Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Laminar Burning Speed of *n*-Hexane–Air Mixtures

S. Coronel¹ R. Mével¹ P. Vervish¹ P. A. Boettcher¹ V. Thomas¹ N. Chaumeix² N. Darabiha³ J. E. Shepherd¹

¹Graduate Aeronatical Laboratories, California Institute of Technology,

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

³Laboratoire EM2C-CNRS UPR 288, École Centrale Paris

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University of Utah May 19 - 22, 2013



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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Summary				

- 1. Motivation • Accidental Ignition
- 2. Previous Work
- 3. Materials and Methods
- 4. Results
- 5. Conclusions



Previous Work	Materials and Methods	Results	Conclusions
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Accidental ignition

- $\rightarrow\,$ electrostatic ignition of fuel
- \rightarrow lightning strike
- → electrical faults in pumps, fuel quantity instrumentation
- ightarrow 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)
 - ightarrow laminar burning speed



TWA 800, NY 747-100, July 17, 1996



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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Summary				

1. Motivation

2. Previous Work

- Laminar Burning Speed
- 3. Materials and Methods

4. Results

5. Conclusions

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Laminar	Burning Speed			

Davis and Law :

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

• Farrell et al. :

$$\rightarrow$$
 T₀ = 450 K and P₀ = 304 kPa

• Kelley et al. :

$$\rightarrow$$
 T₀ = 353 K and P₀ = 100-1000 kPa

Ji et al. :

$$\rightarrow$$
 T₀ = 353 K and P₀ = 100 kPa



• Kelley et al. :

 \rightarrow T₀ = 353 K and P₀ = 100-1000 kPa

Ji et al. :

$$\rightarrow$$
 T₀ = 353 K and P₀ = 100 kPa



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P = 1 atm P = 1 atm



$$P = 1$$
 atm

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P = 1 atm

n-hexane-air $P_0 \leq 100 \text{ kPa}$ $T_0 = 296$ -380 K

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Summary				

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1. Motivation

2. Previous Work

3. Materials and Methods

- Experimental Setup
- Burning Speed Measurements

4. Results

5. Conclusions

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Exporim	ontal Satur · (Compustion Voscal		

Experimental Setup . Compustion vesser





Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Experiment	al Setup : Cor	mbustion Vessel		

11.7 cm diameter windows





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11.7 cm diameter windows





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pressure manometer







pressure manometer























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- Observe changes in the density gradient of the fluid due to variations in the refractive index





- Observe changes in the density gradient of the fluid due to variations in the refractive index
- Visualize flame :





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 - \rightarrow very hot flame propagating into cold unburned reactants





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- Visualize flame :
 - \rightarrow very hot flame propagating into cold unburned reactants
- High speed camera :
 - ightarrow 10,000 frames per second





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



Motivation	Previous Work	Materials and Methods	Results	Conclusions
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 $t=5.0\;ms$



t = 9.7 ms



t = 17.1 ms

- Edge detection using the Canny method (MATLAB)
- Fit ellipse to detected edge
 - ightarrow use area of ellipse to find an equivalent radius

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Linear extrapolation to unstretched flame speed

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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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, H₀ cannot be rejected
- Difference between the two data sets is zero ($\alpha = 0.02$ confidence level)

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 $\begin{aligned} H_0: \mu_1 &= \mu_2 \text{ and } H_a: \mu_1 \neq \mu_2 \\ \mu_1 &= \text{present study mean} \\ \mu_2 &= \text{Davis and Law mean} \end{aligned}$

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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Summary				

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- 1. Motivation
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 - Experimental Results
 - Modeling Results
- 5. Conclusions

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



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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Droccuro	Effoct			
FIESSULE	LIECL			



 $T_0 = 296 \text{ K}$

- Uncertainty at 50 kPa \approx 5%

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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Droccuro	Effoct			
FIESSULE	LIECL			



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

Motivation	Previous Work	Materials and Methods	Results	Conclusions
0	0	0000	0000000	000
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FIESSULE	LIECL			



- Uncertainty at 50 kPa pprox 5%
- t-test ($\alpha = 0.2$ confidence level) \rightarrow statistically significant difference
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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Pressure	Effect			



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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Tempera	ture Effect			



• From $T_0 = 296-380$ K

- $ightarrow\,$ 64% increase at $\phi=$ 0.9
- ightarrow 47% increase at $\phi=1.1$
- \rightarrow 53% increase at $\phi = 1.4$
- Rate of burning speed increase with temperature for fixed ϕ
 - ightarrow 0.27 cm/s/K for $\phi=$ 0.9
 - ightarrow 0.25 cm/s/K for $\phi = 1.1$
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Markstein I	_ength			



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



$$\phi = 0.91$$



 $\phi = 1.65$

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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Markstei	n Length			



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 $\phi = 1.65$

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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Reaction M	lodels			

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

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Equivalence Ratio Effect



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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Pressure	Effect			



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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Tempera	ture Effect			



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

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Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Summary				

- 1. Motivation
- 2. Previous Work
- 3. Materials and Methods
- 4. Results
- 5. Conclusions
 - Experiments
 - Reaction Models

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Experime	ntal Conclusio	ons		

- Increase in the laminar burning speed from P_0 = 100 kPa to 50 kPa \rightarrow α = 0.2 confidence level
- Highest rate of burning speed increase with temperature \rightarrow lean mixtures
- Lowest rate of burning speed increase with temperature ightarrow rich mixtures
- Pressure dependency agreement with thermal flame theory of Mallard and Le Chatelier $\rightarrow n=1.5$

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• Transition from positive to negative Markstein lengths consistent with Kelley et al. data

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Comparison	of JetSURF,	Ramirez et al.,	and Blanquart	I
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 $\phi pprox$ 1.30-1.60
- At $T_0=$ 353 K, the Blanquart model prediction is <10% at $\phi pprox$ 1.45-1.70

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 The Ramirez et al. model systematically underestimates the laminar burning speed

Motivation	Previous Work	Materials and Methods	Results	Conclusions
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Acknowle	edgements			

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Thank You

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