Laminar Burning Velocity Measurements over Wide Ranging Temperatures and Pressures

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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
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

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The Bremen Drop Tower


- 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 m$^3$ of polystyrene 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 m$^3$ of air in 1.5 to 2 h
- air pressure after evacuation: 10 Pa (0.0001 bar)
Oxford Zero Gravity Experiments

Multi-Zone Modelling of the Burned Gas


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

**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

Combustion Bomb

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

- Air heater
- Heated injection block
- Syringe actuator
- Mass flow controller
- Combustion bomb in temperature regulated chamber
- Needle valve controlling flow of exhaust to lambda sensor
Calculating $S_u$

$p_0$, $T_0$, fuel $\rightarrow$ BOMB Program

$p(t)$ $\rightarrow$ LabView

$p(kT)$ $\rightarrow$ burnvel

$p(r)$ $\rightarrow$ bvcalc

$p(kT)$ $\rightarrow$ Su($p$, $T$, $\Phi$, $p_0$, $T_0$) $\rightarrow$ fitcorr

Correlation Results for $P_0 = 1$ bar, $T_0 = 298$ K

Eqivalence Ratio

$S_u$ (cm/s)

Correlation Results for $P_0 = 1$ bar, $T_0 = 298$ K

Eqivalence Ratio

$S_u$ (cm/s)
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 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:

\[ S_u = S_s \frac{\rho_b}{\rho_u} \]
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

**2 bar**

**4 bar**
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:

\[ T = \frac{T_u}{298} \quad ; \quad P = \frac{P_u}{1.0} \]

\[ \eta = \eta_0 + (\phi - 1)\eta_1 \quad ; \quad \beta = \beta_0 + (\phi - 1)\beta_1 \]

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.
Any questions?