On the accurate determination of laminar burning velocity from constant-volume propagating spherical flames

Zheng Chen, Yiqing Wang

College of Engineering, Peking University

Peking University

3rd International Workshop on Laminar Burning Velocity, Lisbon, April 14, 2019
Laminar flame speed measurements

Stationary flame method:
- Bunsen flame
- flat flame (heat flux method)
- counterflow or stagnation flame

Propagating flame method:
- cylindrical tube method
- soap bubble method
- propagating spherical flame method

High pressure & temperature!

Propagating spherical flame method

Constant-Pressure Method
small flame, negligible P rise
Both $S_u^0$ and Markstein length

Constant-Volume Method
large flame with P rise
Engine-relevant $T_u$ and P
Data from the constant-volume method

- Same constant-volume method for the same fuel CH$_4$
- Large discrepancy!

Discrepancy among $S_u^0$ measured by OPF

CH$_4$/air, $T_u=298$ K, $P=1$ atm

- Large discrepancy, 18%, at $\phi=1$
- Large discrepancy at very lean or rich conditions

Possible causes for uncertainty

Small radius $\rightarrow$ large radius

Symbols: Exp. (Movileanu et al. 2009); Line: CFD

- Flame instability
- Chamber geometry
- Buoyancy, Radiation
- Ignition
- Stretch
- Wall heat loss
- CFD Data process

$P(t) \rightarrow S_u$

$CH_4/air, T_u=298 K, P=1 \text{ atm}$

(Qiao et al. 2007)

(Flame instability)

(Jomaas et al. 2013)

(Cylindrical chamber)

(Buoyancy)
Data process

- Assumptions
  - 1D spherical flame, no instability
  - ideal gas, uniform pressure distribution
  - isentropic compressed of unburned gas
  - negligible radiation and buoyancy ...

\[ S_u = \frac{dR_f}{dt} - \frac{R_W^3 - R_f^3}{3P\gamma_u R_f^2} \frac{dP}{dt} \]

\[ R_f/R_W = \left[ 1 - (1 - x)\left(\frac{P_0}{P}\right)^{1/\gamma_u} \right]^{1/3} \]

\[ S_u = \frac{R_W}{3} \left[ 1 - (1 - x)\left(\frac{P_0}{P}\right)^{1/\gamma_u} \right]^{-2/3} \left(\frac{P_0}{P}\right)^{1/\gamma_u} \frac{dx}{dt} \]

\[ S_u = S_u(P) \quad T_u / T_u,0 = (P / P_0)^{(1-1/\gamma_u)} \]

\[ x: \text{burned mass fraction, } x = m_b / m_0, \ x = x(P) \]
Data process

\[ S_u = \frac{R_w}{3} \left[ 1 - (1 - x)(\frac{P_0}{P})^{1/\gamma_u} \right]^{2/3} \frac{(P_0)^{1/\gamma_u}}{P} dx \frac{dt}{dt} \]

\[ x: \text{burned mass fraction}, \ x = \frac{m_b}{m_0}, \ x = x(P) \]

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Year</th>
<th>Eq. nos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ x = \frac{(P-P_0)}{(P_0-P_c)} ]</td>
<td>Lewis &amp; von Elbe</td>
<td>1951</td>
</tr>
<tr>
<td>[ x(P) = \frac{(T_c/T_b)(P/P_0-(P/P_0)^{1/\gamma_u})}{P_c/P_0-(P_c/P_0)^{1/\gamma_u}} ]</td>
<td>1959</td>
<td>(15)</td>
</tr>
<tr>
<td>[ x(P) = \frac{P-P_0(P/P_0)^{1/\gamma_u}}{P_c-P_0(P/P_0)^{1/\gamma_u}} ]</td>
<td>1963</td>
<td>(16)</td>
</tr>
<tr>
<td>[ x(P) = \frac{p^{1/\gamma_u} - p_0^{1/\gamma_u}}{p_c^{1/\gamma_u} - p_0^{1/\gamma_u}} ]</td>
<td>1969</td>
<td>(17)</td>
</tr>
<tr>
<td>[ x(P) = \frac{z[(P/P_0)^{1/\gamma_u} - 1]}{(P/P_0)^{1/\gamma_u} - 2}, \ z = \frac{T_0}{\rho_0} + \frac{(1-T_0/P_0)(P_0/P_0-1)}{(P_c/P_0-1)} ]</td>
<td>Luijten et al.</td>
<td>2009</td>
</tr>
<tr>
<td>[ x = \frac{P-P_0 f(P)}{P_c-P_0 f(P)}, \ f(P) = \frac{1}{\gamma_u} - 1 + \frac{2}{\gamma_u - 1} \left( \frac{P}{P_0} \right)^{\gamma_u - 1} ]</td>
<td>1994</td>
<td>(15), (21)</td>
</tr>
<tr>
<td>[ \gamma^* = \ln \left( \frac{P_c}{P_0} \left(1 - \frac{T_c}{T_b} \right) \right) ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[ x = \frac{P-P_0 f(P)}{P_c-P_0 f(P)}, \ f(P) = \frac{1}{\gamma_u} - 1 + \frac{2}{\gamma_u - 1} \left( \frac{P}{P_0} \right)^{\gamma_u - 1}, \ \gamma_{b,\text{shift}} = \frac{\gamma_u + 8}{8} ]</td>
<td>2016</td>
<td>(19), (20)</td>
</tr>
</tbody>
</table>

CH\textsubscript{4}/air, \ \phi=1, \ T_0=300 \text{ K}, \ P_0=1 \text{ atm}

**Ignition**

- Important for the constant-pressure method
- Negligible for the constant-volume method

![Graph showing relationship between time and pressure or flame position.](image)

- $P = P(t)$
- $R_f = R_f(t)$
- $P/P_0 < 1.1$
**Stretch**

Chen et al. (2009CTM)

\[ K = \frac{2}{R_f} \frac{dR_f}{dt} \]

\[ S_u = S_u^0 - L_u K \]

\[ \frac{S_u^0 - S_u}{S_u^0} \approx \frac{2L_u}{R_f} \left( \frac{\gamma_u - 1}{\gamma_u} + \frac{P_e}{\gamma_u P} \right) \]

- Important only at the beginning; negligible for \( P/P_0 > 2 \)
- Negligible for high pressures

**Diagram:**

- PREMIX
- without stretch correction (\( S_u \))
- SCFS, \( S_u^0 (L_u=\text{const}) \)
- SCFS, \( S_u^0 (L_u \neq \text{const}) \)

**C\(_3\)H\(_8\)/air, \( \phi=0.8 \)**

\( T_{u0}=300 \text{ K}, P_0=1 \text{ atm} \)
Flame instability

Two facilities:
- Cylindrical chamber, for full optical access and instability
- Spherical chamber, to preserve sphericity and record P

Single facility: spherical chamber + optical access (Fabien Halter)
Chamber geometry

- **Spherical chamber**
- **Cylindrical chamber**

**Graph:**
- \( P \) vs. \( t \)
- \( P_0 \) to \( P_e \)
- Flame reaches the side walls

- **For the cylindrical chamber,** much lower \( P_{\text{max}} \) than \( P_e \)
- **Very close pressure history** before flame reaches wall

*Burke et al. (2010CNF)*
Chamber geometry

- **Spherical chamber**
- **Cylindrical chamber**

For the cylindrical chamber,
- much lower $P_{\text{max}}$ than $P_e$
- Very close pressure history before flame reaches wall

Exp. by Far et al. (2010Fuel)

- JP-8/air, $\phi=0.8$
- $T_{u0}=500$ K, $P_0=5$ atm

Useful for $P(t) \rightarrow S_u$
Buoyancy

- Identical at 1-g and μ-g for $S_u^0 > 15$ cm/s (Ronney 1985)
- Similar pressure history before flame reaches wall
- Non-spherical?
Buoyancy

- 2D simulation by Fluent, $H_2:O_2:N_2=6:1:4.96$, $T_0=300\; K$, $P_0=1\; atm$
- $S_u=170\; cm/s$ @ $400g$ is equivalent to $S_u=8.5\; cm/s$ @ $1g$

$$Ri = \frac{gL}{V^2} \left( \frac{T_b}{T_u} - 1 \right)$$
Radiation

CH₄/air, φ=1.0, T₀=300 K, P₀=1 bar

CH₄/air, φ=0.6, T₀=300 K, P₀=1 bar

- Negligible even for weak mixture: within 2%
- Radiation absorption reduces the difference
- Slow burning fuels, e.g.: refrigerants?
Radiation

\[ S_u = \frac{R_W}{3} \left[ 1 - (1 - x) \left( \frac{P_0}{P} \right)^{1/\gamma_u} \right]^{-2/3} \frac{P_0}{P} \left( \frac{P_0}{P} \right)^{1/\gamma_u} \frac{dx}{dt} \]

\[ P(\text{bar}) \]
\[ S_u(\text{cm/s}) \]

CH\(_4\)/air, \(\phi=1.0\), \(T_{u0}=300\ \text{K}\), \(P_0=1\ \text{bar}\)

- Negligible even for weak mixture: \textit{within 2%}
- Radiation \textit{absorption} reduces the difference
- Slow burning fuels, e.g.: refrigerants?
Radiation

\[ S_u = \frac{dR_f}{dt} - \frac{R^3}{3P\gamma_R R^2_f} \frac{dP}{dt} \]

- "Neglecting radiation heat loss when interpreting experimental data could lead to uncertainty as large as 15%"

\( H_2/\text{CO}/\text{O}_2/\text{He}, \phi=0.8 \quad T_{u0}=298 \text{ K}, \quad P_0=6 \text{ atm} \)

\( \text{CH}_2\text{F}_2/\text{air}, \phi=1 \quad T_{u0}=298 \text{ K}, \quad P_0=1 \text{ atm} \)

Xiouris et al. (2016CNF)  
Burrell et al. (2019PCI)
A thin thermal boundary layer develops near the wall.
A thin thermal boundary layer develops near the wall

Heat loss to the wall results in pressure drop
Wall heat loss

- A thin thermal boundary layer develops near the wall
- Heat loss to the wall results in pressure drop
- Useful data before \( (dP/dt)_{\text{max}} \)
Wall heat loss

CH₄/air, $\phi=1$, $T_{u0}=300$ K, $P_0=1$ bar

- A thin thermal boundary layer develops near the wall
- Heat loss to the wall results in pressure drop
- Useful data before $(dP/dt)_{max}$
Wall heat loss

- A thin thermal boundary layer develops near the wall
- Heat loss to the wall results in pressure drop
- Useful data before \((dP/dt)_{max}\)
Summary

- To avoid stretch effect: $P/P_0 > 2$ or $P > 5$ atm
- To avoid wall heat loss: $P/P_e < 0.75$
- Negligible radiation effect for: $S_u > 10$ cm/s ?
- Negligible buoyancy effect for: $Ri = (T_b/T_u - 1)gL/S_u^2$ ?
- Data processing, burned mass fraction: $x = m_b/m_0$

\[
S_u = \frac{R_w}{3} \left[ 1 - (1 - x) \left( \frac{P_0}{P} \right)^{1/\gamma_s} \right]^{-2/3} \left( \frac{P_0}{P} \right)^{1/\gamma_s} \frac{dx}{dt}
\]

\[
S_u = \frac{dR_f}{dt} - \frac{R_w^3 - R_f^3}{3P \gamma_u R_f^2} \frac{dP}{dt}
\]

(Burrell et al. 2019)
Thank you!

On laminar burning velocity measurement using the \textit{constant-volume} propagating spherical flames

Zheng Chen, Yiqing Wang

Peking University

Email: cz@pku.edu.cn