DEPARTMENT OF ENGINEERING SCIENCE
UNIVERSITY OF OXFORD

Laminar Burning Velocity Measurements over Wide RangingTemperatures and Pressures

Richard Stone

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Introducing laminar burning velocity

- **Experimental values of burning velocities are required:**
  - To help kineticists and modellers validate their schemes and models
  - To provide input for models of flashback, minimum ignition energy and turbulent combustion
- **Laminar burning velocity is dependent upon:**
  - The equivalence ratio of the fuel/air mixture
  - Pressure of the mixture
  - Temperature of the mixture
  - Residuals

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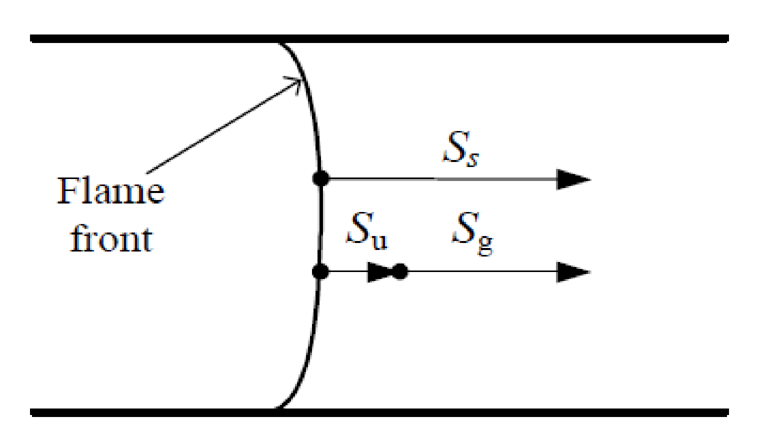
Measuring laminar burning velocity

- **The constant volume vessel is a versatile and accurate method of determining laminar burning velocities**
  - Allows two different techniques:
    - flame front imaging using optical access and
    - analysis of vessel pressure during combustion
  - Generates burning velocities as a function of temperature and pressure from a single experiment over a wide range of pressures and temperatures
  - Flame stretch conditions are well defined
  - Uses small quantities of fuel
- **Data have been obtained for many gases and liquid fuels and their mixtures**

Introducing laminar burning velocity

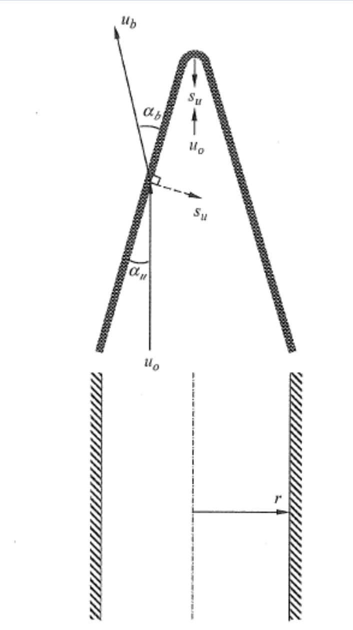
- **Definition of laminar burning velocity:**
  - The velocity at which a flame front moves, relative to the velocity of the gas into which it is propagating
  - Applies to the case of a 1-D flat (un-stretched) flame

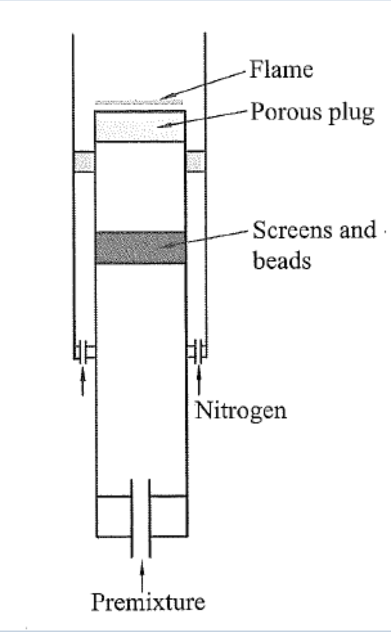


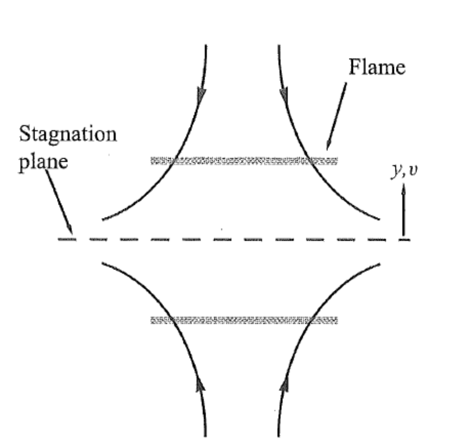
$$S_u = S_s - S_g$$

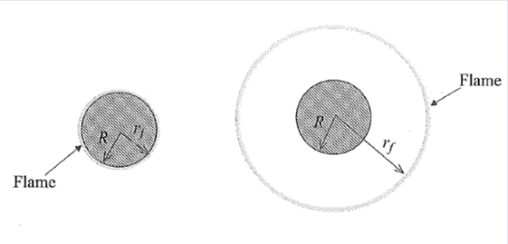
How is Laminar Burning Velocity Measured?

- Open Systems
  - Conical flames
  - Flat flames
  - Stagnation flames
- Closed Systems
  - Spherical Vessels
  - Cylindrical Vessels









C K Law
Combustion Physics
CUP, 2006

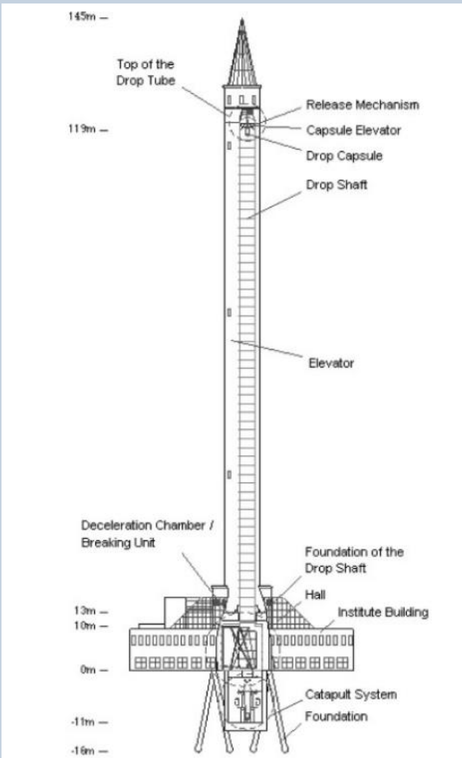
Constant Volume (CV) Measurement Methods

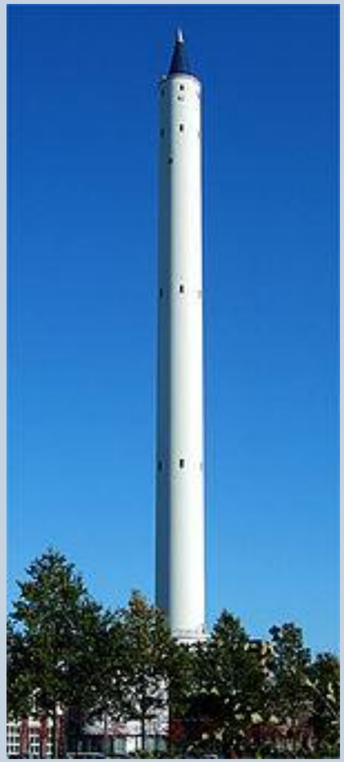
- Measurement Methods
  - Image the flame front before there is significant change in pressure,
  - Use the pressure rise and a thermodynamic analysis

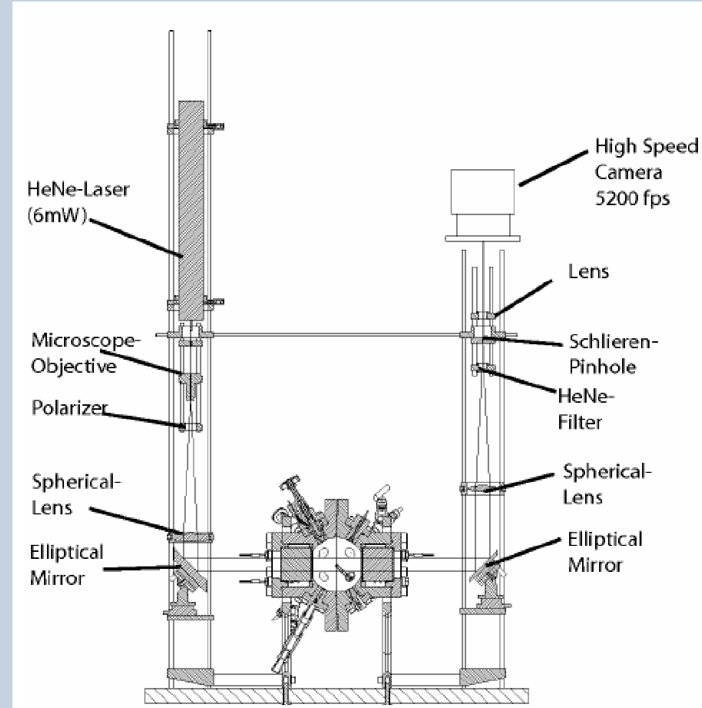
- Oxford Innovations
  - Zero Gravity – Andy Clarke
  - Multi-zone thermodynamic analysis – Khizer Saeed
  - Real Residuals – Steve Marshall
  - Reconciliation of both CV methods – Nathan Hinton

Acknowledegements to support from: BP, British Gas, Shell and EPSRC

The Bremen Drop Tower







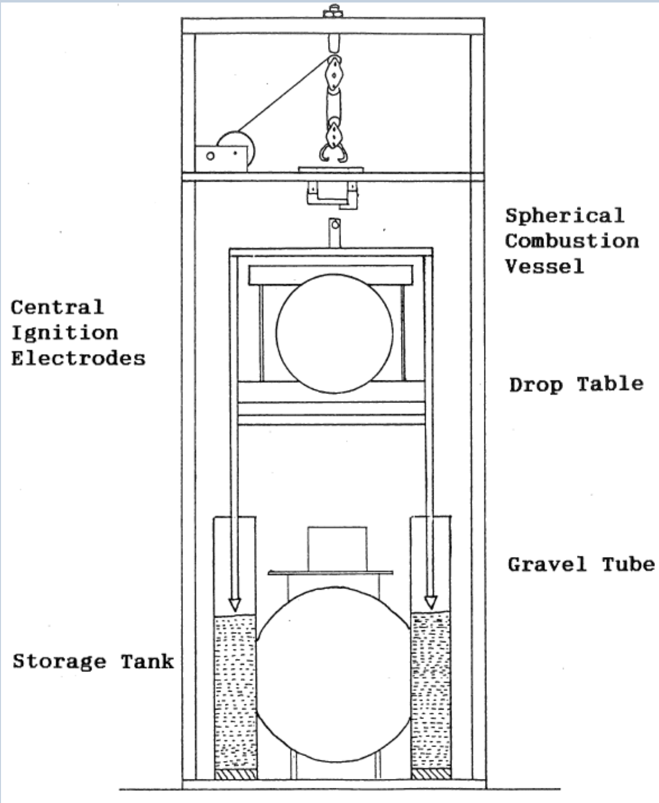
$\Phi = 0.1$ m

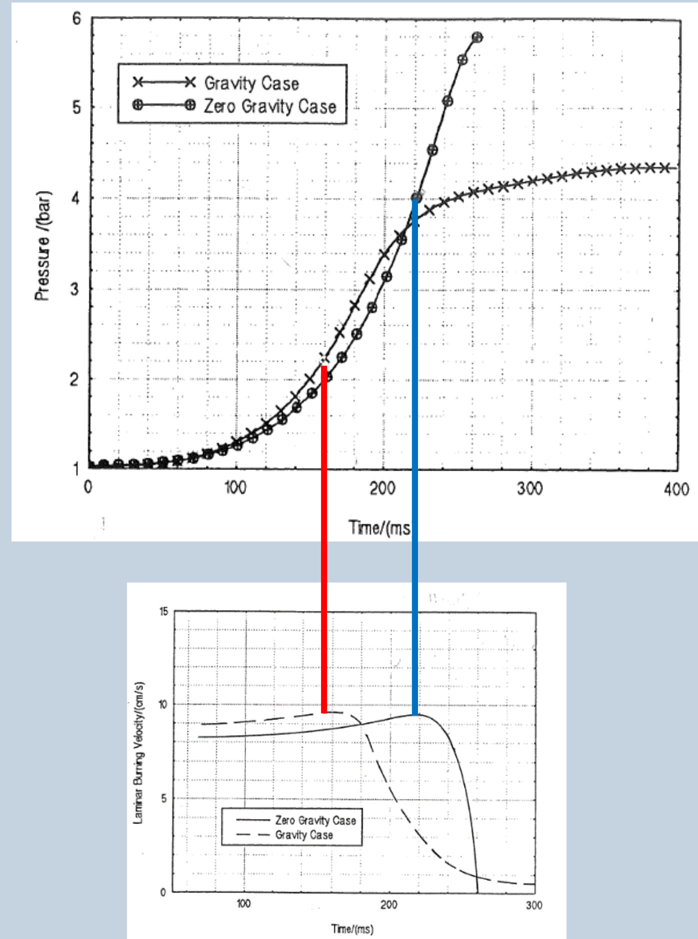
- height of the drop tube: **120 m**
- distance of the fall: **110 m**
- diameter of the drop tube: **3.5 m**
- deceleration unit: filled with **15 m³** of polysterene spheres up to a height of **8.20 m**
- experiment duration:
  drop experiment **4.74 s**
  catapult experiment **9.3 s**

- maximum speed of fall: **168 km/h**
- maximum weight of experiment capsule: **500 kg**
- vacuum: **18** pumps draw out **1700 m³** of air in **1.5** to **2 h**
- air pressure after evacuation: **10 Pa** (0.0001 bar)

Jerzembeck, Sven, and Norbert Peters. *Laminar Spherical Flame Kernel Investigation of Very Rich Premixed Hydrocarbon-Air-Mixtures in a Closed Vessel under Microgravity Conditions*. No. 2008-01-0471. SAE Technical Paper, 2008.

Oxford Zero Gravity Experiments





Stone, Richard, Andrew Clarke, and Paul Beckwith. "Correlations for the laminar-burning velocity of methane/diluent/air mixtures obtained in free-fall experiments." *Combustion and Flame* 114, no. 3-4 (1998): 546-555.

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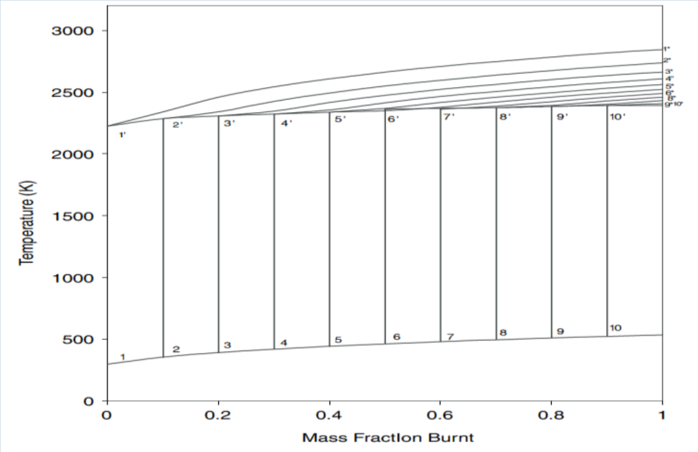
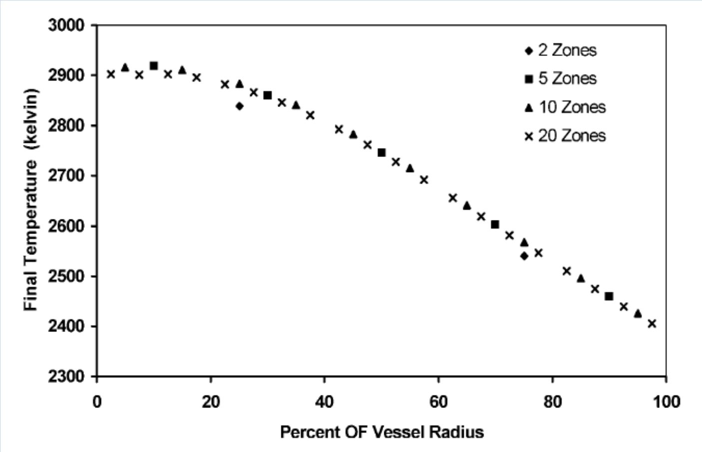
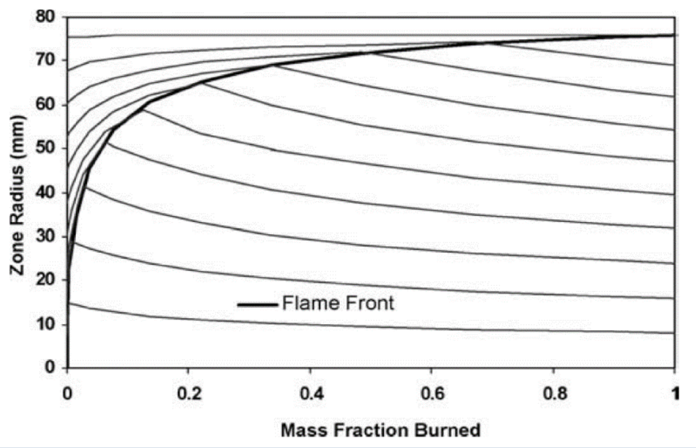
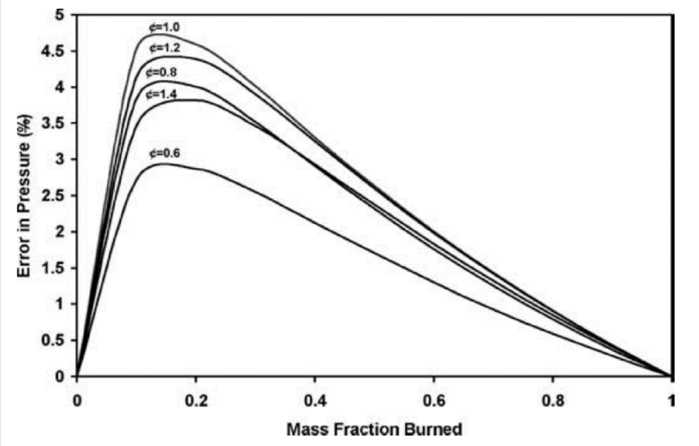
Multi-Zone Modelling of the Burned Gas







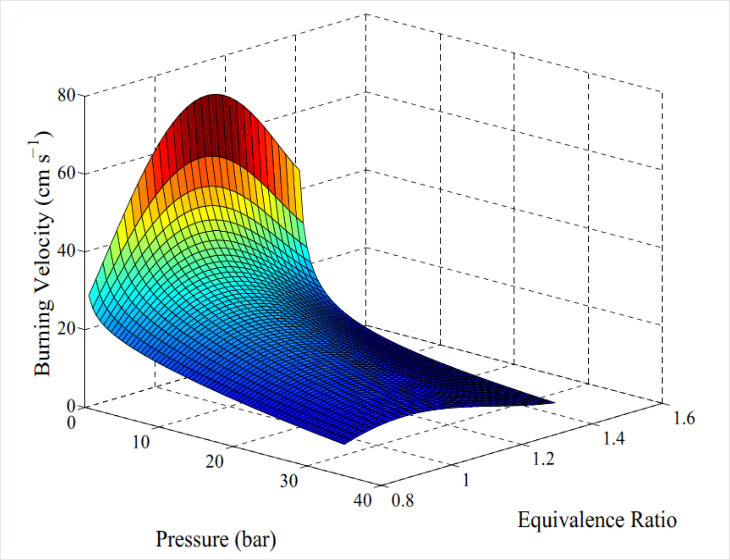


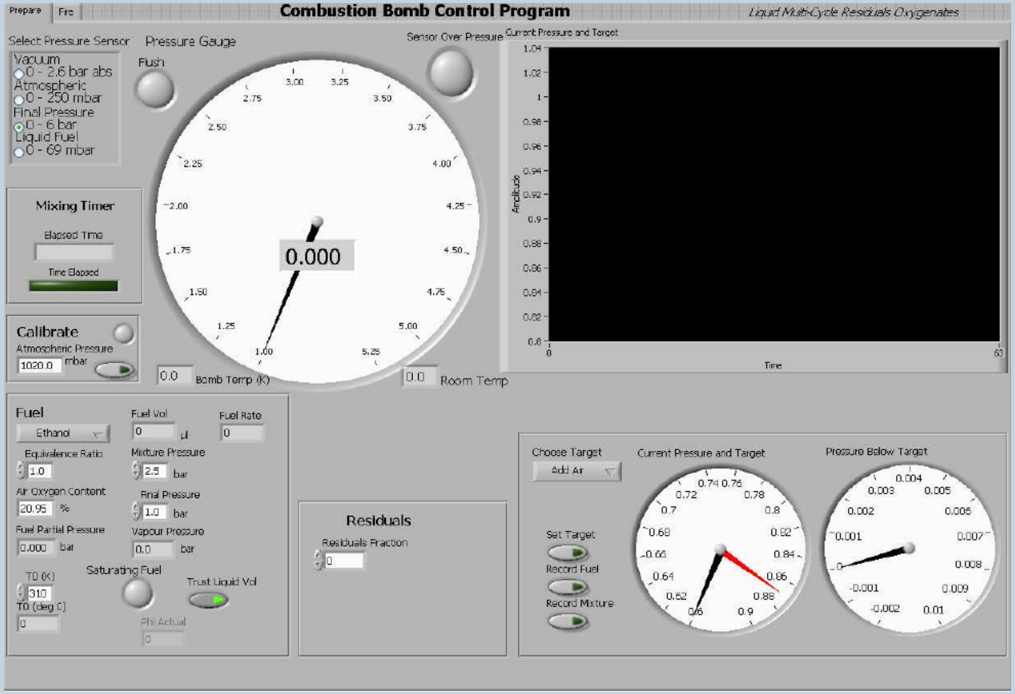
Saeed, Khizer, and C. R. Stone. "Measurements of the laminar burning velocity for mixtures of methanol and air from a constant-volume vessel using a multizone model." *Combustion and Flame* 139, no. 1-2 (2004): 152-166.

Saeed, Khizer, and C. R. Stone. "The modelling of premixed laminar combustion in a closed vessel." *Combustion Theory and Modelling* 8, no. 4 (2004): 721-743.

Real Residuals

- Metghalchi and Keck pioneered the use of a N2/CO2 mixture to represent combustion residuals
  - But what about rich mixtures with CO and H2 present?
- THEO fuels





Marshall, S. P., S. Taylor, C. R. Stone, T. J. Davies, and R. F. Cracknell. "Laminar burning velocity measurements of liquid fuels at elevated pressures and temperatures with combustion residuals." *Combustion and Flame* 158, no. 10 (2011): 1920-1932.

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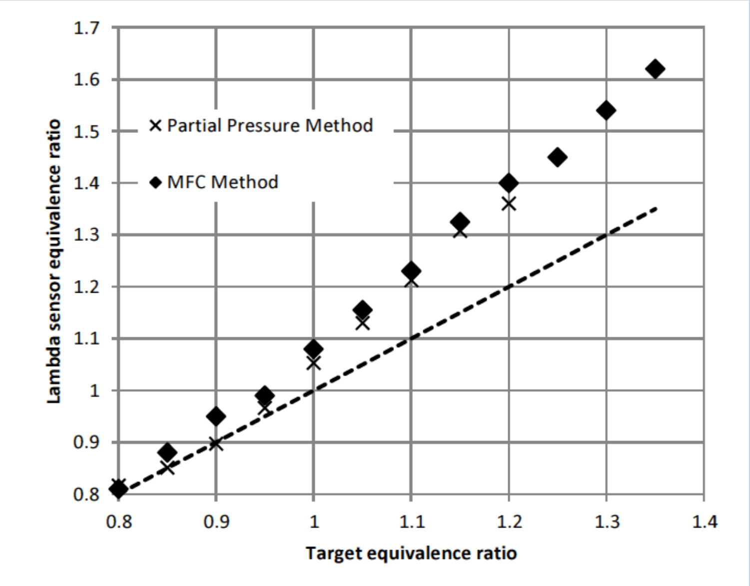
Constant Volume Vessel Methods Reconciliation; Lambda Sensor Challenge

- Lambda Sensors work well with weak and stoichiometric mixtures
  - Tests were undertaken with 2 independent methods of mixture preparation
  - For liquid fuels measure mass before and after injecting the fuel



Hinton, Nathan, Richard Stone, and Roger Cracknell. "Laminar burning velocity measurements in constant volume vessels–reconciliation of flame front imaging and pressure rise methods." *Fuel* 211 (2018): 446-457.

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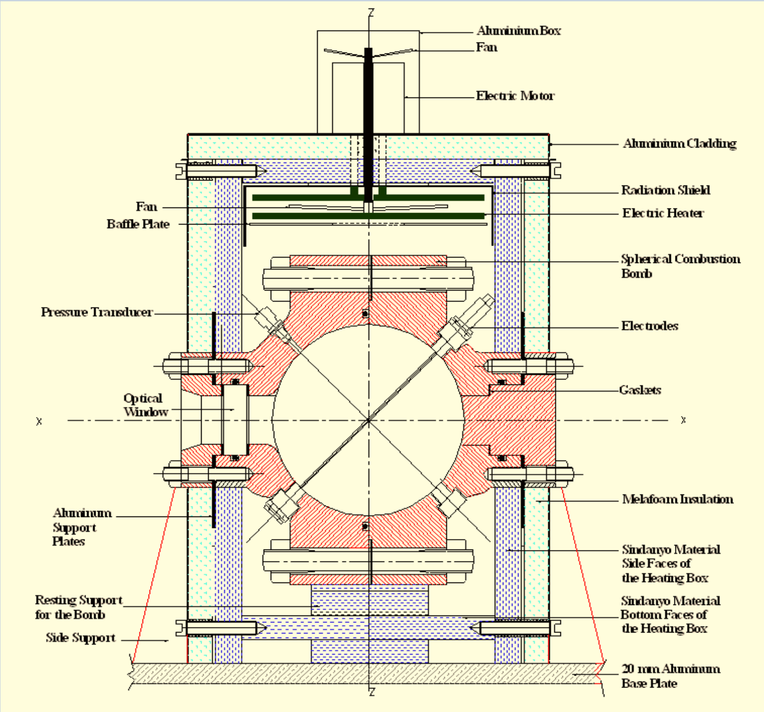
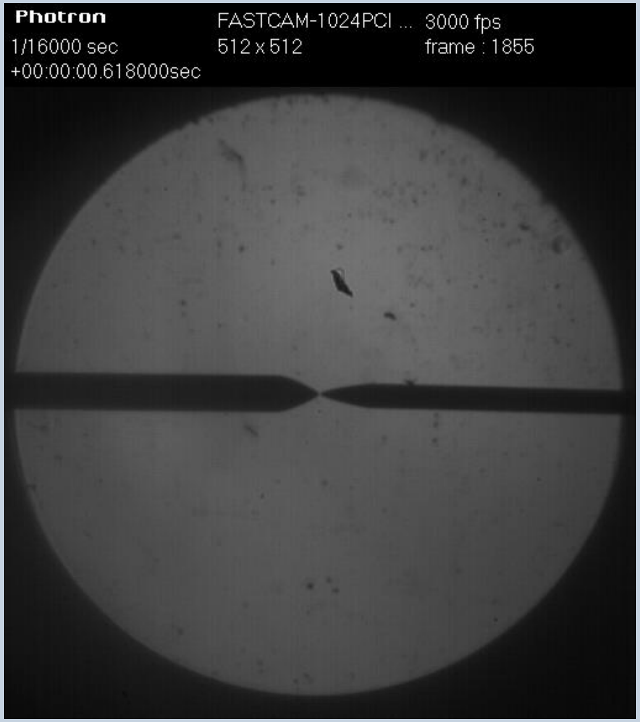
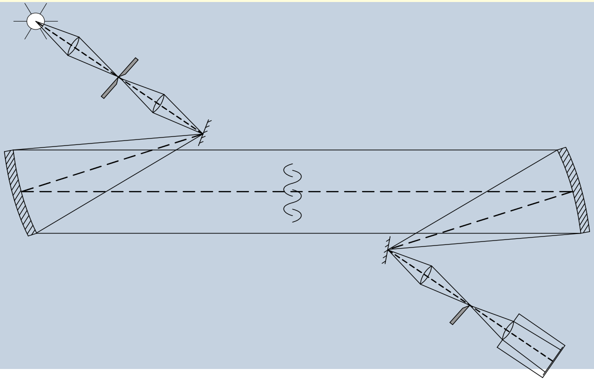
Combustion Bomb







http://www.youtube.com/watch?feature=player_embedded&v=E841wOOp0iQ

Experimental setup

Combustion bomb in temperature regulated chamber

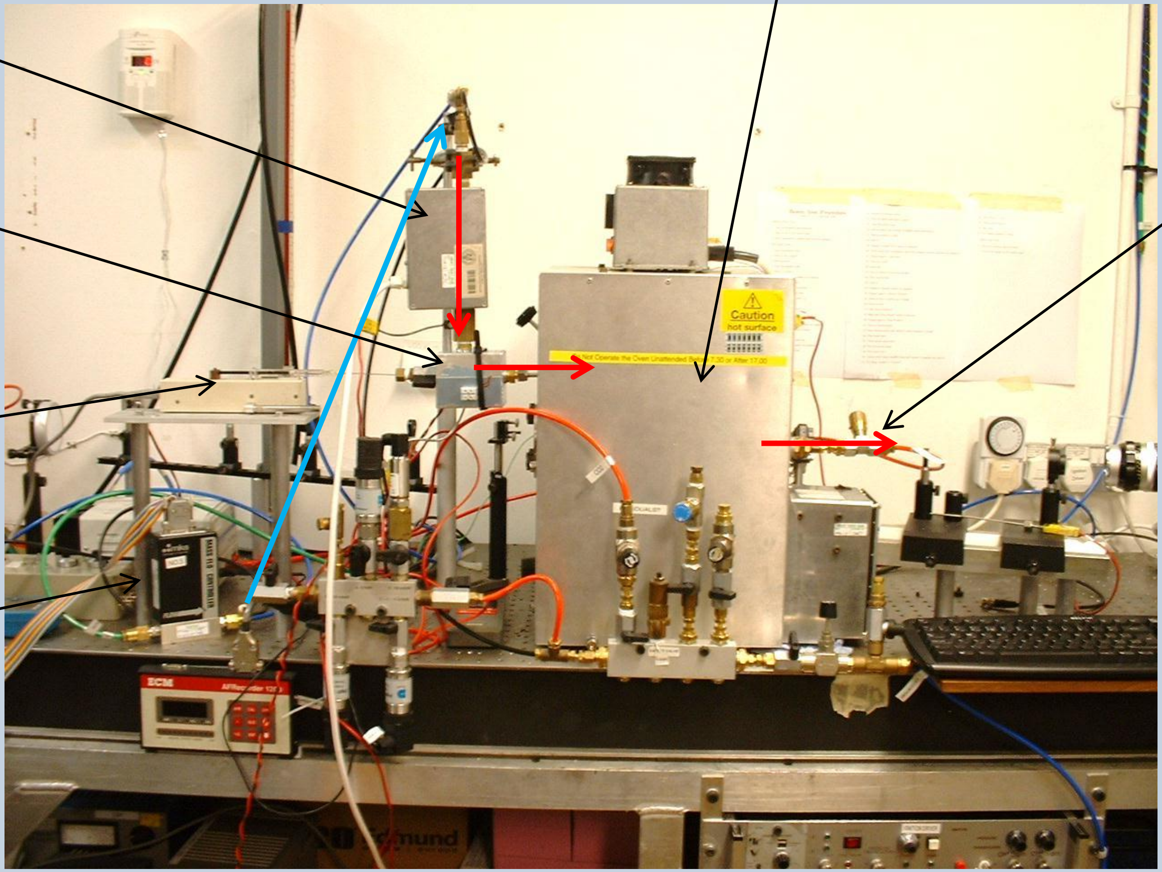
Air heater

Heated injection block

Syringe actuator

Mass flow controller

Needle valve controlling flow of exhaust to lambda sensor



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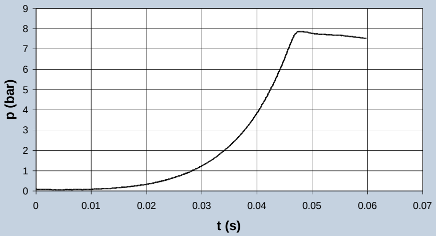
Calculating S_u

p_0, T_0, fuel

BOMB Program

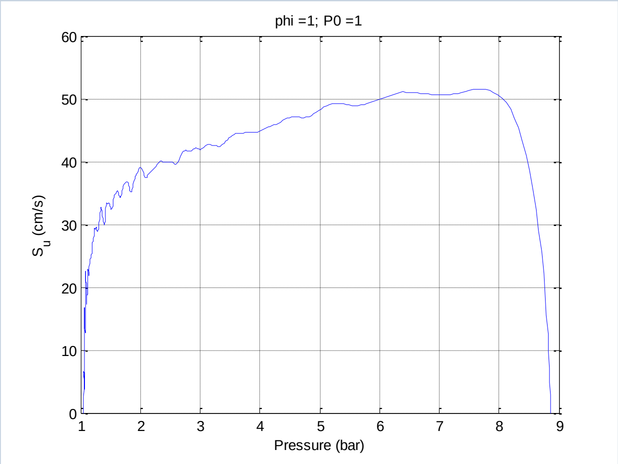
p(t)



p(r)

LabView

p(kT)

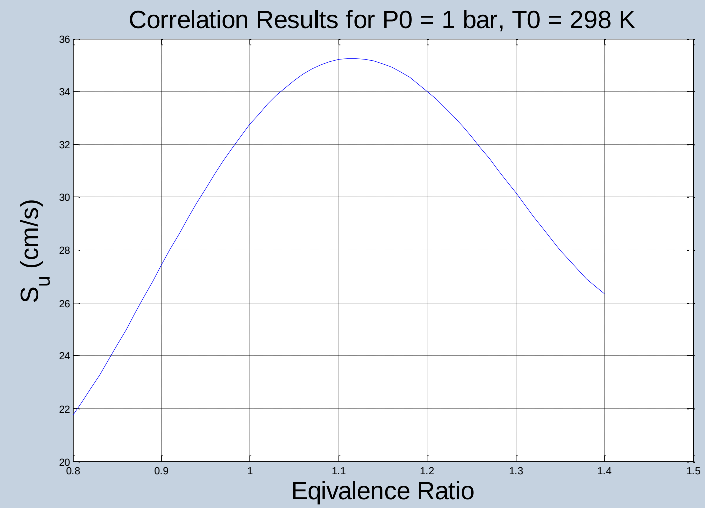


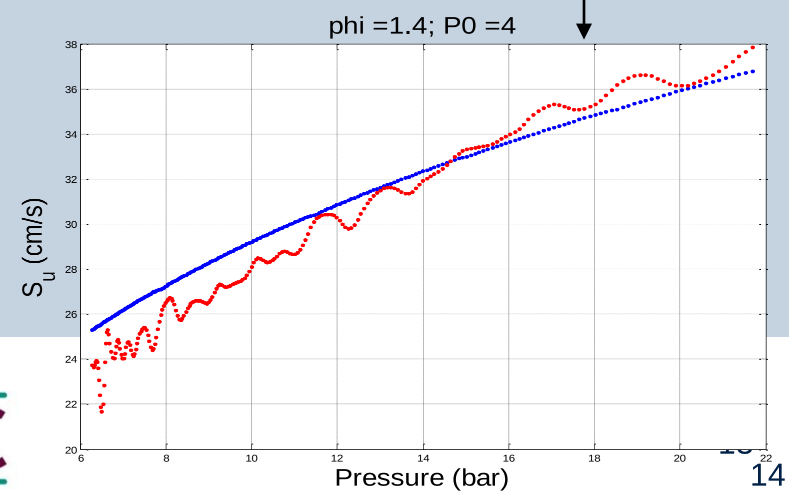
burnvel

bvcalc

$Su(p,T,\Phi,p_0,T_0)$

fitcorr





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Flame stretch

- Definition of laminar burning velocity is based upon a 1-D flame with parallel velocity components
- Outwardly propagating spherical flames are stretched due to:
  - Curvature, causing the velocity components to diverge
  - Strain, due to the increasing size of an elemental area of the surface as the flame propagates
- Overall stretch rate for a spherically expanding flame is given by:

$$\alpha = \frac{2}{r_b} S_f$$

- Stretch can either increase or decrease the burning velocity of a mixture, so its effect is important when considering early flame propagation and turbulent combustion

Determining Burning Velocity from Schlieren Images - 1/2

- Flame speed can be deduced from the Schlieren images of flame front propagation.
- Spherically expanding flames are initially highly stretched, so un-stretched flame speed is obtained by extrapolating back to of zero stretch:

$$S_s - S_f = L_b \alpha$$

- For the case of no pressure rise, flame speed is related to burning velocity by the ratio of burned and unburned gas density:

$$S_u = S_s \frac{\rho_b}{\rho_u}$$

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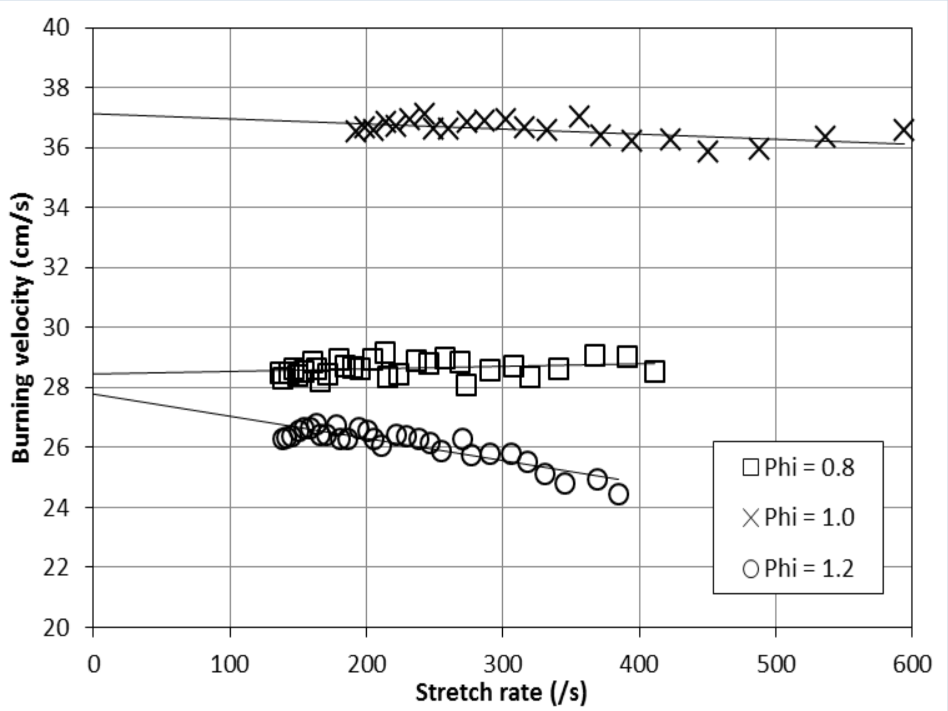
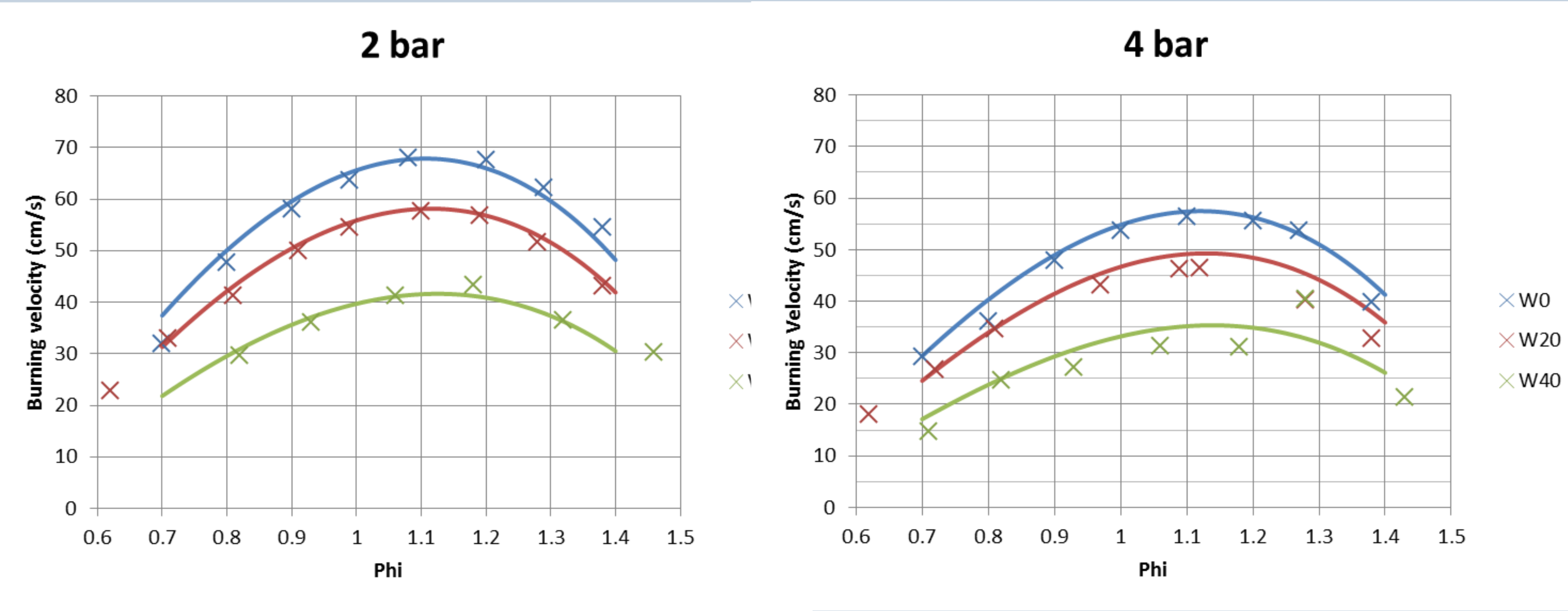
Determining Burning Velocity from Schlieren Images - 2/2



Stretch rate against burning velocity for biogas mixtures of 80% methane at T_0 = 450 K and P_0 = 4 bar.

Flame Front Imaging Data at 450 K

- Ethanol/Water mixtures



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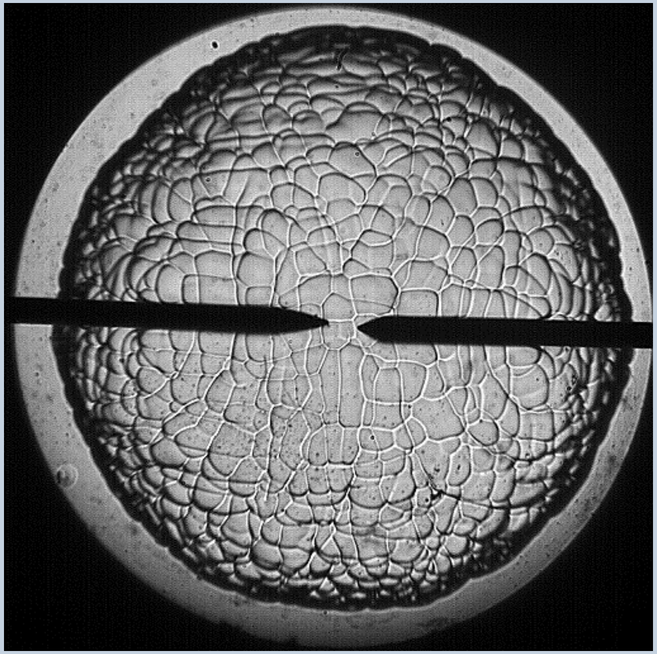
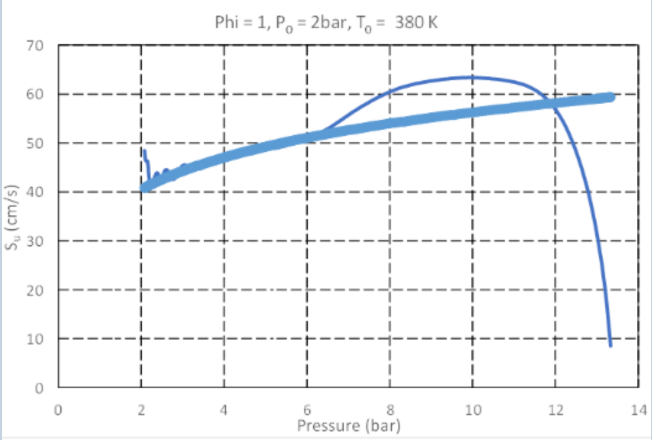
Cellularity

- Flame fronts of some mixtures become cellular at certain conditions
- Strongly influenced by the Lewis number of the mixture
- Causes a significant increase in the flame propagation due to increased surface area
- Onset of cellularity violates assumptions of a smooth flame front and stretch





Correlation of the Data

Correlation fitting routine produces a correlation from the data derived from the pressure record in the form:

$$S_u = \left[S_{u,0} + S_{u,1}(\phi - 1) + S_{u,2}(\phi - 1)^2 + S_{u,3}(\phi - 1)^3 + S_{u,4}(\phi - 1)^4\right] \times T^{\eta}\, P^{\beta}$$

Where:

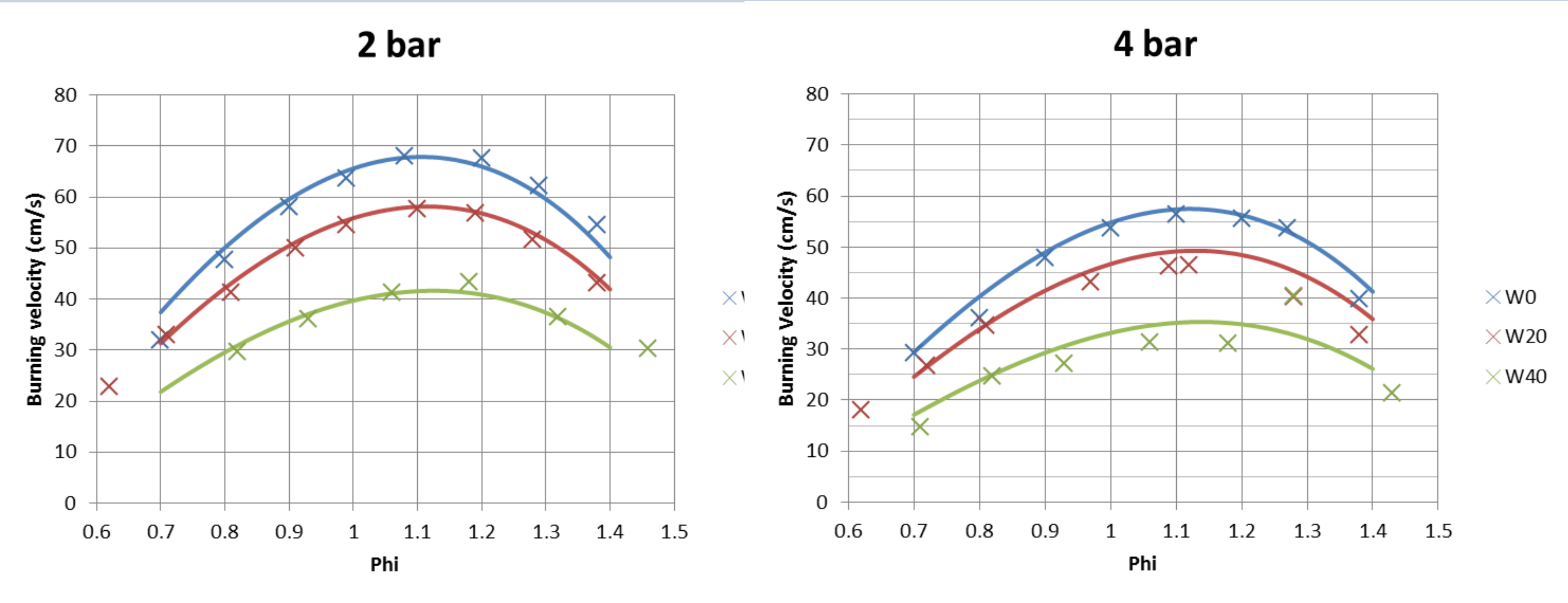
$$T = \frac{T_u}{298}\ ;\ P = \frac{P_u}{1.0}$$

$$\eta = \eta_0 + (\phi - 1)\eta_1\ ;\ \beta = \beta_0 + (\phi - 1)\beta_1$$

Correlations can then be plotted for desired conditions of P and T within the range for which data was fitted.

Flame Front Imaging Data at 450 K

- Ethanol/Water mixtures



Conclusions

- **Good agreement between the constant pressure and constant volume methods**
  - **Unlike some researchers**
- **Laminar burning velocity measurements at pressures up to 30 bar and temperatures up to 800 K.**
- **Effects of stretch measured at pressures up to 4 bar and temperatures up to 450 K.**
- **Data obtained for methane, butane, propylene, biogas, pentane, heptane, toluene, iso-octane, ethyl-benzene, methanol, ethanol, aqueous ethanol.**

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Any questions?