Measurement of key values in combustion: The heat flux burner method to determine laminar burning velocities

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Outline

1. Introduction
2. Burner and test rig
3. Results and discussion
4. Conclusion
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Introduction

laminar burning velocity / flame speed

- propagation speed of a reactive flame front to the fresh reactant side in a stationary/resting fuel-oxidizer mixture.

- characteristics:
  - adiabatic
  - laminar
  - planar (unstretched and non-curvature)

- depending on $T$, $p$, $\lambda$, fuel, (oxidizer)
Introduction

Introduction

Several measuring techniques to determine the laminar burning velocity

- Bunsen method
- Counterflow method
- Heat-Flux burner
- Flame tube method
- Constant volume spherical flame method

Review paper by Egolfopoulos et al. 2014
Introduction

The heat flux burner is a suitable burner for laminar flame research

- $S_L$
- Species Concentrations
- Flame Structure
- ...

- Chemical Kinetics
- Flame Structure
- ...

Experiments  Modeling
Flame diagnostics at TU Bergakademie Freiberg

Furthermore, a range of model burner systems are available:
• flat flame burner (McKenna and Heat-Flux burner)
• counter flow burner
• constant volume bomb chamber

Counter flame burner
(auto-ignition; extinction)

Flat flame burner
(soot investigation)

Constant volume bomb chamber
(laminar burning velocity)
(gaseous and liquids fuels up to 20 bar)
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Burner and test rig

Eindhoven (TUE)
- thermocouple: type E
- temperature difference: 60 K
- effective burner plate-Ø: 30 mm

Lund (LU)
- thermocouple: type T
- temperature difference: 70 K (298 K) / 50 K (318 K)
- effective burner plate-Ø: 29,3 mm
- evaporation system with carrier gas / coriolis-MFC for liquid fuels

Öl-Wärme-Institut (OWI)
- thermocouple: type E
- temperature difference: 75 K
- effective burner plate-Ø: 29,3 mm
- evaporation with porous matrix and pump

Bergakademie Freiberg (TUBAF)
- thermocouple: type E
- temperature difference: 70 K
- effective burner plate-Ø: 29,3 mm
- adapted direct evaporator system / coriolis-MFC for liquid fuels
Burner and test rig

measuring principle

- measuring radial temperature profile within the burner plate.
- stabilization of a quasi-adiabatic flame on top of the burner plate.
- heat flux between flame / burner plate and burner plate / fuel-oxidizer mixture must be equalized.
- $u_g < S_L \rightarrow$ positive heat flux $\rightarrow$ burner plate achieve higher temperature compared to heating circuit
- $u_g > S_L \rightarrow$ negative heat flux $\rightarrow$ burner plate achieve lower temperature compared to heating circuit
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Results and discussion

Laminar burning velocity of methane

Table 1 – Mean values of measured burning velocities for methane/air mixtures at 298 K

<table>
<thead>
<tr>
<th>φ</th>
<th>Mean value, cm/s</th>
<th>Mean deviation, cm/s</th>
<th>Standard deviation, cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>16.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.8</td>
<td>24.8</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>0.9</td>
<td>31.9</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>1</td>
<td>36.9</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1.1</td>
<td>38.3</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>1.2</td>
<td>34.9</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>1.3</td>
<td>26.9</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 2 – Average differences between the results of different labs for methane/air mixtures at 298 K

<table>
<thead>
<tr>
<th>Average difference [cm/s]</th>
<th>TUBAF</th>
<th>OWI</th>
<th>TUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>LU</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>TUBAF</td>
<td>-</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>OWI</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Results and discussion

Laminar burning velocity of ethanol

\[ \text{C}_2\text{H}_5\text{OH} - \text{air} \]
318 K, 1 atm

Table 3 – Mean values of measured burning velocities for ethanol/air mixtures at 318 K

<table>
<thead>
<tr>
<th>( \phi )</th>
<th>Mean value, cm/s</th>
<th>Mean deviation, cm/s</th>
<th>Standard deviation, cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>23.1</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>0.8</td>
<td>33.1</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>0.9</td>
<td>41.4</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td>46.9</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1.1</td>
<td>48.8</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>1.2</td>
<td>47.4</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>1.3</td>
<td>42.1</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>1.4</td>
<td>34.5</td>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 4 – Average differences between the results of different labs for ethanol/air mixtures at 318 K

<table>
<thead>
<tr>
<th>Average difference [cm/s]</th>
<th>TUBAF</th>
<th>OWI</th>
</tr>
</thead>
<tbody>
<tr>
<td>LU</td>
<td>0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>TUBAF</td>
<td>-</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Results and discussion

Laminar burning velocity of methanol

CH$_3$OH – air
298 K, 1 atm

Table 5 – Mean values of measured burning velocities for methanol/air mixtures at 298 K

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>Mean value, cm/s</th>
<th>Mean deviation, cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>18.5</td>
<td>0.1</td>
</tr>
<tr>
<td>0.8</td>
<td>28.1</td>
<td>0.2</td>
</tr>
<tr>
<td>0.9</td>
<td>36.4</td>
<td>0.0</td>
</tr>
<tr>
<td>1.0</td>
<td>42.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>


$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$

$MD = \frac{1}{N} \sum_{i=1}^{N} |x_i - \bar{x}|$
Results and discussion

Laminar burning velocity of syngas

\[ \text{H}_2\text{-N}_2\text{-Air, H}_2\text{/N}_2 \text{ ratio, } T_u=298 \text{ K} \]

\[
\begin{array}{c|c|c|c}
\text{laminar burning velocity / cm s}^{-1} & 70 & 60 & 50 \\
0 & 60 & 50 & 40 \\
1 & 50 & 40 & 30 \\
2 & 40 & 30 & 20 \\
3 & 30 & 20 & 10 \\
4 & 20 & 10 & 0 \\
\end{array}
\]

equivalence ratio \( \Phi \)

35/65 \quad \text{Connaire 2004} \quad \text{Davis 2005} \quad \text{Starik 2009} \quad \text{H}_2 \text{ ELTE 2013}

Voss et al., 2014,
doi: 10.1016/j.ijhydene.2014.09.093
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Conclusion

- The heat flux burner method has been used to measure the laminar burning velocity of different fuels:
  - methane-air mixtures
  - ethanol-air mixtures
  - methanol-air mixtures
  - syngas mixtures
- In this study the combined standard uncertainty of independent input quantities for the laminar burning velocity, the equivalence ratio is calculated. It is later expanded to a higher level of confidence so it results in an expanded standard uncertainty. The calculation of the uncertainties is based on the “Guide to the Expression of Uncertainty in Measurement” (GUM) from the “Joint Committee for Guides in Metrology” (JCGM).
- Standard deviations were over wide ranges < 0.7 cm/s.
- Heat-Flux burner in combination with a direct evaporizer, coriolis mass flow controller and hydraulic accumulator ensure high reproducibility and accuracy.
Heat Flux Method
for accurate measurement of the laminar burning velocity
www.heatfluxburner.org

www.heatfluxburner.org
Thank you for your attention

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