Laminar Burning Speed of *n*-Hexane–Air Mixtures

S. Coronel[1] R. Mével[1] P. Vervish[1] P. A. Boettcher[1] V. Thomas[1]
N. Chaumeix[2] N. Darabiha[3] J. E. Shepherd[1]

[1]Graduate Aeronatical Laboratories, California Institute of Technology,

[2]Institut de Combustion, Aérothermique, Réactivité et Environnement CNRS,

[3]Laboratoire EM2C-CNRS UPR 288, École Centrale Paris

8th US National Combustion Meeting

University of Utah
May 19 - 22, 2013

Summary

Accidental Ignition

- Accidental ignition
  - → electrostatic ignition of fuel
  - → lightning strike
  - → electrical faults in pumps, fuel quantity instrumentation
  - → hot surface ignition
- Characterize fuel-oxidizer properties (*n*-hexane)
  - → ignition delay time (Burcat et al. and Zhukov et al.)
  - → heating rate on the low temperature oxidation of hexane by air (Boettcher et al.)
  - → minimum ignition temperature (Boettcher)
  - → minimum ignition energy (Bane)
  - → laminar burning speed

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Summary

Laminar Burning Speed

- Davis and Law :
  - $\rightarrow$ T_0 = 296 K and P_0 = 100 kPa
- Farrell et al. :
  - $\rightarrow$ T_0 = 450 K and P_0 = 304 kPa
- Kelley et al. :
  - $\rightarrow$ T_0 = 353 K and P_0 = 100-1000 kPa
- Ji et al. :
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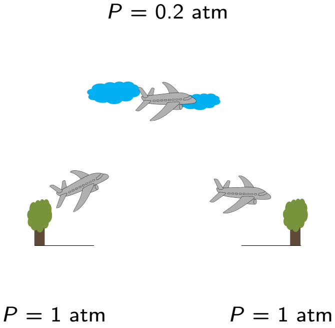

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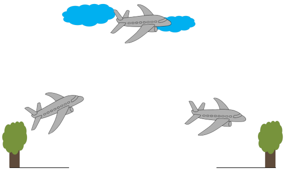
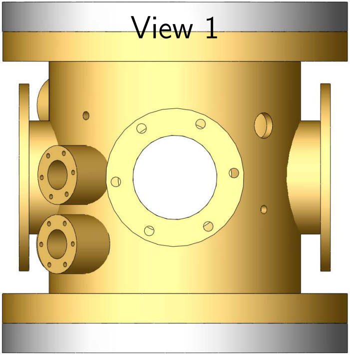
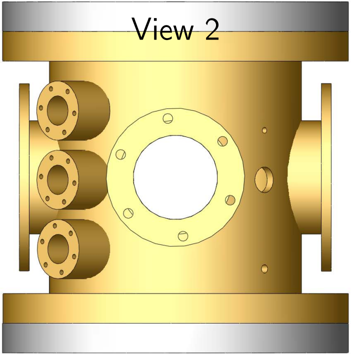


n-hexane–air
$P_0 \leq 100$ kPa
$T_0 = 296$-380 K

Summary

Experimental Setup : Combustion Vessel





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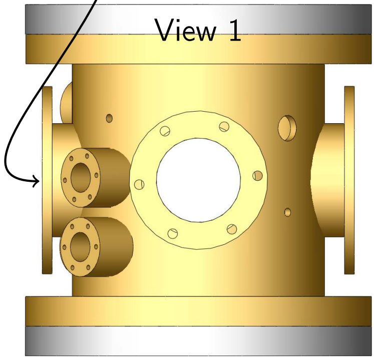
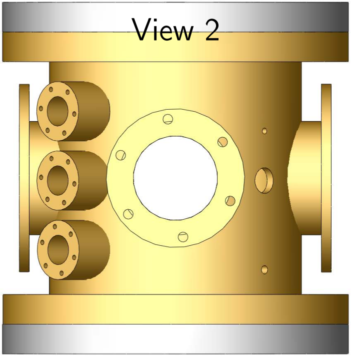
11.7 cm diameter windows





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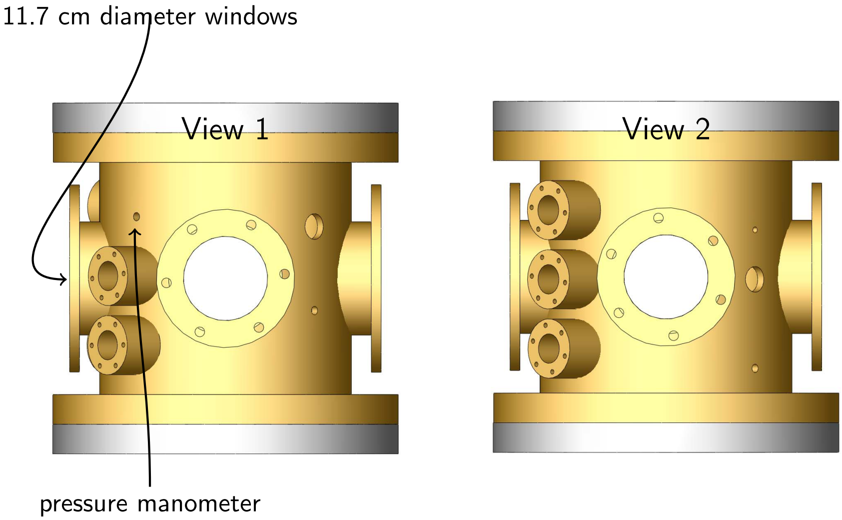

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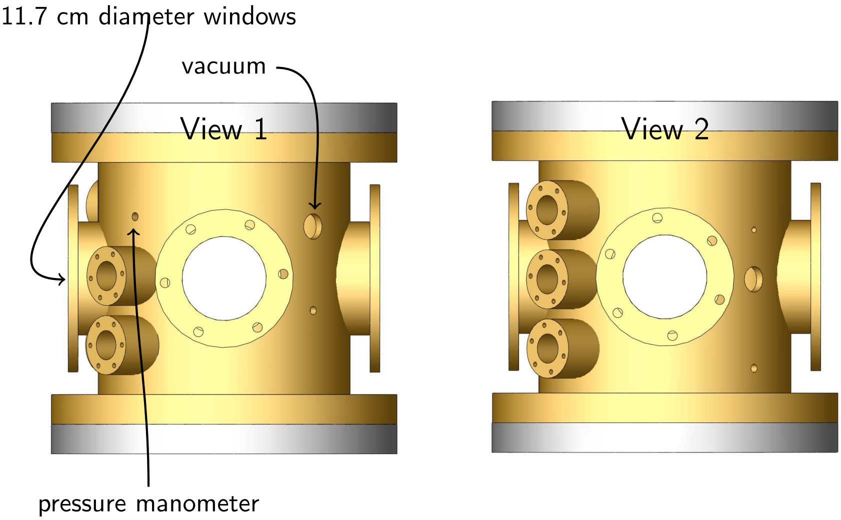

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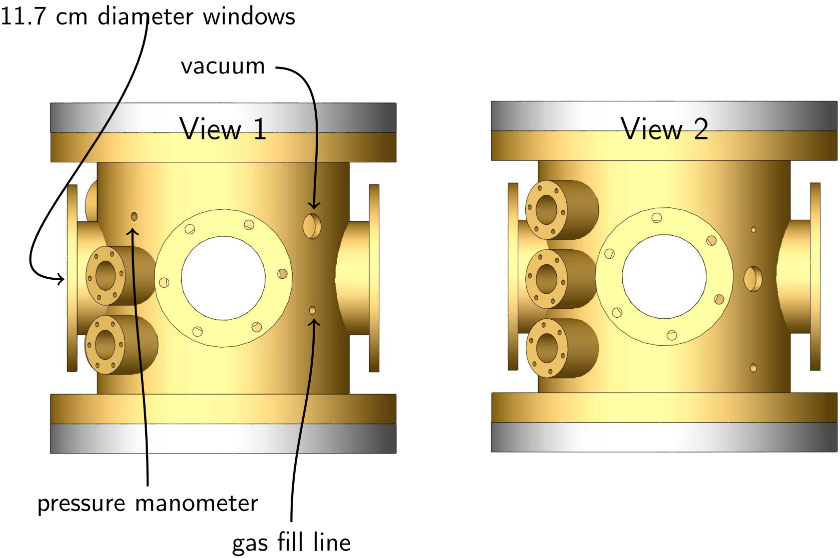

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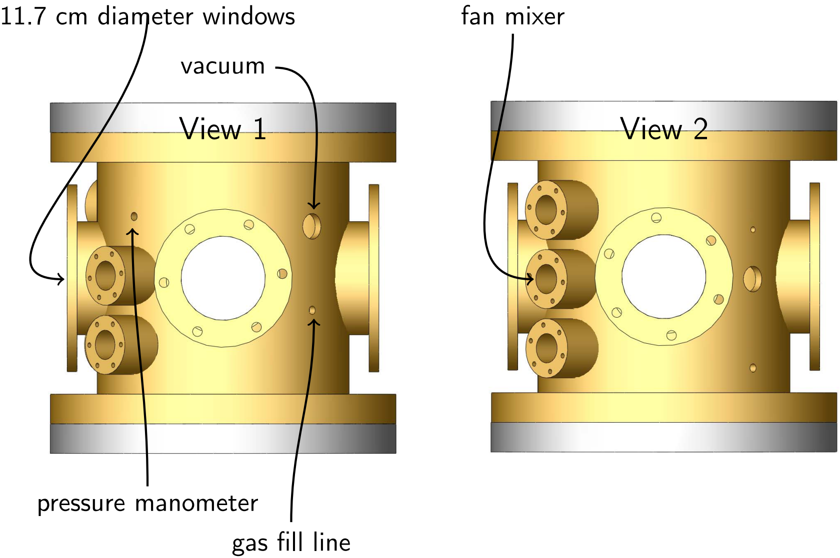

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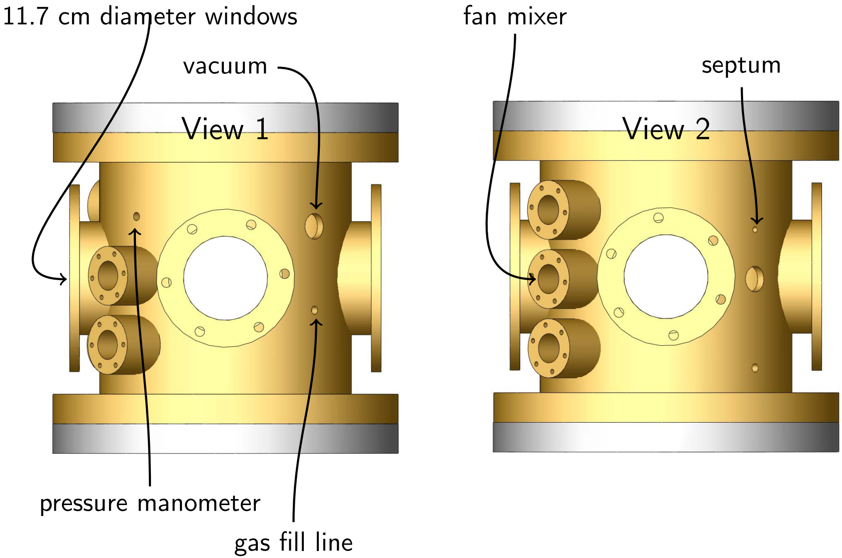

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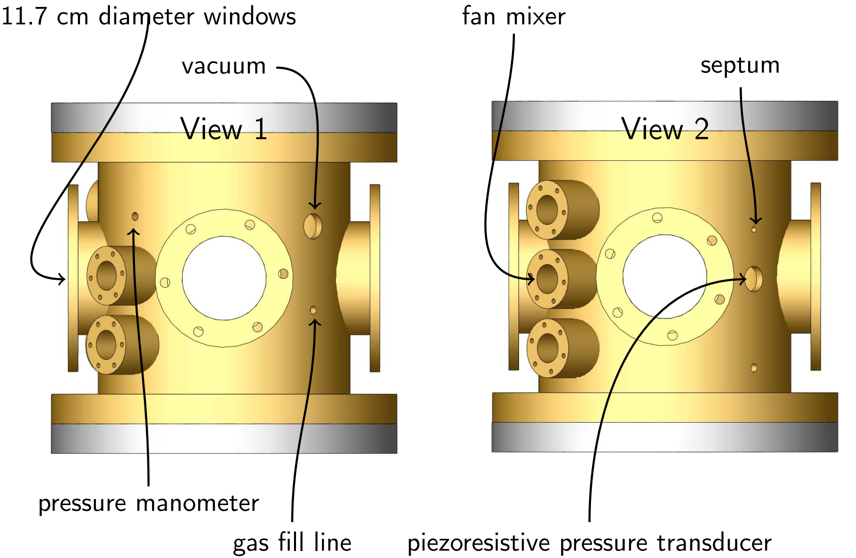

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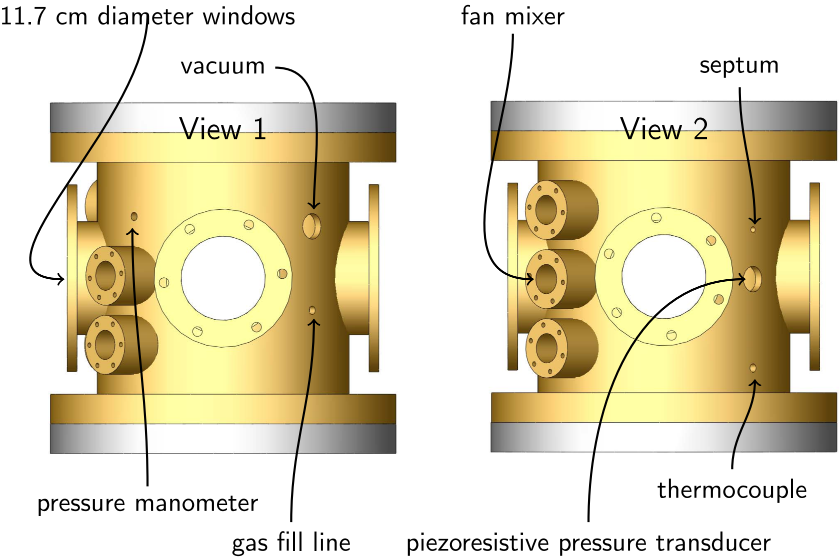
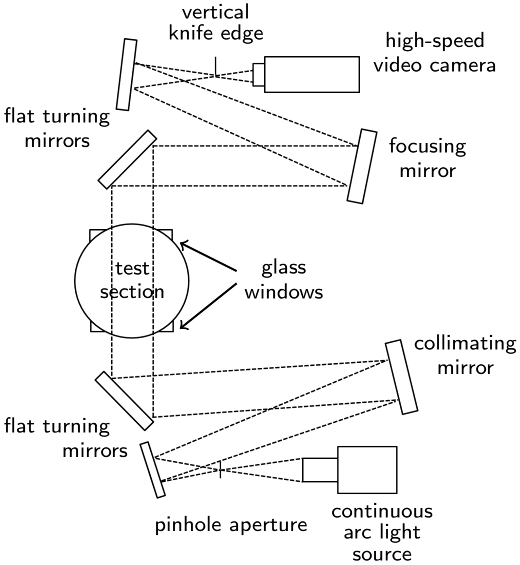


Experimental Setup : Schlieren Setup

- Observe changes in the density gradient of the fluid due to variations in the refractive index
- Visualize flame :
  - → very hot flame propagating into cold unburned reactants
- High speed camera :
  - → 10,000 frames per second
  - → 512×512 resolution



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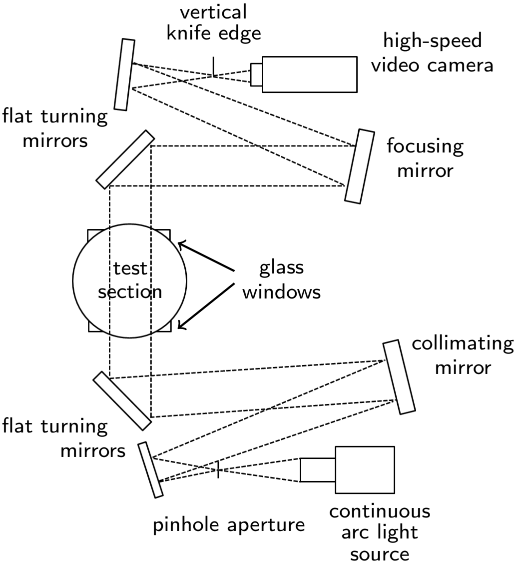

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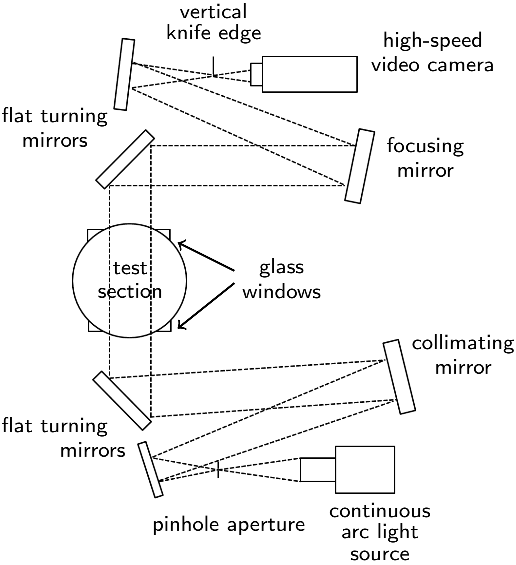

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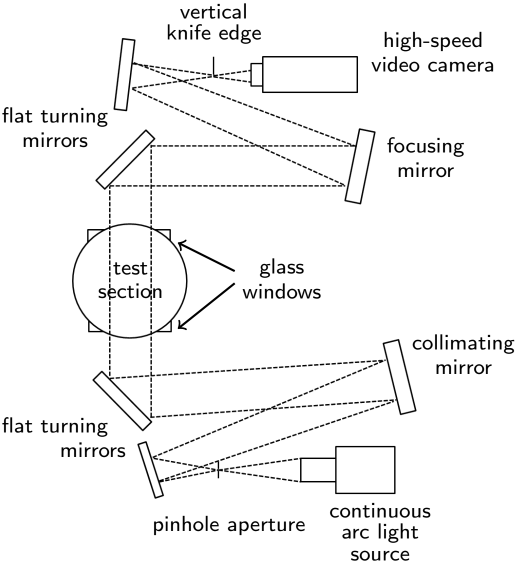

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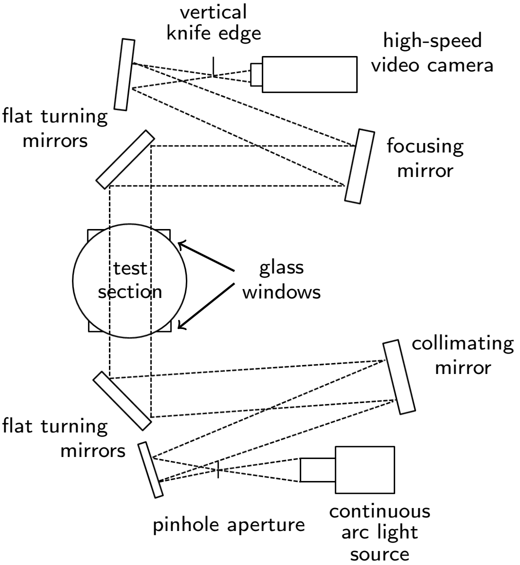

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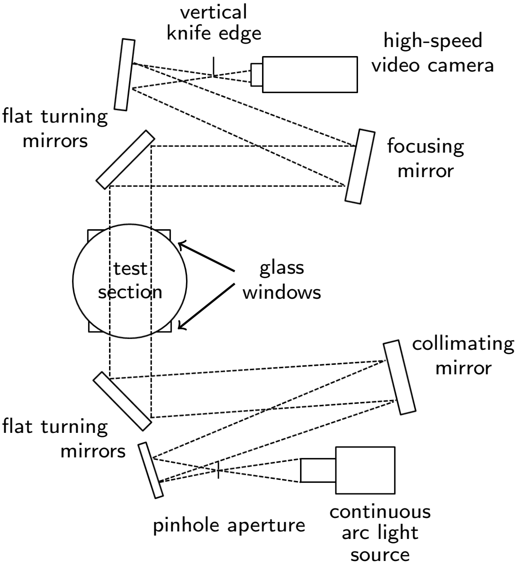
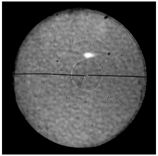
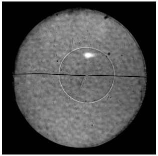


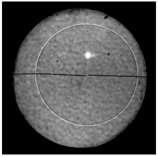
Burning Speed Measurements



t = 5.0 ms



t = 9.7 ms



t = 17.1 ms

- Edge detection using the Canny method (MATLAB)
- Fit ellipse to detected edge
  - → use area of ellipse to find an equivalent radius
- Linear extrapolation to unstretched flame speed

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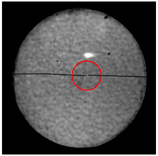

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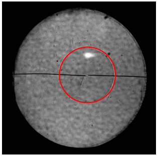

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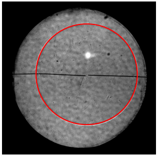

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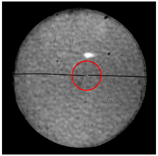

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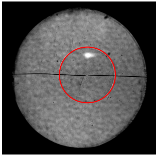

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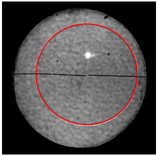

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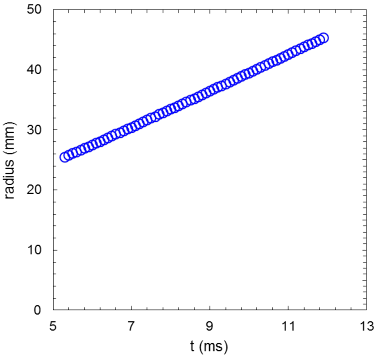

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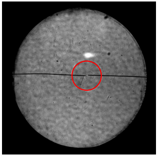

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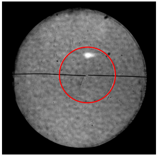

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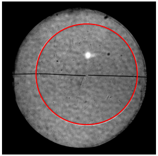

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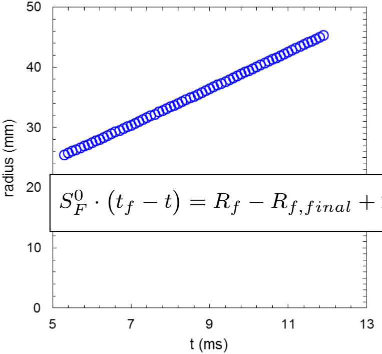

$$S_L = S_L^0 - L \cdot K$$

$$S_F^0 \cdot (t_f - t) = R_f - R_{f,final} + 2 \cdot L \cdot ln\left(\frac{R_f}{R_{f,final}}\right) + C$$

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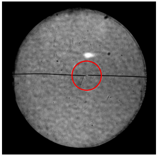

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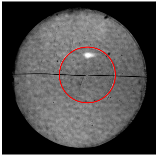

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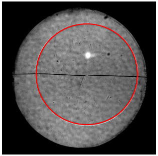

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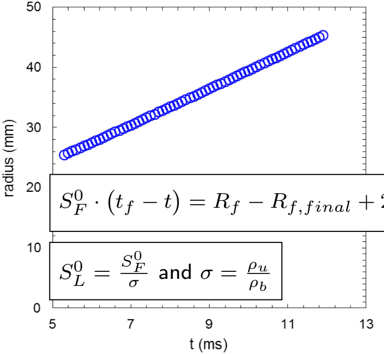

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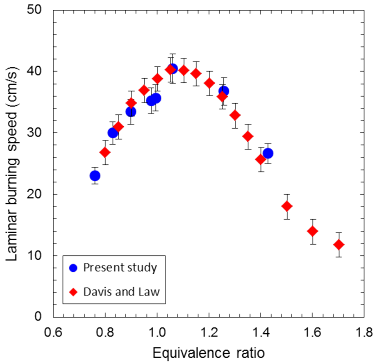
$$S_L^0 = \frac{S_F^0}{\sigma} \text{ and } \sigma = \frac{\rho_u}{\rho_b}$$

Validation of Burning Speed Measurements



$T_0 = 296$ K and $P_0 = 100$ kPa

- Two-tailed z-test ($\phi =$ 0.8-1.4)

  $H_0 : \mu_1 = \mu_2$ and $H_a : \mu_1 \neq \mu_2$
  $\mu_1 =$ present study mean
  $\mu_2 =$ Davis and Law mean

- Null hypothesis, H_0 cannot be rejected
- Difference between the two data sets is zero ($\alpha = 0.02$ confidence level)

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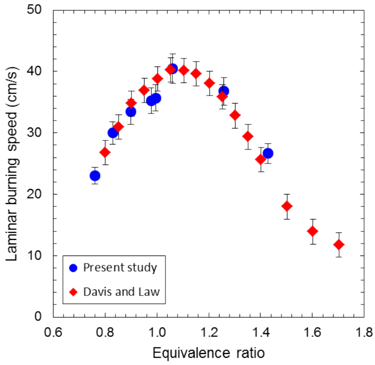

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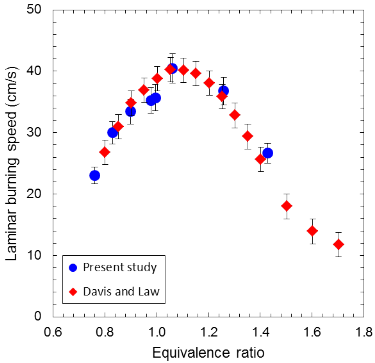


$T_0 = 296$ K and $P_0 = 100$ kPa

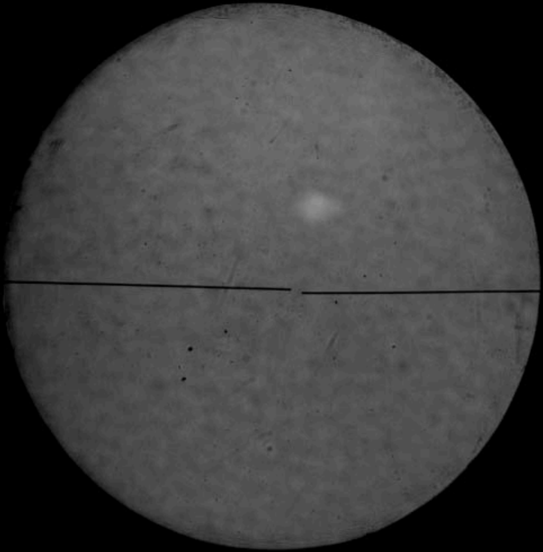
- Two-tailed z-test ($\phi = 0.8$-1.4)

  $H_0 : \mu_1 = \mu_2$ and $H_a : \mu_1 \neq \mu_2$
  $\mu_1 =$ present study mean
  $\mu_2 =$ Davis and Law mean

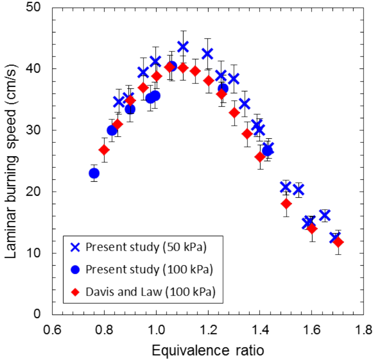
- Null hypothesis, H_0 cannot be rejected
- Difference between the two data sets is zero ($\alpha = 0.02$ confidence level)

Summary

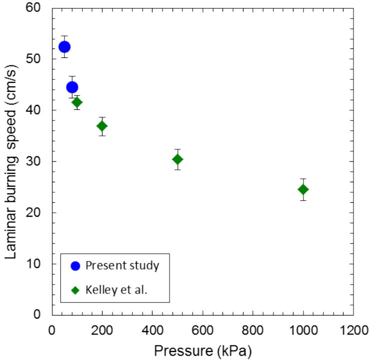
$T_0 = 380$ K, $P_0 = 50$ kPa, $\phi = 1.10$



Pressure Effect



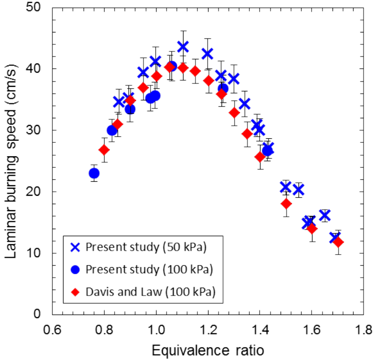
$T_0 = 296$ K



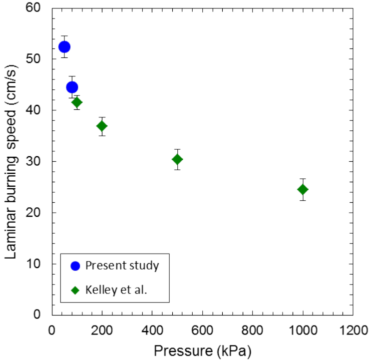
$T_0 = 353$ K and $\phi = 0.9$

- Uncertainty at 50 kPa $\approx 5\%$
- t-test ($\alpha = 0.2$ confidence level)
  - $\rightarrow$ statistically significant difference
- Decrease in burning speed with increase in pressure
  - $\rightarrow$ increase in the upstream gas density

Pressure Effect



$T_0 = 296$ K



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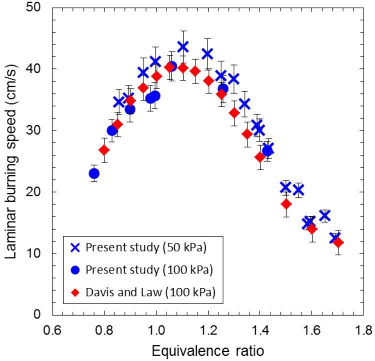
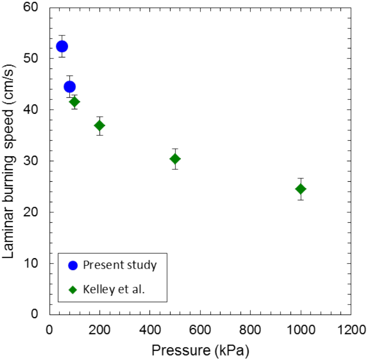
Pressure Effect



$T_0 = 296$ K



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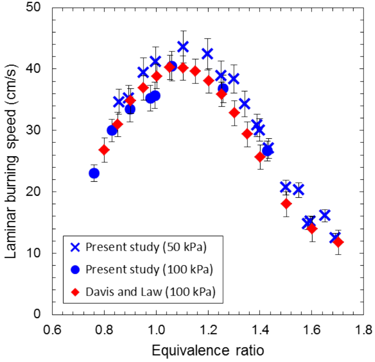

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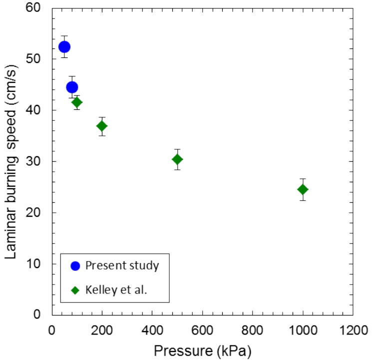

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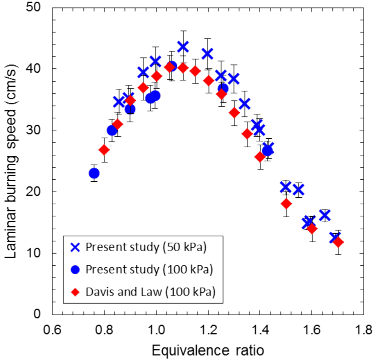

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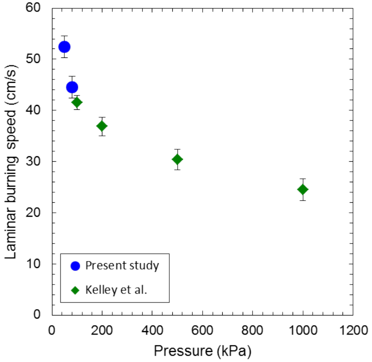

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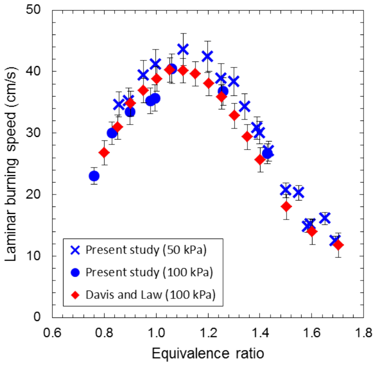

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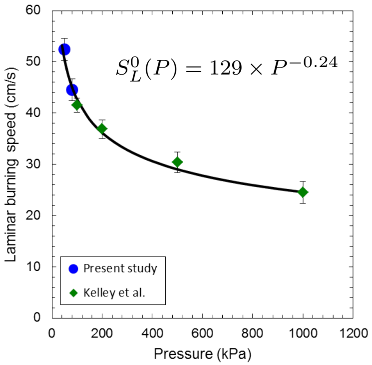

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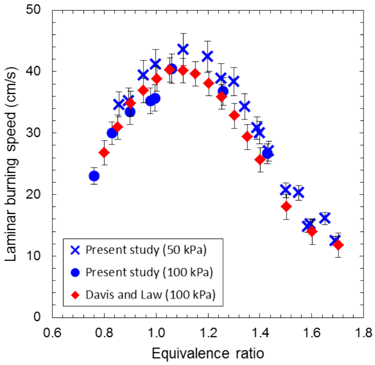

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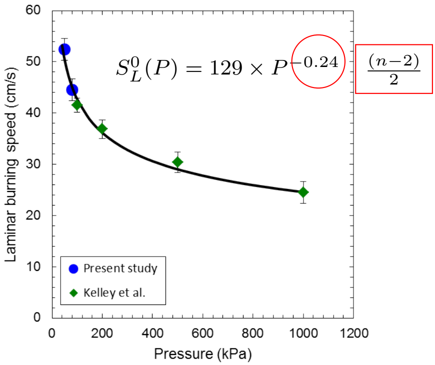

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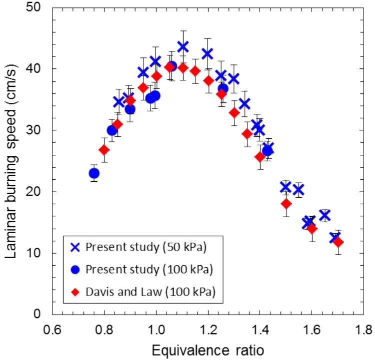

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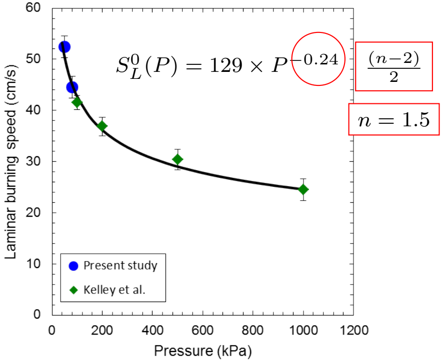

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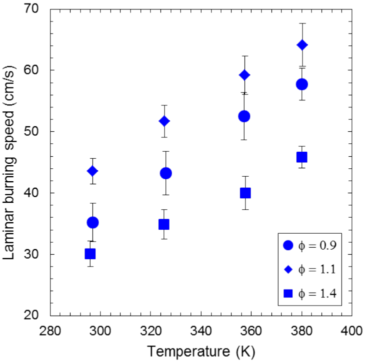
Temperature Effect



$P_0 = 50$ kPa

- From $T_0 = 296$–380 K
  - → 64% increase at $\phi = 0.9$
  - → 47% increase at $\phi = 1.1$
  - → 53% increase at $\phi = 1.4$
- Rate of burning speed increase with temperature for fixed ϕ
  - → 0.27 cm/s/K for $\phi = 0.9$
  - → 0.25 cm/s/K for $\phi = 1.1$
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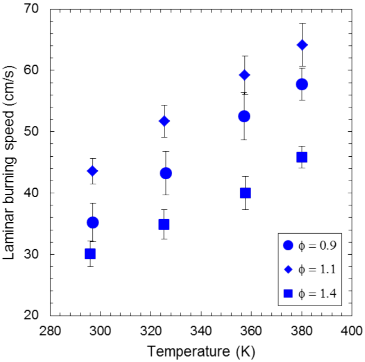

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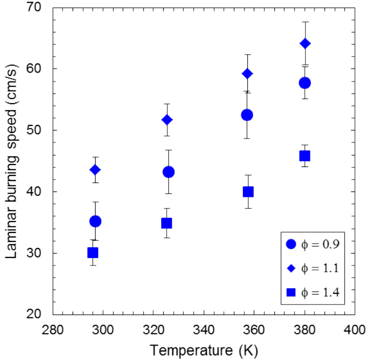

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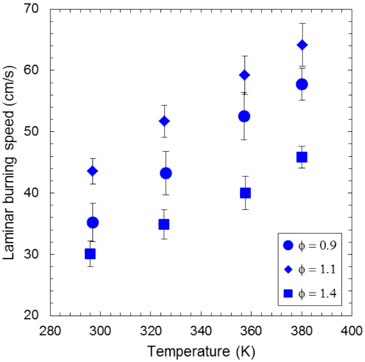

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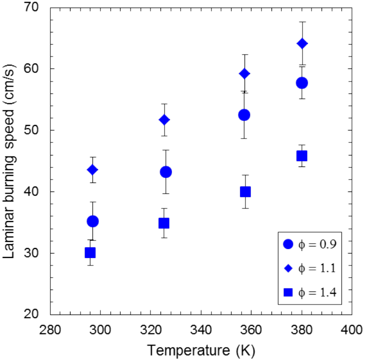

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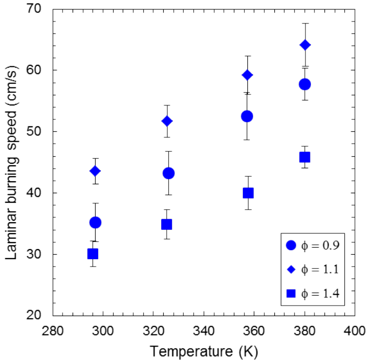

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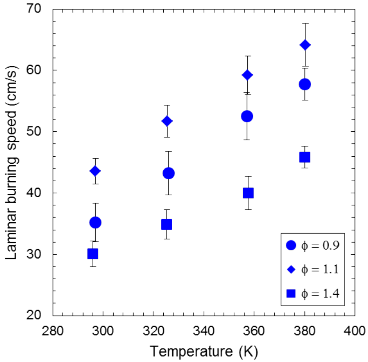

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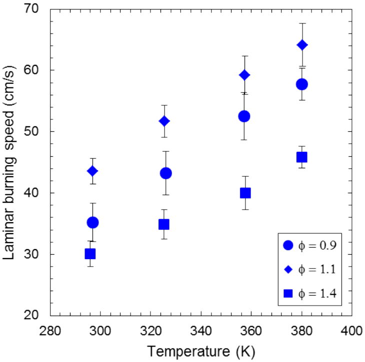

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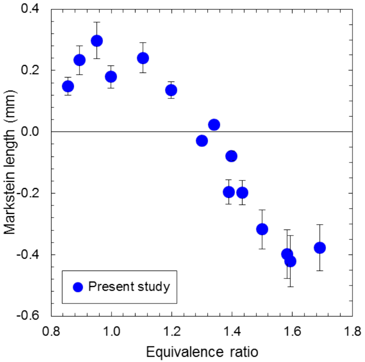
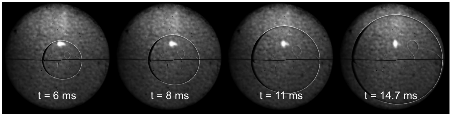
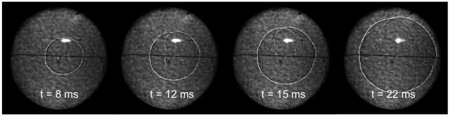
Markstein Length



$T_0 = 296$ K and $P_0 = 50$ kPa



$\phi = 0.91$



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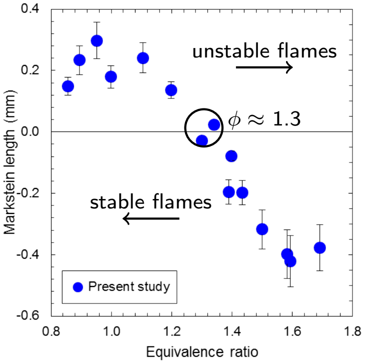
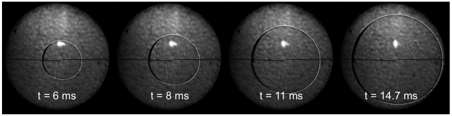
Markstein Length



$T_0 = 296$ K and $P_0 = 50$ kPa



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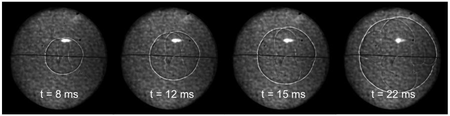
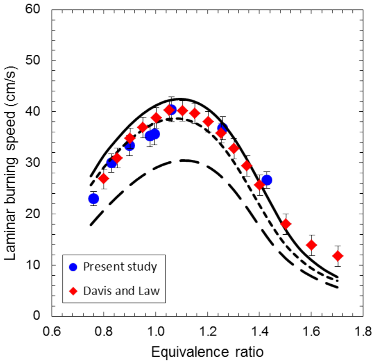


$\phi = 1.65$

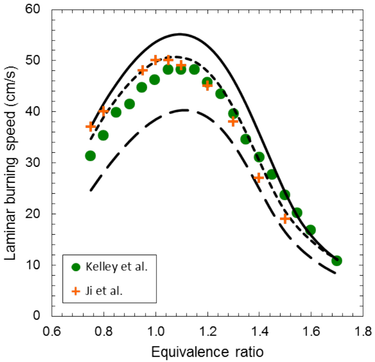
Reaction Models

- JetSURF model
  - → 2163 reactions
  - → 348 species
- Ramirez et al. model
  - → 1789 reactions
  - → 401 species
- Blanquart (CIT) model
  - → 1119 reactions
  - → 155 species
- Regath software
  - → FORTRAN 90 package
  - → thermodynamics and chemical routines
- Results
  - → 1D freely propagating flame
  - → mixture averaged transport
  - → no thermal diffusion

Equivalence Ratio Effect



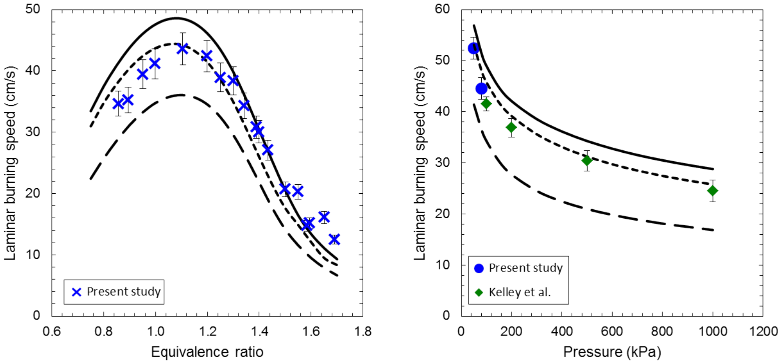
$T_0 = 296$ K and $P_0 = 100$ kPa



$T_0 = 353$ K and $P_0 = 100$ kPa

JetSurf : - - - - ; Ramirez et al. : — — ; Blanquart : ———

Pressure Effect



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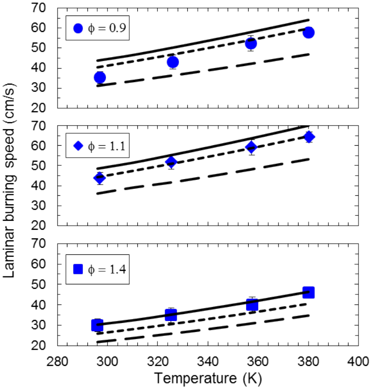
$T_0 = 353$ K and $\phi = 0.9$

JetSurf : - - - - ; Ramirez et al. : — — ; Blanquart : ———

Temperature Effect



$P_0 = 50$ kPa

JetSurf : - - - - ; Ramirez et al. : — — ; Blanquart : ——

Summary

Experimental Conclusions

- Increase in the laminar burning speed from $P_0 = 100$ kPa to 50 kPa $\rightarrow$ $\alpha = 0.2$ confidence level
- Highest rate of burning speed increase with temperature $\rightarrow$ lean mixtures
- Lowest rate of burning speed increase with temperature $\rightarrow$ rich mixtures
- Pressure dependency agreement with thermal flame theory of Mallard and Le Chatelier $\rightarrow$ $n = 1.5$
- Transition from positive to negative Markstein lengths consistent with Kelley et al. data

Comparison of JetSURF, Ramirez et al., and Blanquart Models

- At $T_0 = 296$ K, the JetSURF model prediction is $<$12% at approximately $\phi \leq 1.30$
- At $T_0 = 353$ K, the JetSURF model prediction is $<$10% at approximately $\phi \leq 1.45$
- At $T_0 = 296$ K, the Blanquart model prediction is $<$12% at $\phi \approx$ 1.30-1.60
- At $T_0 = 353$ K, the Blanquart model prediction is $<$10% at $\phi \approx$ 1.45-1.70
- The Ramirez et al. model systematically underestimates the laminar burning speed

Acknowledgements

The present work was carried out in the Explosion Dynamics Laboratory of the California Institute of Technology and was supported by The Boeing Company through a Strategic Research and Development Relationship Agreement CT-BA-GTA-1.

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