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Effect of Hydrogen Addition on Burning Rate and Surface Density of Turbulent Lean Premixed Methane-Air Flames

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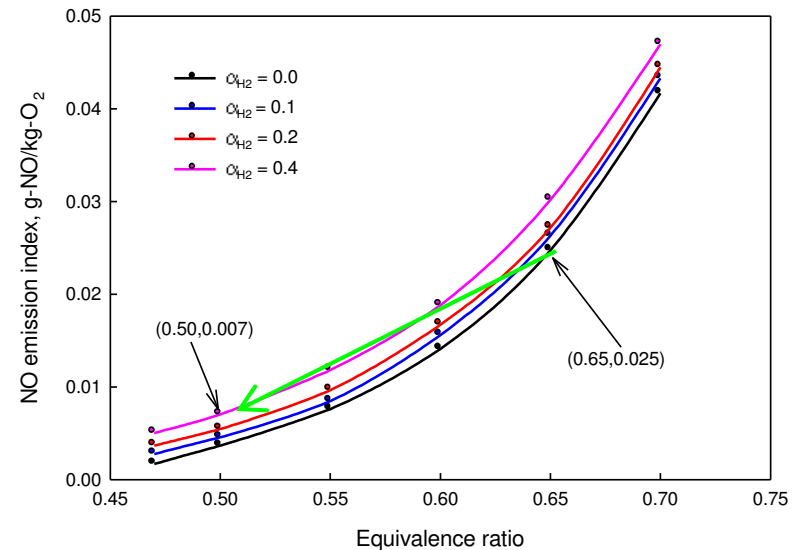
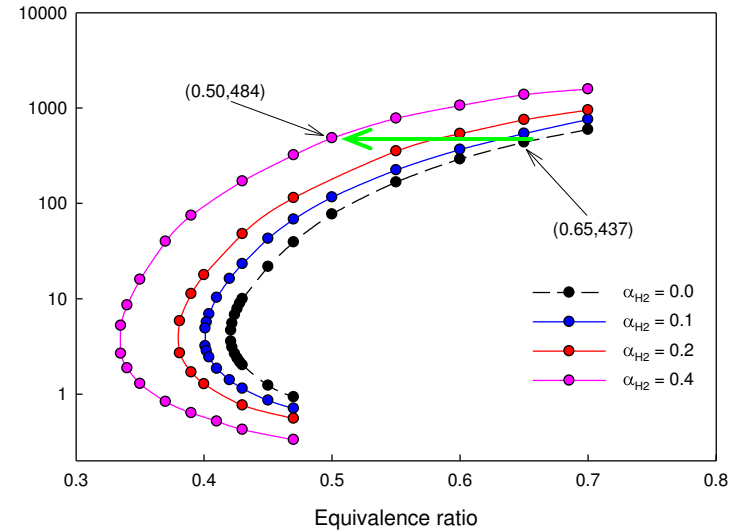
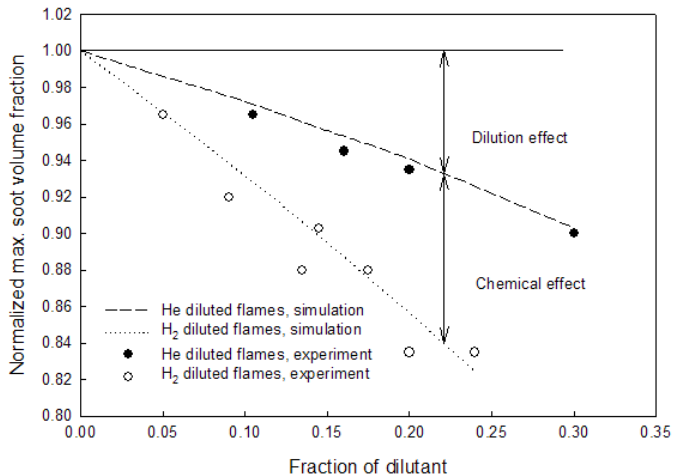
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Background (1)

- H₂ is a clean burning component, but relatively expensive
- Mixing a small amount of H₂ with other fuels is an effective way to use H₂
- H₂ enriched combustion significantly improves fuel efficiency and reduces pollutant (NO_x, PM) emissions



Background (2)

- How does H₂ addition affect flame speed?
 - H₂ enrichment increases laminar flame speed
 - Contradictory results exist for turbulent flame speed
 - Traditional theory predicts a decrease in the ratio of turbulent to laminar flame speeds with the addition of H₂
 - supported by Liu and Lenze (1988) and Mandilas et al. (2007)
 - but inconsistent with the results of Goix and Shepherd (1993), Hawkes et al. (2004) and Cohé et al. (2007)
 - Does H₂ addition affect flame surface characteristics?
 - Further study is needed

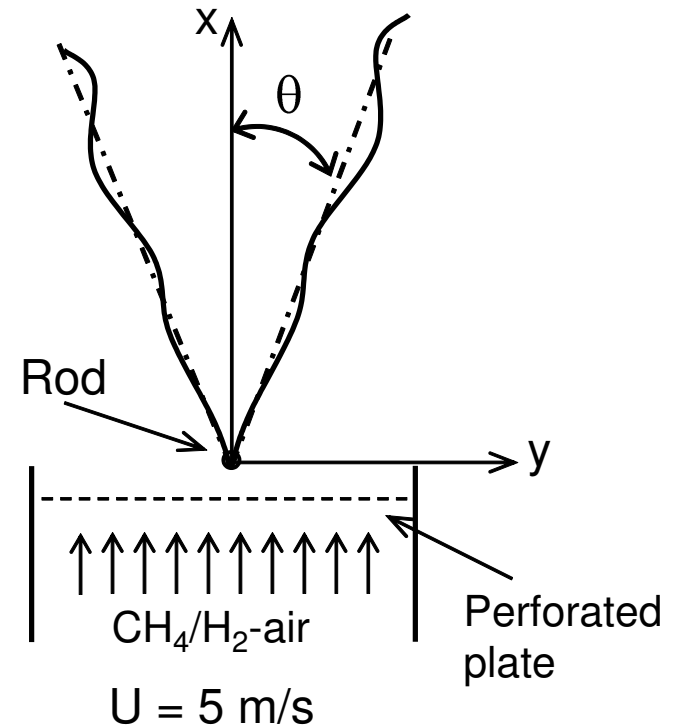
$$\frac{S_T}{S_L} = 1 + A \left(\frac{v'}{S_L} \right)^n$$

Objective

- Investigate the effect of H₂ addition on flame surface density and burning velocity of lean premixed CH₄/air flames

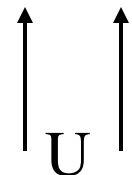
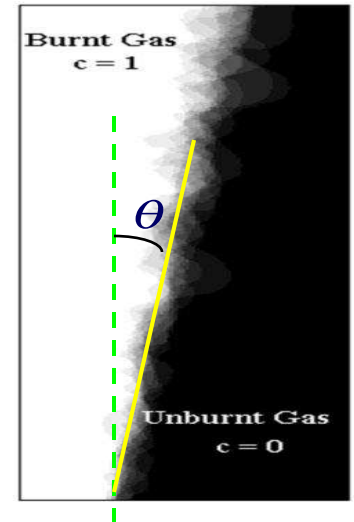
Flame Configuration

- V-shaped CH₄/air premixed flames
- Turbulence
 - Set 1: turbulent intensity = 4%, integral length scale = 4.8 mm, Re = 60
 - Set 2: turbulent intensity = 8%, integral length scale = 7.3 mm, Re = 180
- $\phi = 0.55, 0.6$
- $V'/S_L = 1 \sim 2$
- H₂ fraction: $V_{H_2}/(V_{H_2}+V_{CH_4}) = 0 \sim 0.3$

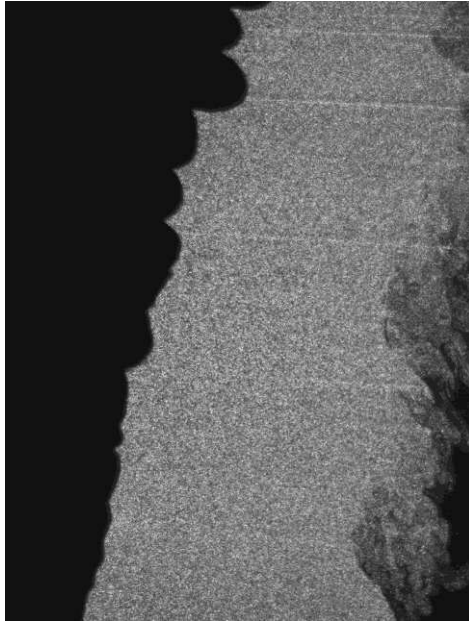


Experimental Methodology

- Laser tomography technique was employed
 - Unburned mixture was seeded by incense particles and illuminated by laser sheet
 - Tomography of flame front was recorded by a CCD camera
 - 300 images were taken for each flame
 - Images were analyzed and binarized by a Matlab based software
 - Mean progress variable, changing from 0 (unburnt side) to 1 (burnt side), was obtained by averaging the 300 images
- Flame brush thickness: the horizontal distance from 0 to 1
- Burning velocity: $S_T = U * \sin\theta$
- Flame surface density: $F_{SD} = \frac{1}{n} \sum \frac{dL}{ds}$



Typical Images



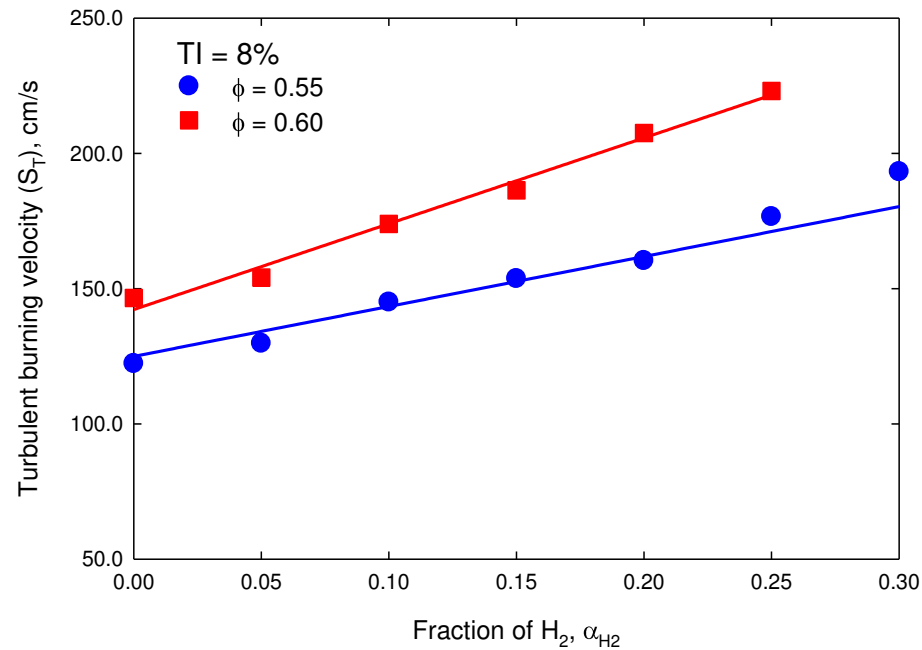
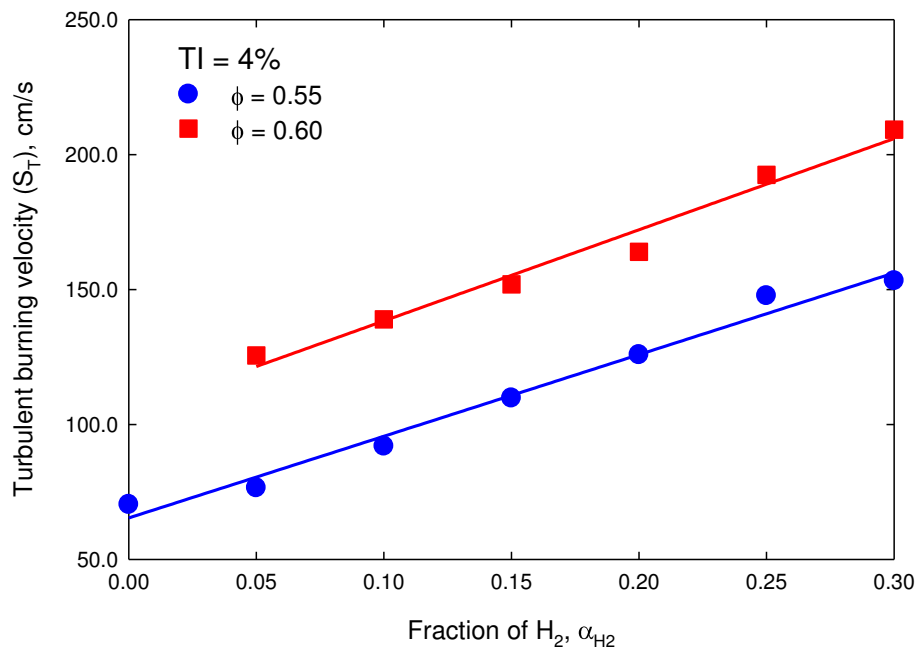
$\alpha_{H_2}: 0\%$



$\alpha_{H_2}: 0.3$

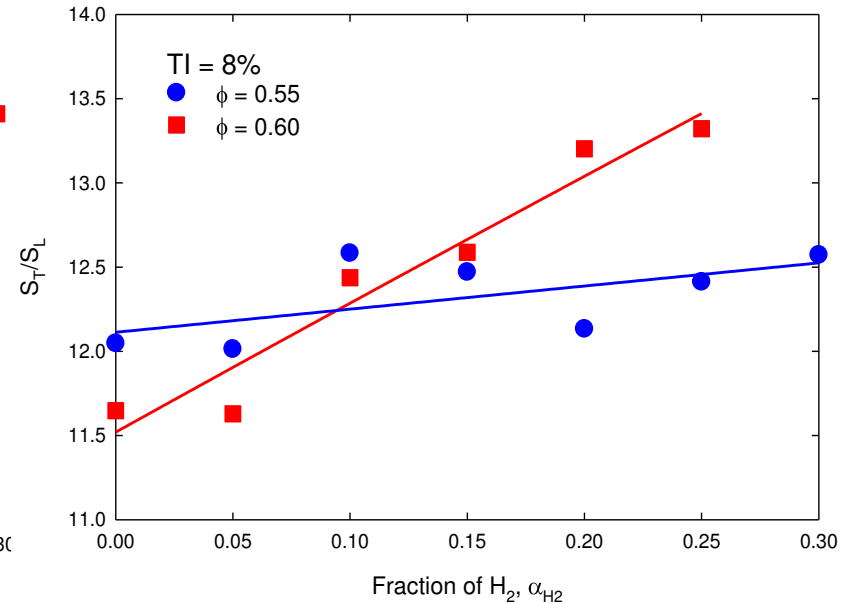
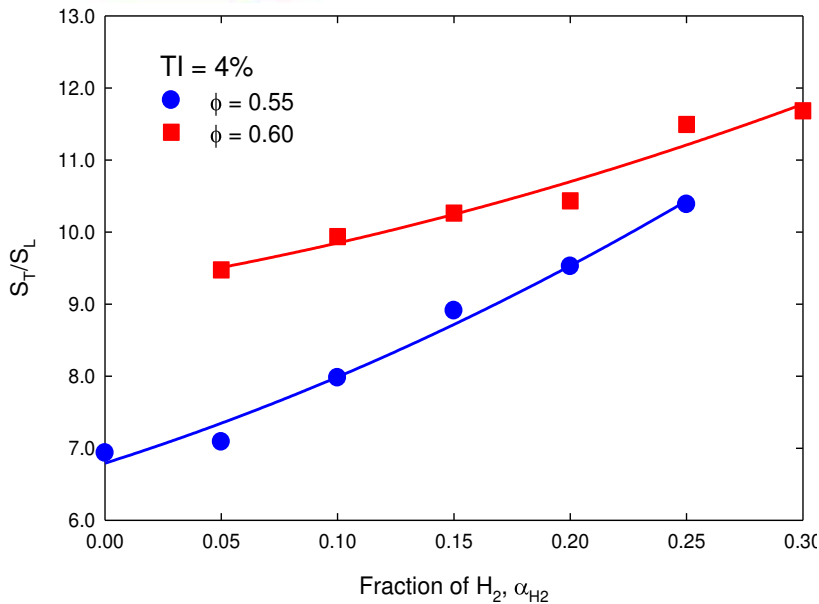
- H₂ addition increases the wrinkle extent of flame surface at a constant equivalence ratio and turbulence level

Burning Velocity



- H₂ addition leads to increase in burning velocity

Ratio of Turbulent to Laminar Burning Velocities

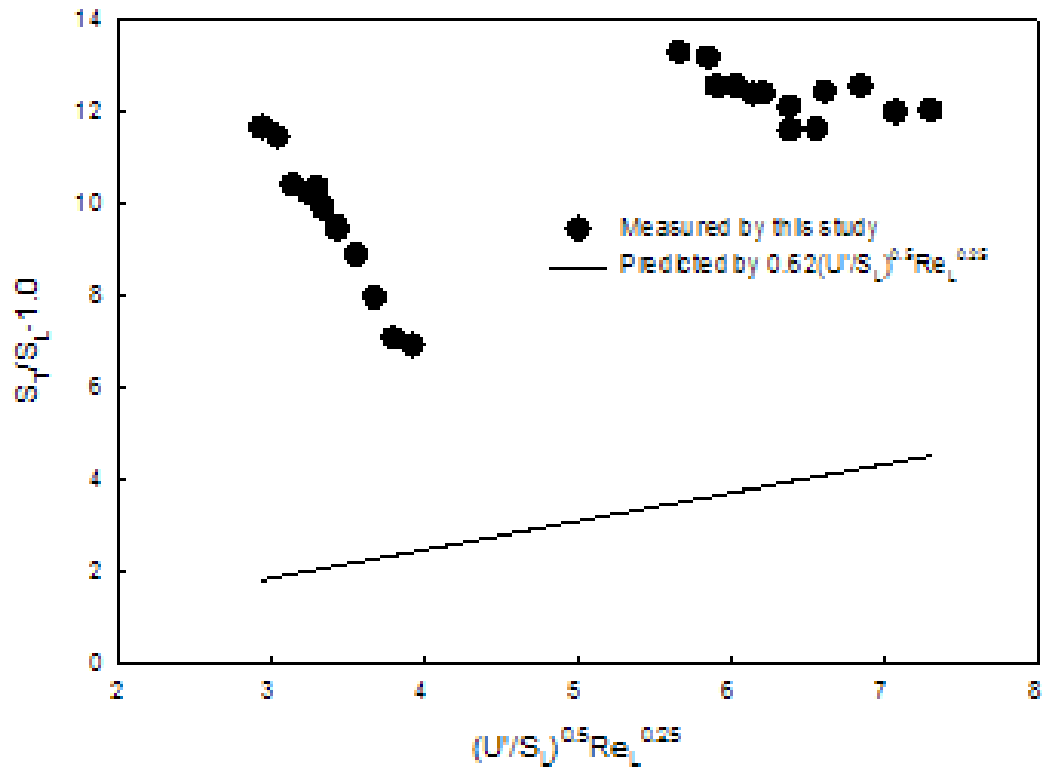


- H₂ addition results in increase in the ratio too, implying that turbulent burning velocity increases faster than laminar burning velocity when H₂ is added

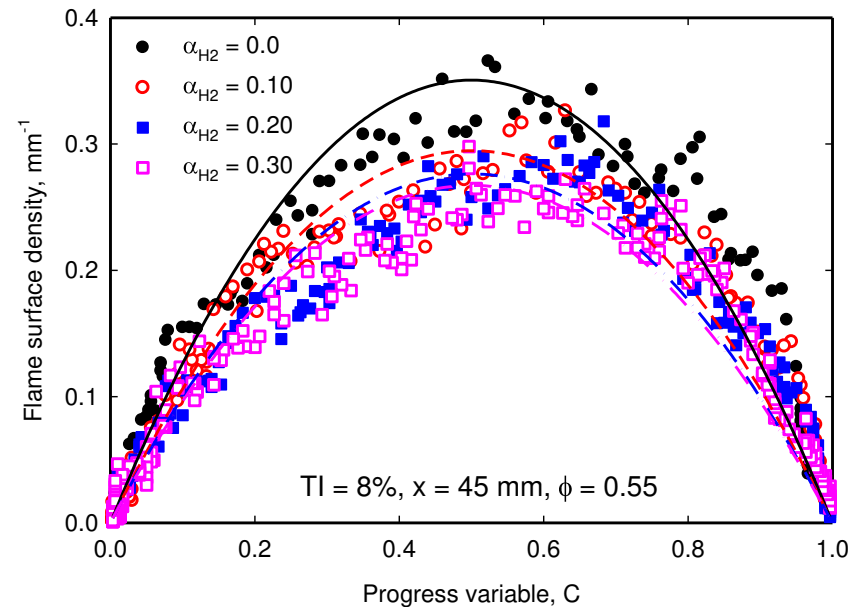
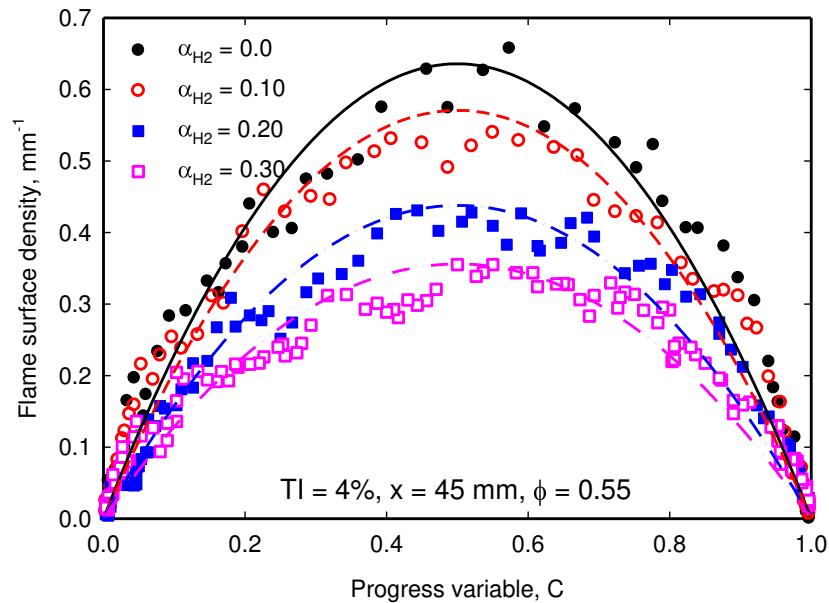
- Inconsistent with traditional theory?

- **Why?**

$$\longrightarrow \frac{S_T}{S_L} = 1 + A \left(\frac{v'}{S_L} \right)^n$$

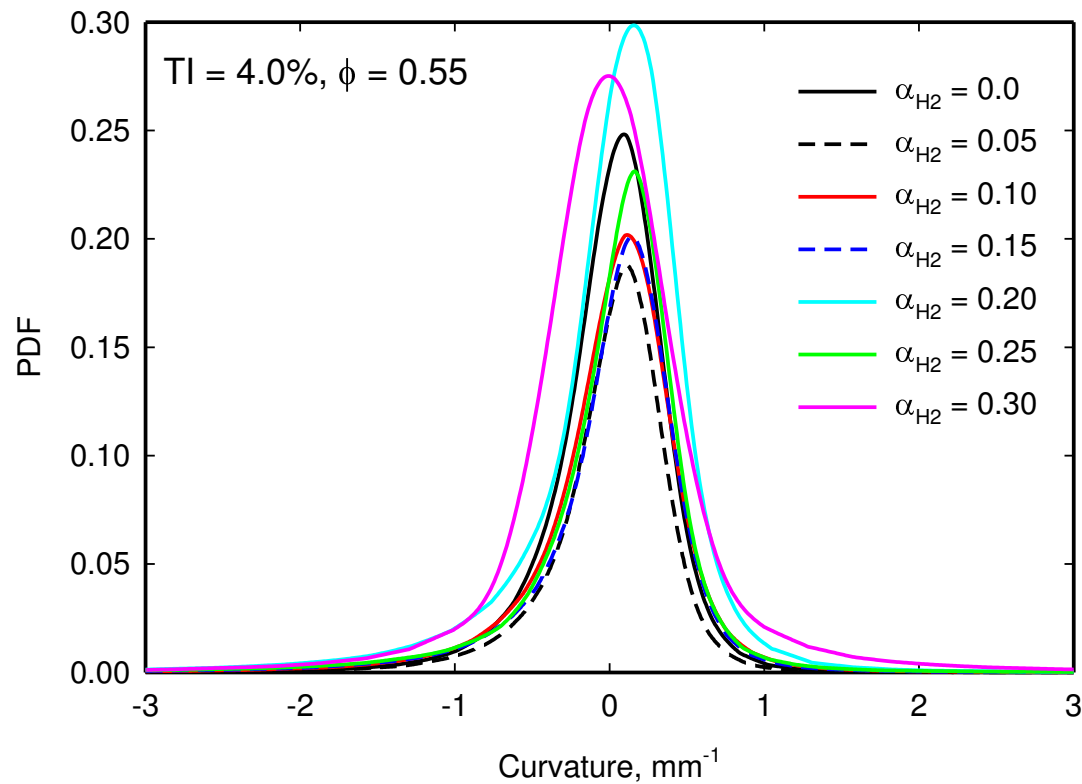


Flame Surface Density



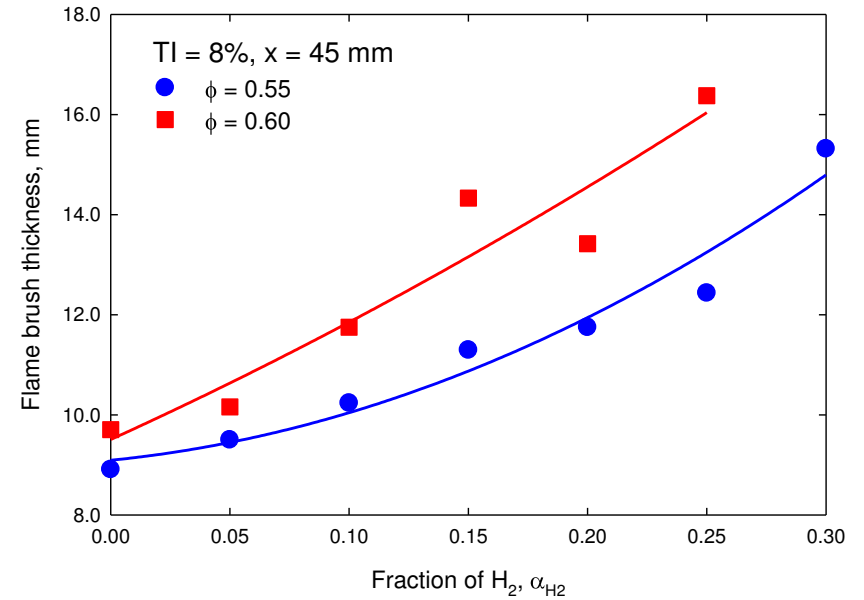
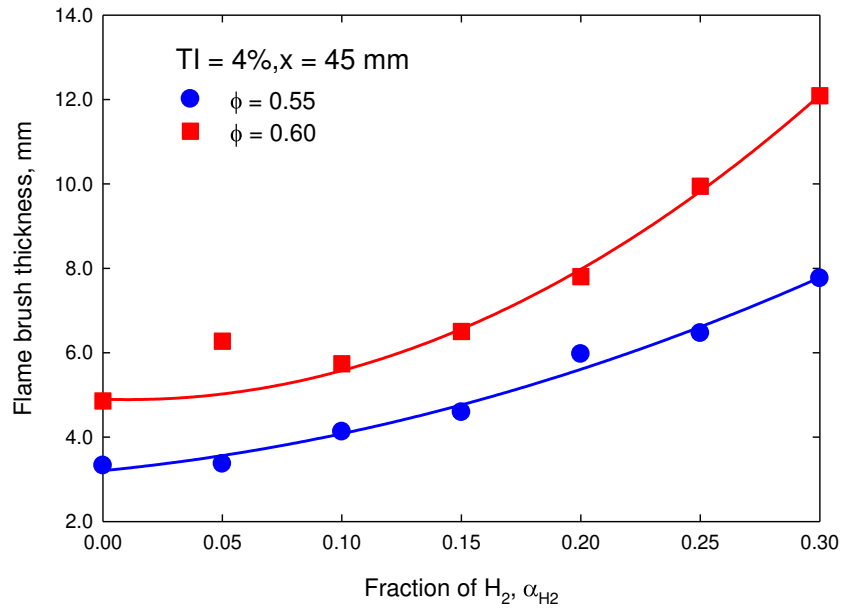
- Flame surface density slightly decreases with the addition of H_2

Curvature



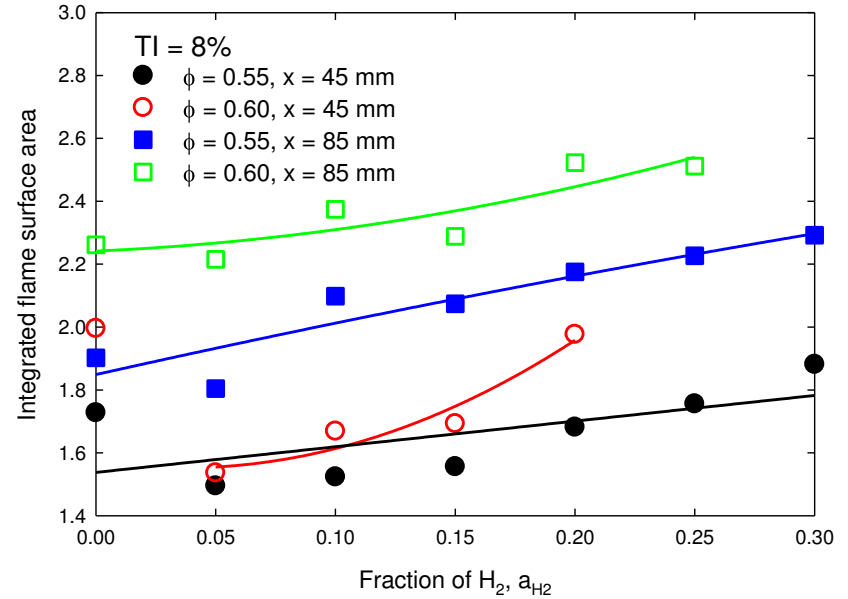
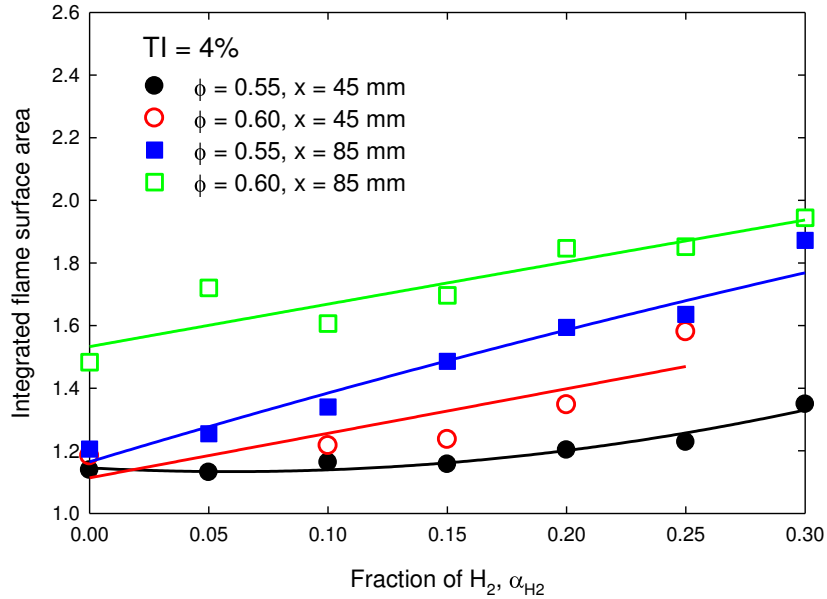
- No clear trend can be observed for the variation of curvature with the addition of H_2

Flame Brush Thickness

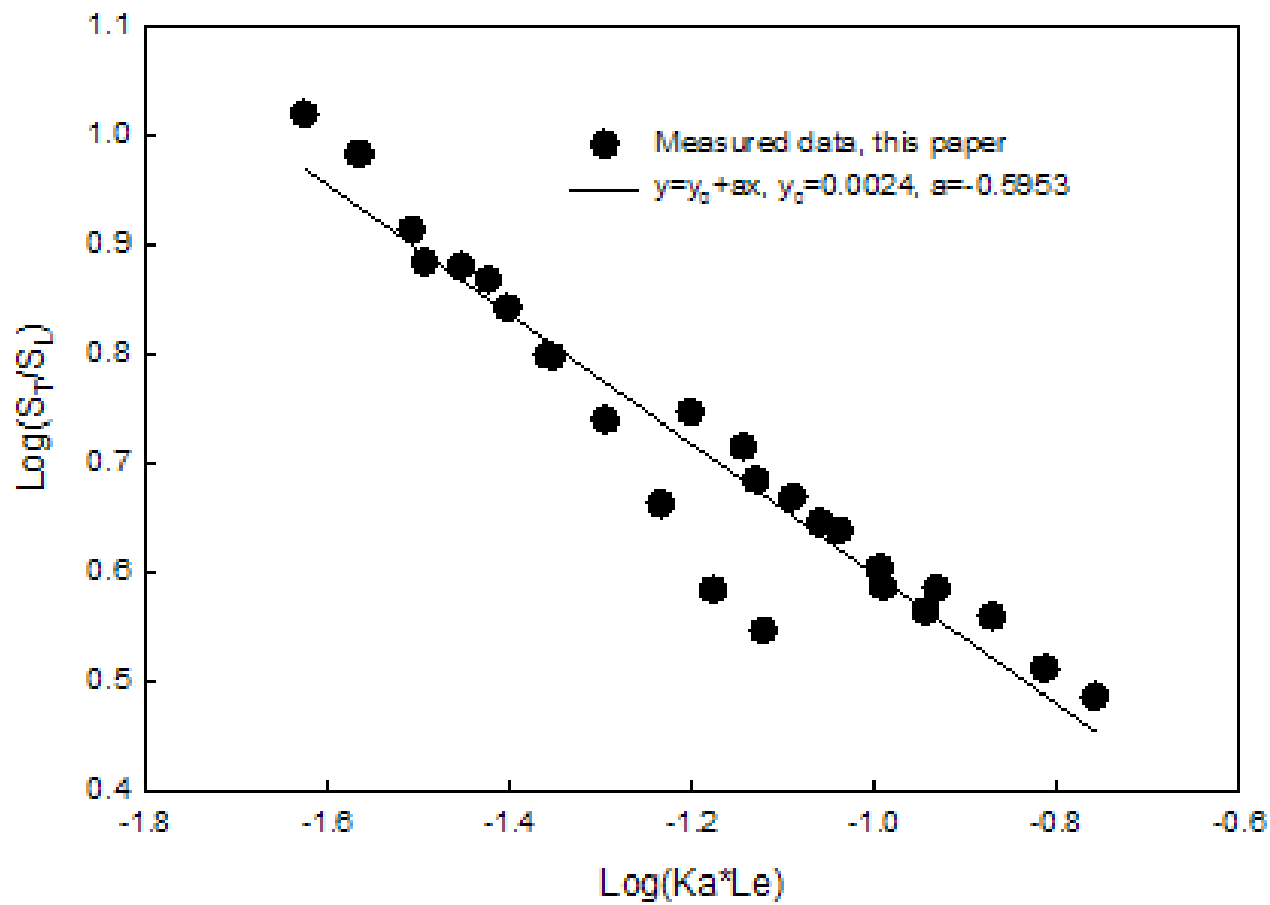


- H_2 addition leads to increase in flame brush thickness

Integrated Flame Surface Area



- H₂ addition causes increase in integrated flame surface area, which may increase burning velocity ($S_T \propto F * S_L$)



Conclusions

- Addition of H_2 leads to increase in turbulent burning velocity for CH_4 /air premixed flames
- The increase of turbulent burning velocity is faster than that of laminar burning velocity, which contradicts traditional theory
- H_2 addition causes increase in turbulent burning velocity due to not only the physical and chemical property effect (laminar burning velocity), but also the variation in flame structure
 - H_2 addition increases flame brush thickness

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