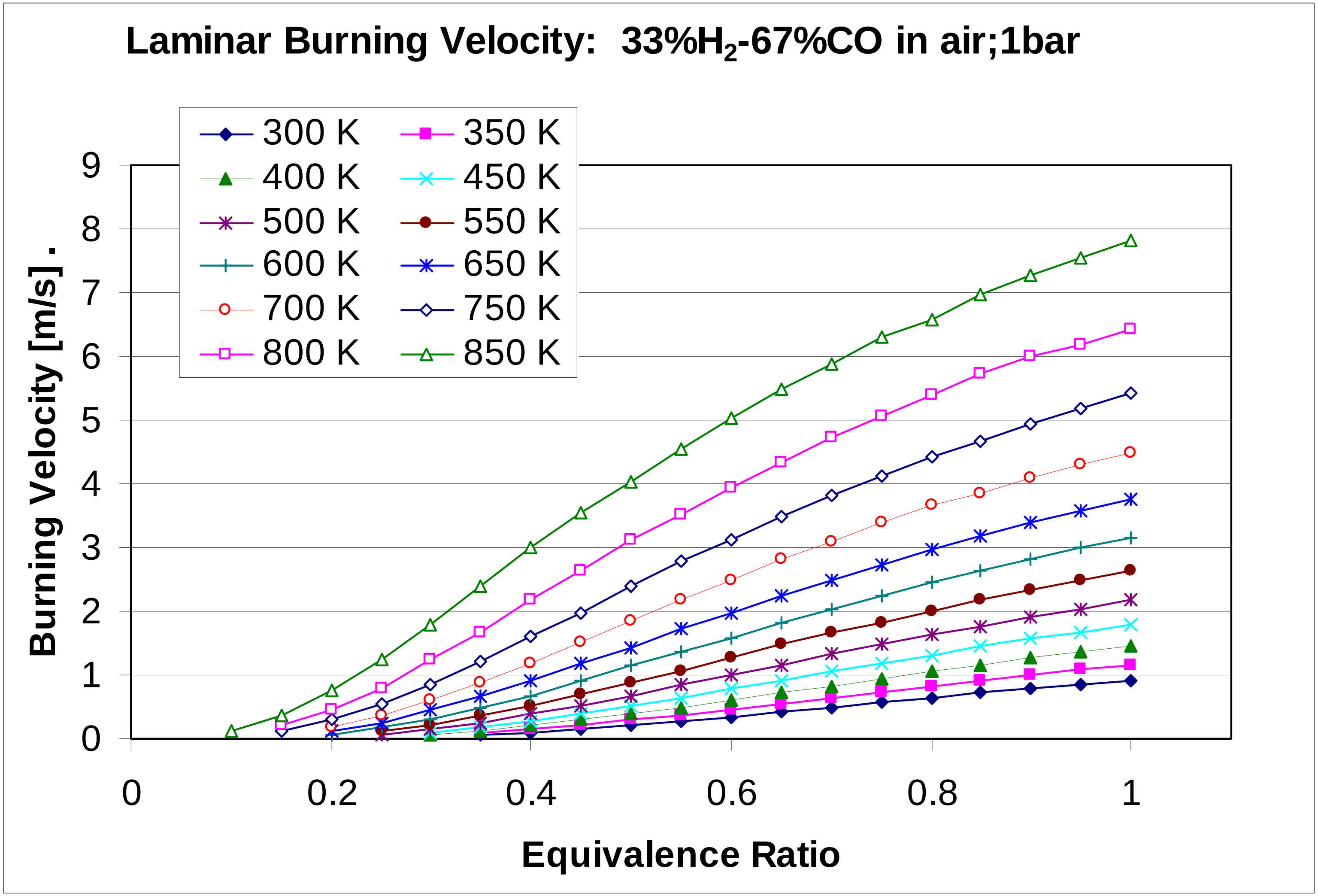
Radial air inflow

Predicted distribution of temperature in a low NO_X combustor

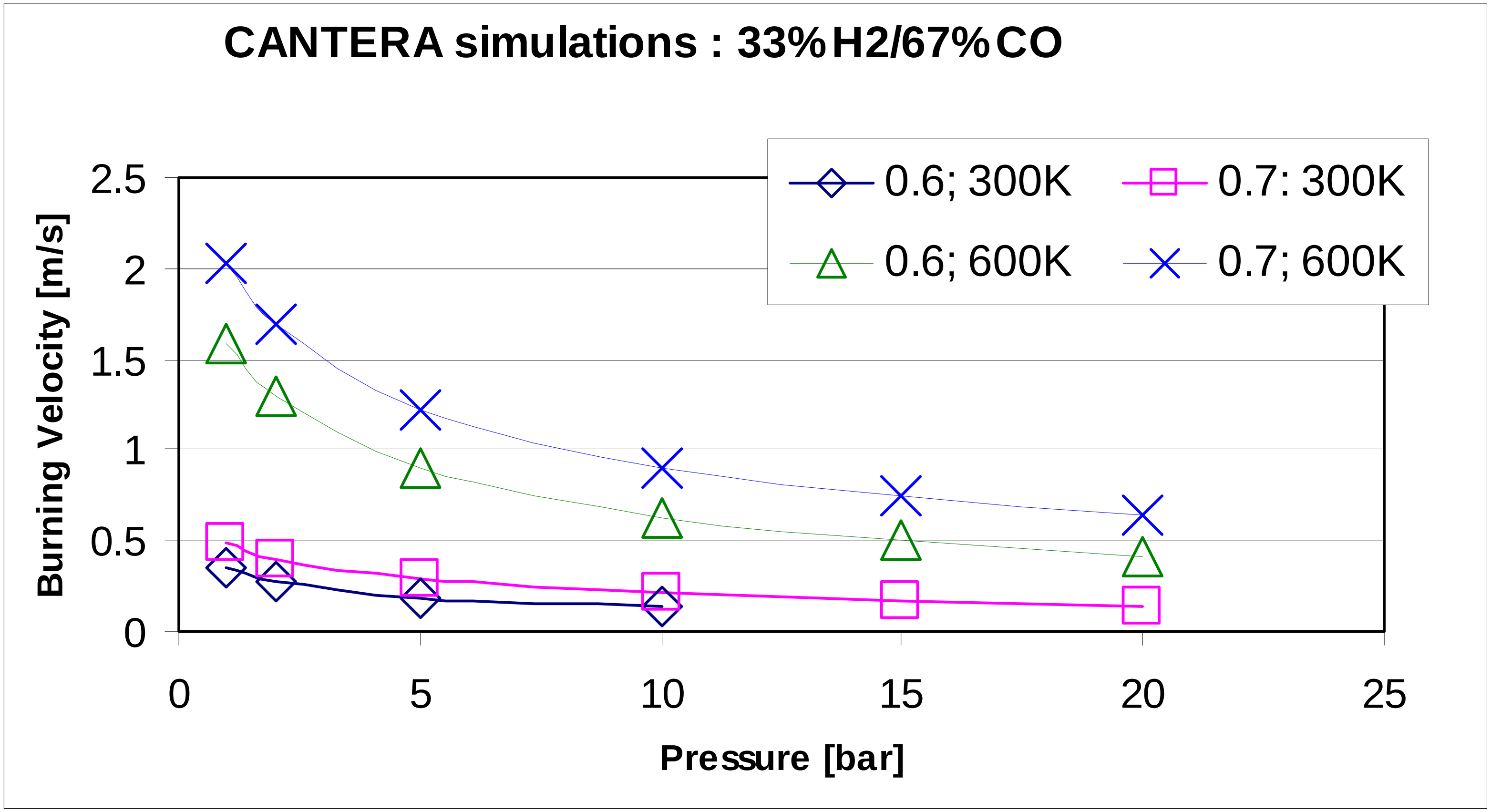
Typical gas turbine combustor sector simulation

In respect of the combined cycle gas turbine, the variation in fuel composition will directly influence a range of important combustion characteristics, including amongst others

- calorific value
- combustor volume
- flame stability – blow-out, flashback, autoignition
- emissions performance
- wall heat transfer and durability



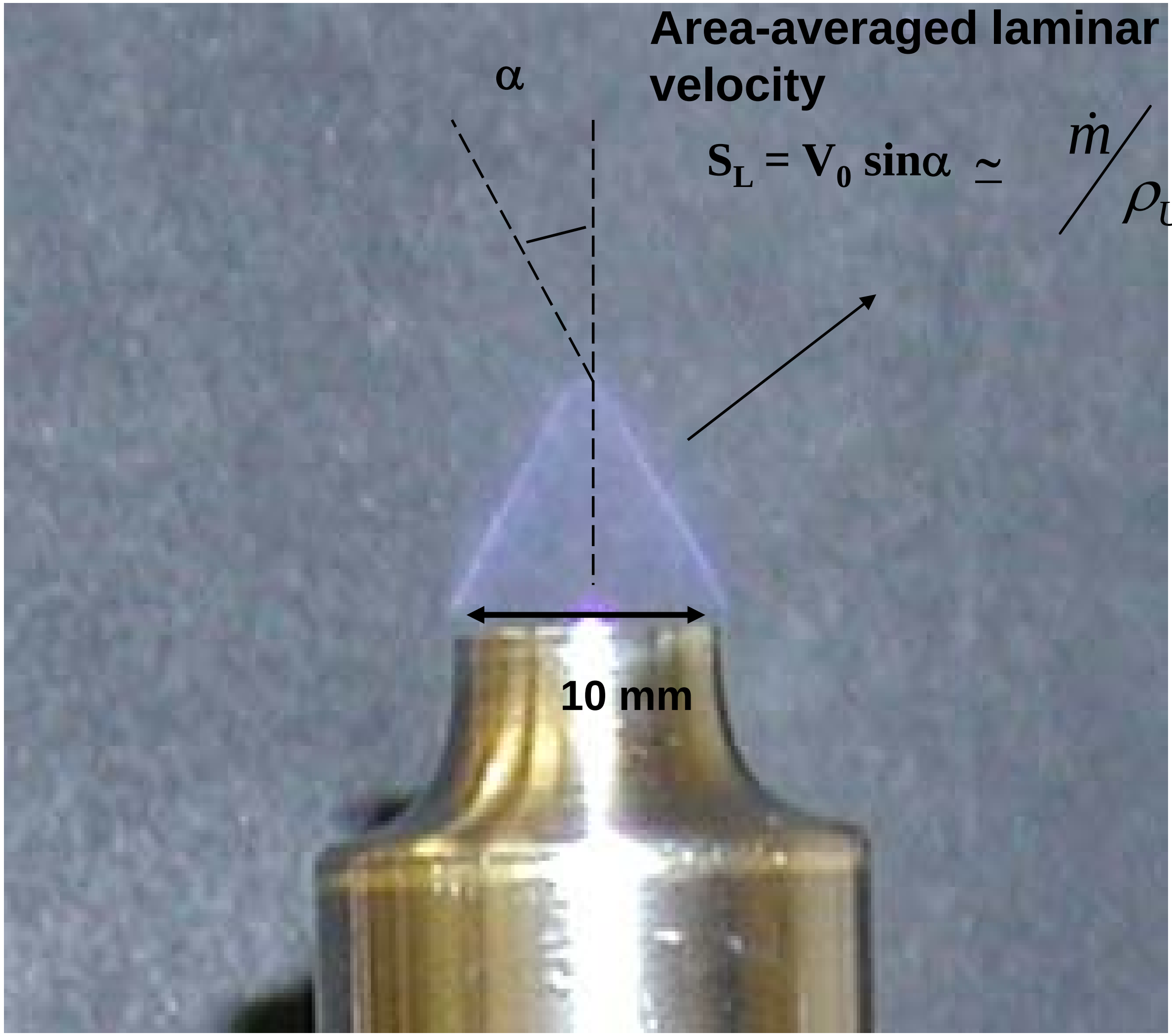
Numerical simulation : GRI reaction mechanism [53 species; 325 reactions]



Numerical simulation: Variation of burning velocity with pressure

Experimental and Numerical Investigation of Burning Velocity

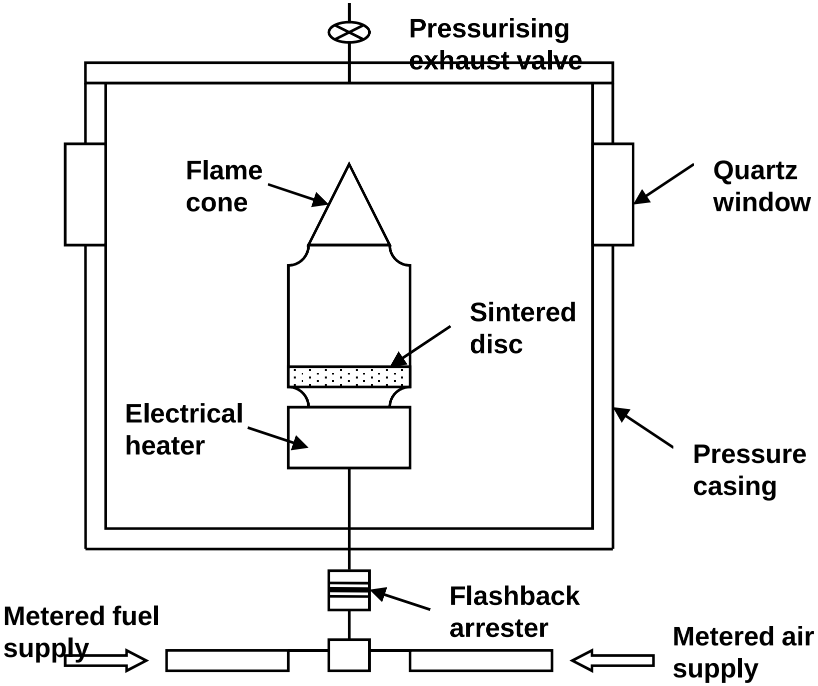
	Flame A	Flame B	Flame C	
Fuel Composition	H_2 28.5 % CO 1.5% N_2 70 %	H_2 33% CO 67%	H_2 50% CO 50%	Natural Gas
Calorific Value (LCV) [MJ/kg]	3.6	13.8	17.5	48.2
Stoichiometric Air-fuel Ratio (mass)	1.0	3.5	4.6	16.5

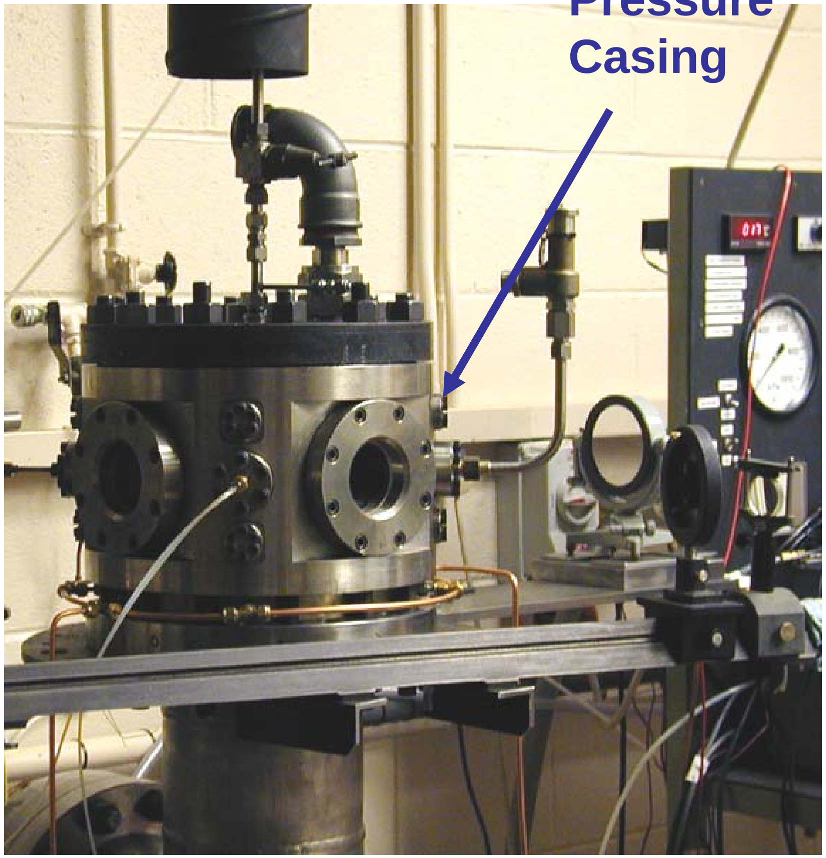


Area-averaged laminar burning velocity

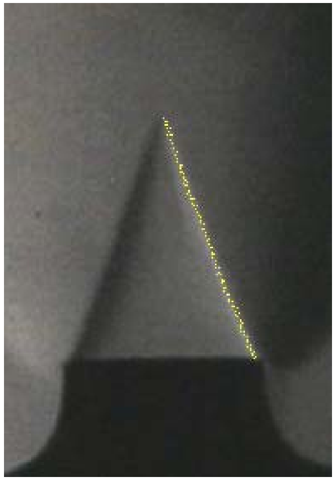
$$S_L = V_0 \sin\alpha \simeq \dot{m} / \rho_U A_{flame}$$

Lean premixed propane-air flame

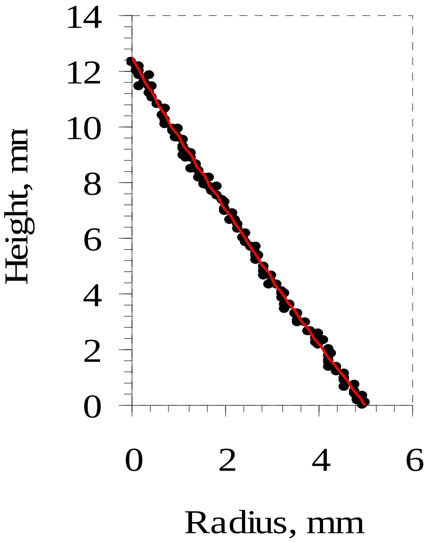




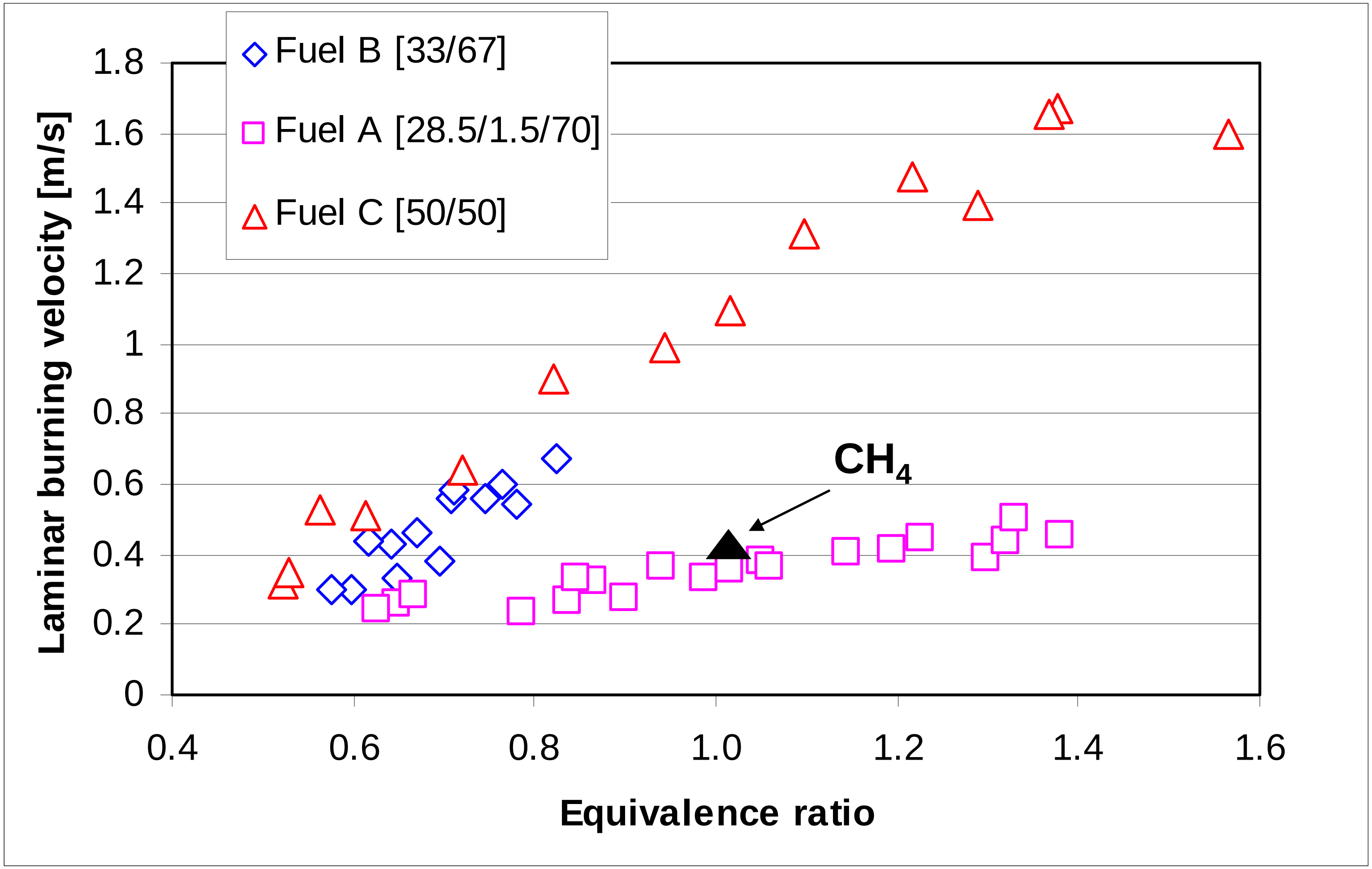
Pressure Casing



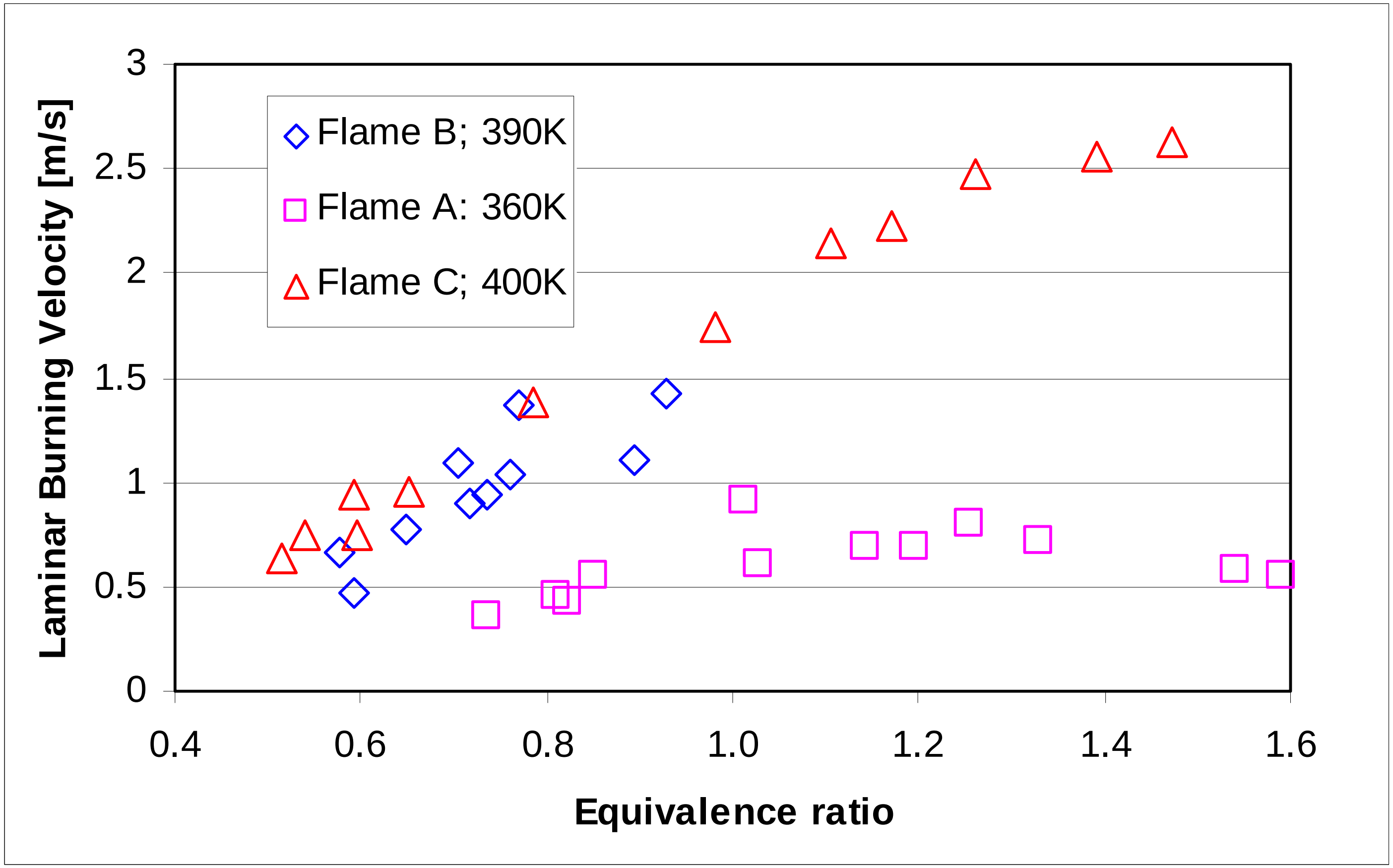
Schlieren image



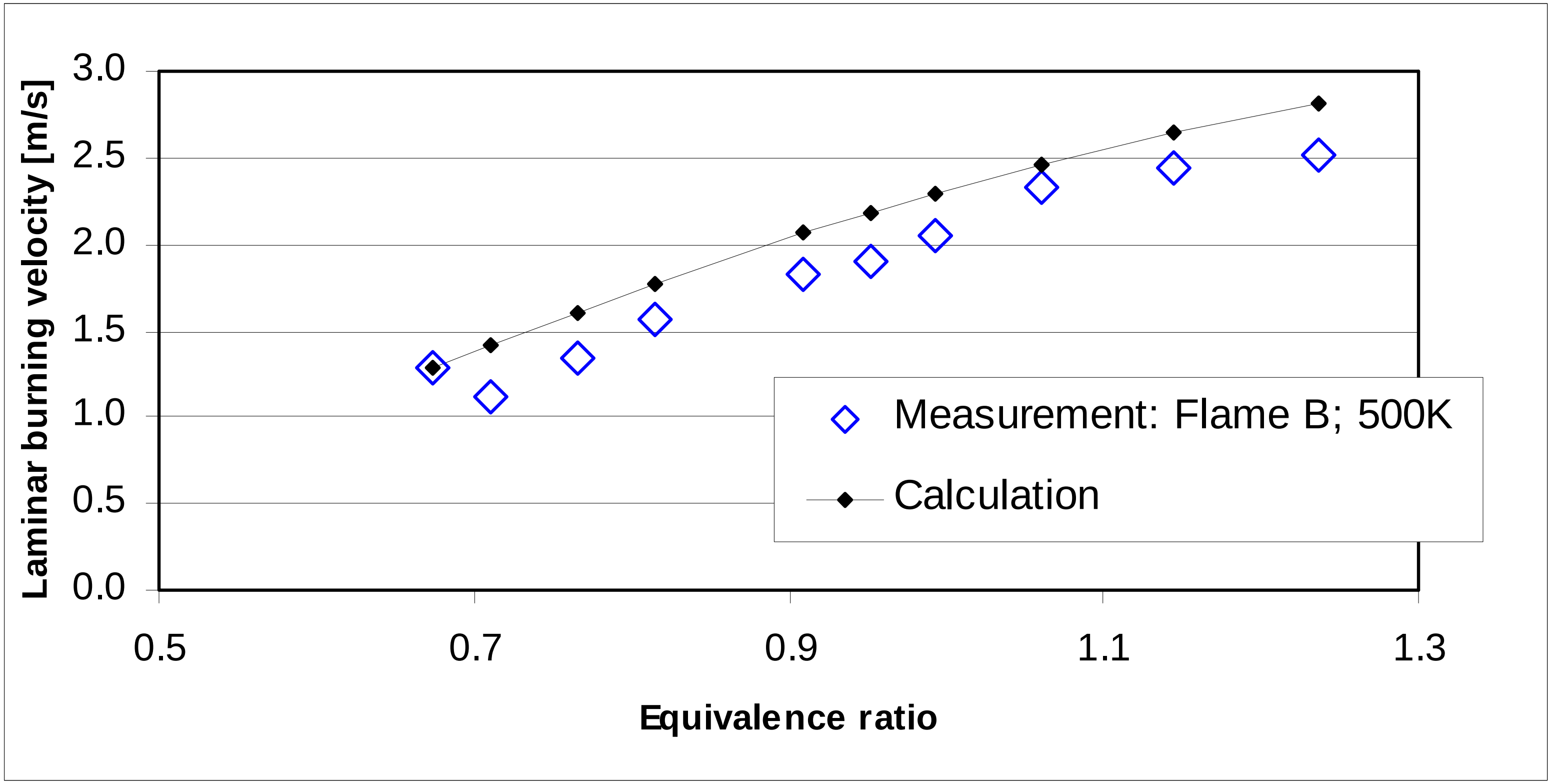
Edge detection and digitisation



Variation of measured laminar burning velocity with mixture equivalence ratio for the three syngas mixtures (A,B,C) burning in air; reactant temperature 290K and atmospheric pressure.



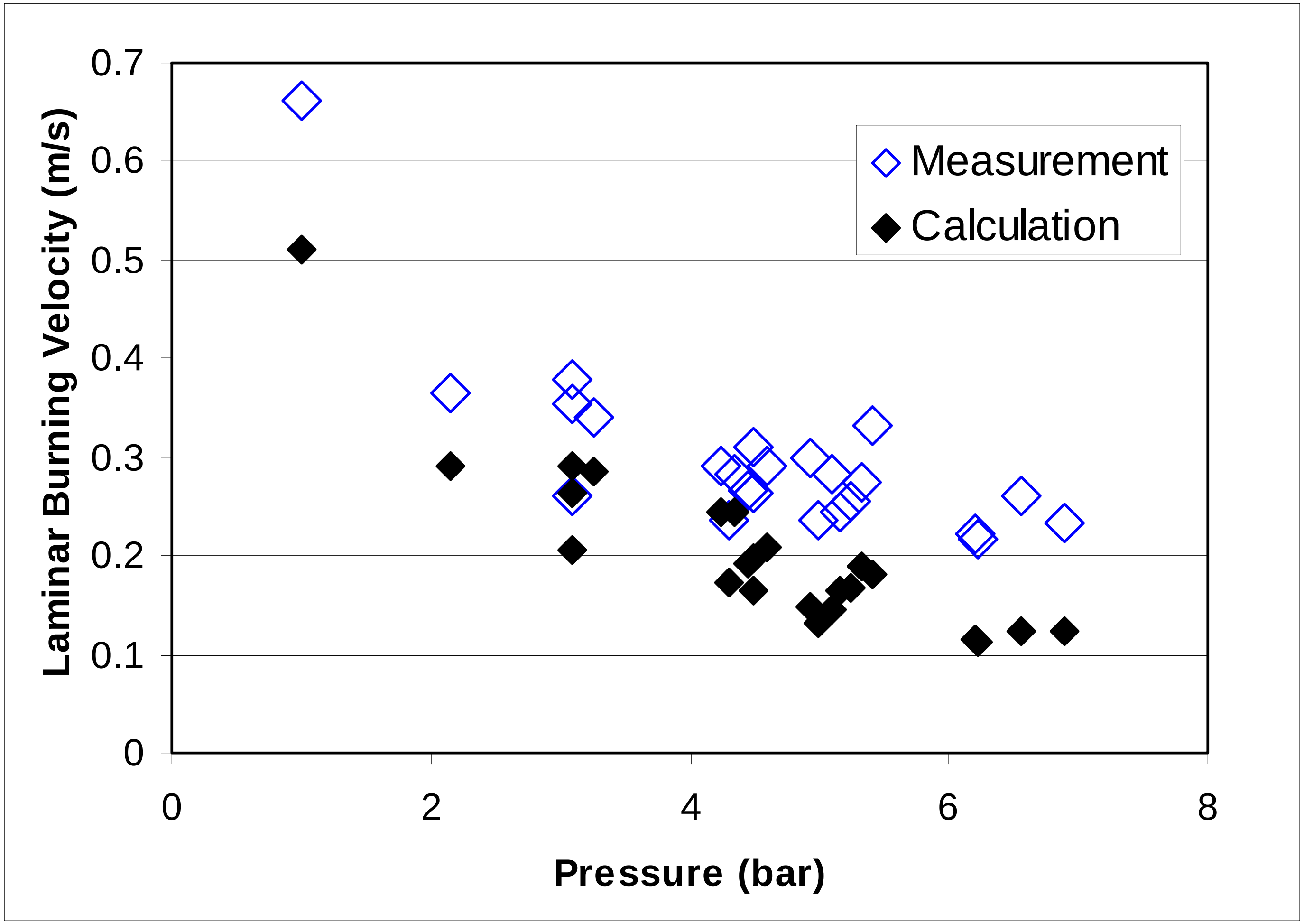
Variation of measured laminar burning velocity with mixture equivalence ratio for the three syngas mixtures (A,B,C) burning in air; reactant temperature 400K and atmospheric pressure.



Variation of measured and computed laminar burning velocity with mixture equivalence ratio for the syngas mixture B (33% H2 / 67% CO) burning in air; reactant temperature 500K and atmospheric pressure.

Numerical Simulations

- One-dimensional laminar flame calculation with ‘complete’ chemistry based on the GRI mechanism 3.0 for which a number of codes are available – for example, CHEMKIN, Cantera, Cosilab.
- Artificial Neural Network trained on sample 1-D flame computations to generate burning velocity data for any arbitrarily defined reactant initial conditions.
- CFD combustor simulations incorporating strained flame data on burning velocity.

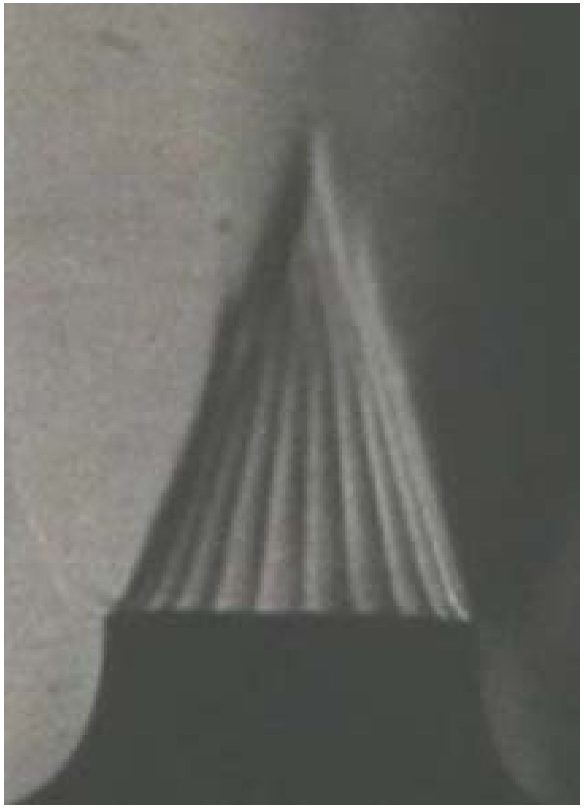


Variation of laminar burning velocity with pressure for the 33%H2/67%CO fuel at a reactant mixture temperature of 400K and lean equivalence ratios in the range 0.45-0.55.

Schlieren images of distorted (cellular) lean H2/CO flames.

Flame B

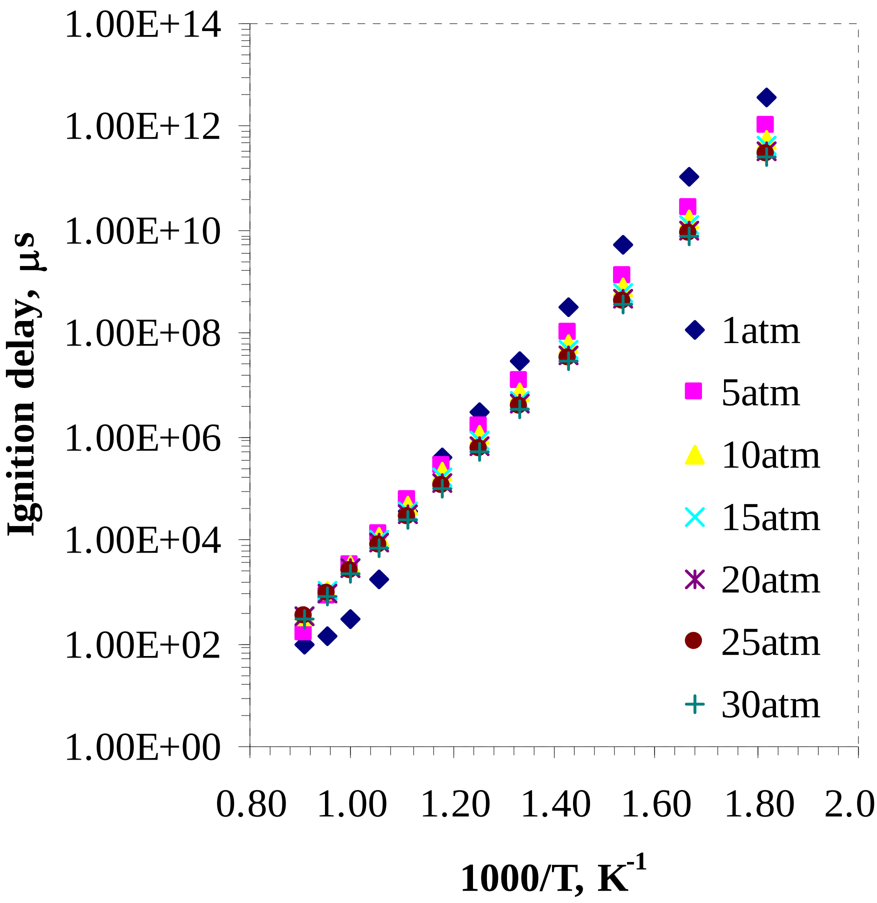
f = 0.53 ; T = 293K ; p = 1 bar



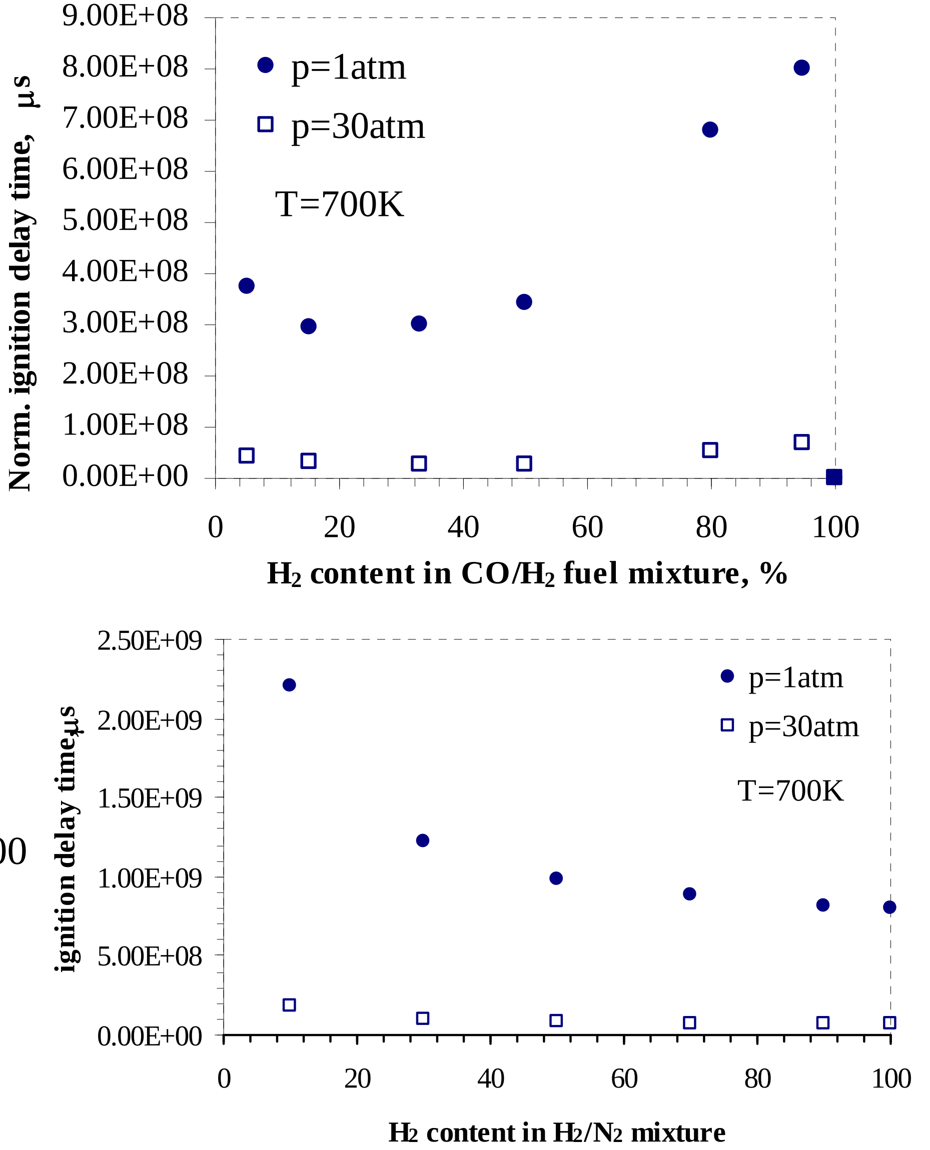
Flame A

f = 0.38 ; T = 473K ; p = 4 bar

Numerical simulations – ignition delay



Effect of pressure



Effect of mixture composition

Combustion Modelling

Combustion process incorporated through a variable describing the progress of chemical reaction (eg. a normalised gas temperature or product mass fraction)

$$\frac{\partial}{\partial x_j}\left(\rho u_j c\right) - \frac{\partial}{\partial x_j}\left(\frac{\mu}{\sigma}\frac{\partial c}{\partial x_j}\right) = \rho S_c$$

convection diffusion chemistry

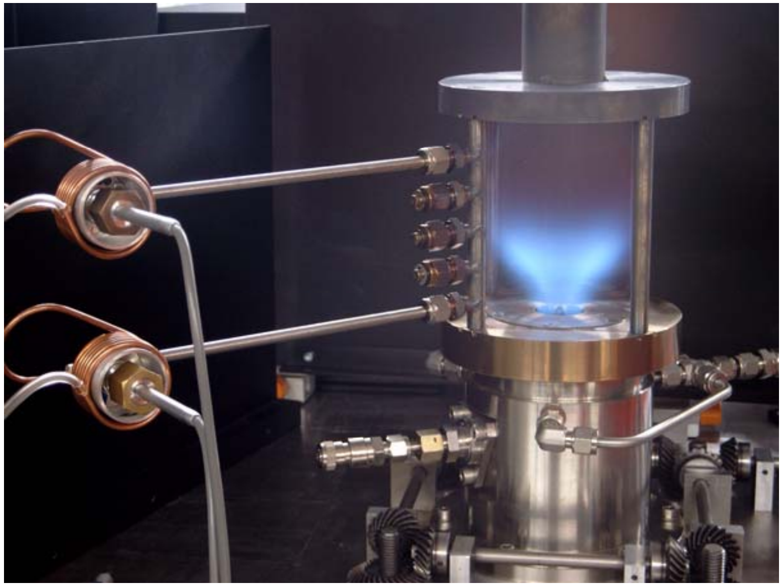
where $$\rho S_c = A(\chi) u'^{3/4} \underline{U_{lam}(\varphi, \chi)}^{1/2} (\ell / \alpha)^{1/4}$$

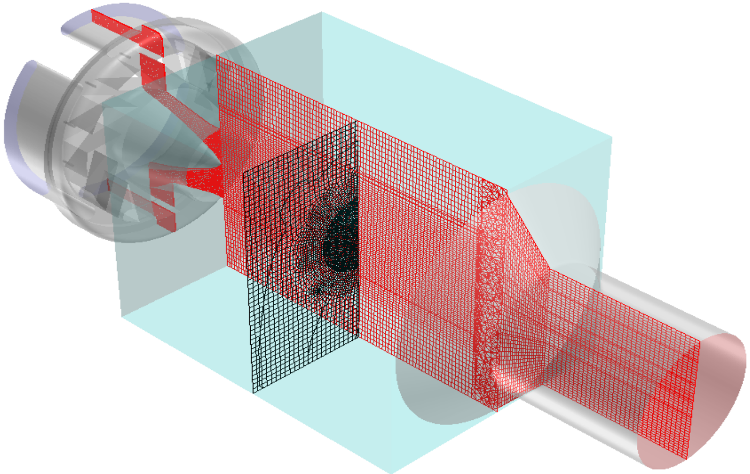
Laminar burning velocity as a function of the local mixture equivalence ratio and the hydrodynamic stretch

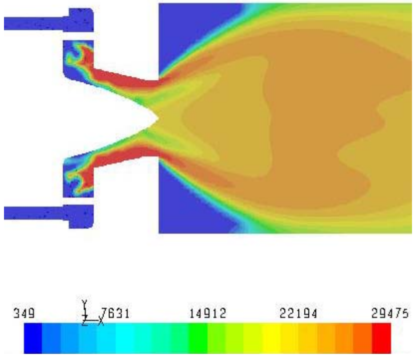
Computational domain and boundary conditions

- Mesh and boundary conditions from PRECCINSTA project
- Mesh size 1600000 cells
- Experiments with CH_4, ϕ=0.84, T=295K, P=1atm
- Simulations performed :
  - CH_4 – model validation
  - $CO/H_2/N_2$ fuel mixtures:
    - 12%CO/88%H_2 fuel mixture
    - 1.5%CO/28.5%H_2/70%N_2
    - 50%CO/50%H_2

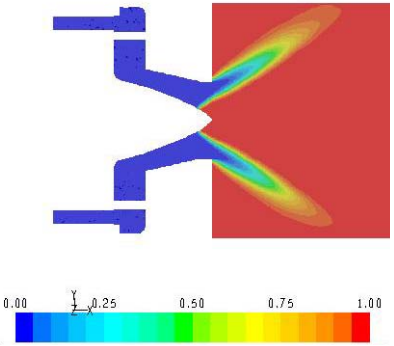
- Unstrained and strained flames



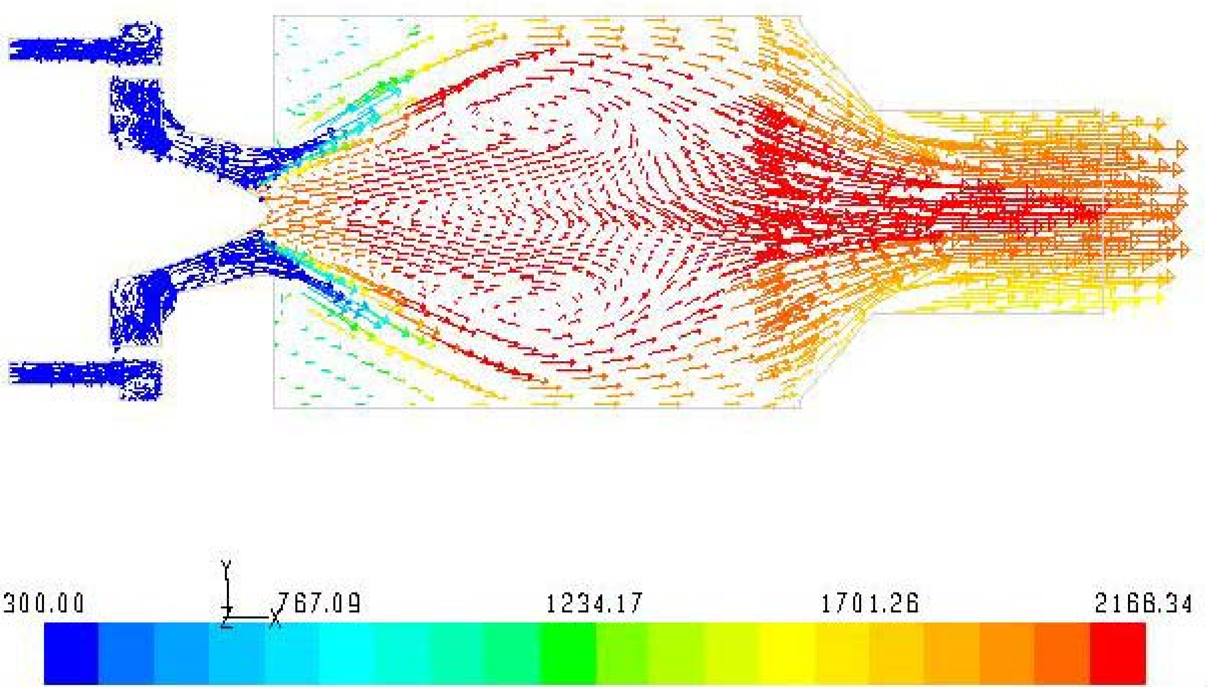




Extinction strain rate



Reaction progress variable



Velocity vectors coloured by temperature : 12 % CO / 88% H_2

(PRECCINSTA combustor : FLUENT simulation)

Summary Conclusions

- Measurements of laminar burning velocity are reported for a range of syngas fuels at pre-heat temperatures up to 600K and pressures up to 6 bar.

- For the more readily accessible experimental conditions, the trends of increasing burning velocity for H_2 / CO syngas mixtures with equivalence ratio and reactant temperature; and the decrease with increasing pressure, that are observed experimentally are captured by numerical simulations using the GRI 3.0 mechanism

- This agreement deteriorates at higher pressures and lean mixtures but the interpretation is complicated by the observed growth of flame surface distortion and hydrodynamic disturbance as the pipe Reynolds number approaches the levels characteristic of laminar-turbulent transition.

- The high hydrogen content makes syngas laminar flames prone to thermo-diffusive disturbance and this may prove a significant factor in practical turbulent combustion applications.