Ignition of *n*-Hexane–Air by Moving Hot Particles: Effect of Particle Diameter

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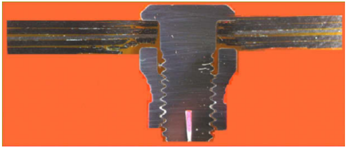
Hot Particle Ignition Sources

- Lightning attaches to the top of the fastener and causes damage to the resin and fibers on the backface of the composite laminate
- The breakup of the composite is due to its poor electrical conductivity that leads to resistive heating



P. Feraboli, M. Miller. Composites Part A: Applied Science and Manufacturing, Volume 40, Issues 6-7, July 2009, Pages 954-967

Ignition at edge of carbon fiber composite structure, Boeing

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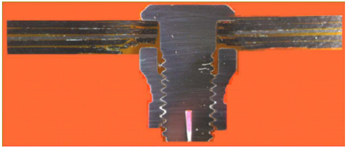

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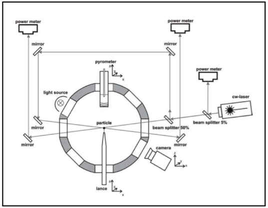
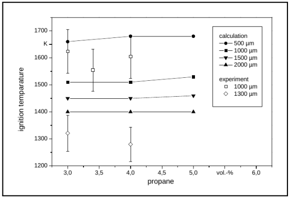
Stationary Hot Particle Ignition

- H. Bothe et al. In Explosion Safety in Hazardous Areas, 1999. International Conference on (Conf. Publ. No. 469), pages 44–49, 1999
- T. H. Dubaniewicz et al. (2000, 2003)
- T. H. Dubaniewicz. Journal of Laser Applications, 18 (2006) 312–319



- M. Beyer and D. Markus. Sci. Tech. Energetic Materials, (2012)
- D. Roth et al. Combustion Science and Technology, 186 (2014) 1606–1617



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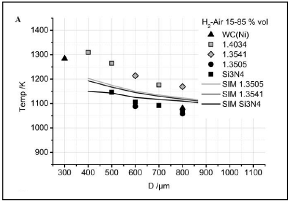
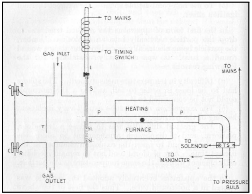
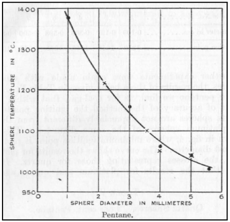


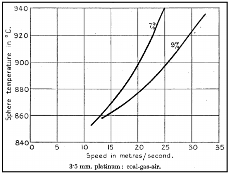
Roth et al. (2014)

Moving Hot Particle Ignition





R. Silver (1937)



S. Patterson (1940)

- R. S. Silver. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 23 (1937) 633-657
- S. Patterson. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 28 (1939) 1-22
- S. Patterson. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 30 (1940) 437-457

Current study

Material	d (mm)	V_p (m/s)	T_{sphere} (K)
alumina	$6.0, 3.5, 1.8$	$2.3 - 2.4$	$800 - 1200$

Mixture	T_0 (K)	P_0 (kPa)	Φ
n-hexane–air	300	100	$0.7 - 2.2$

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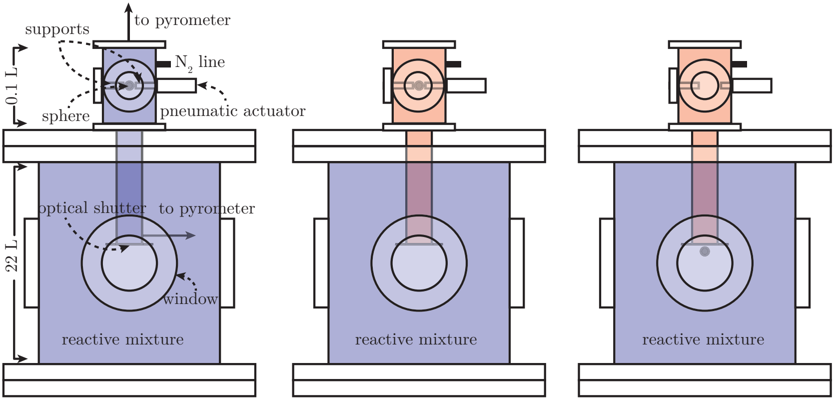
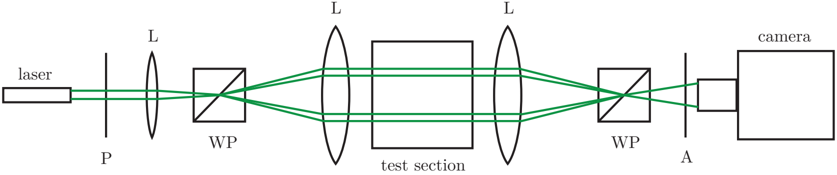
$$\Phi = 0.9$$

Experimental Setup: Combustion Vessel



Optical Diagnostics: Shearing Interferometer



P: polarizer, L: lens, WP: Wollaston prism, A: Analyzer

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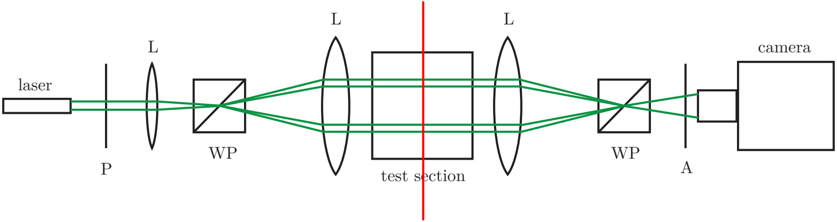

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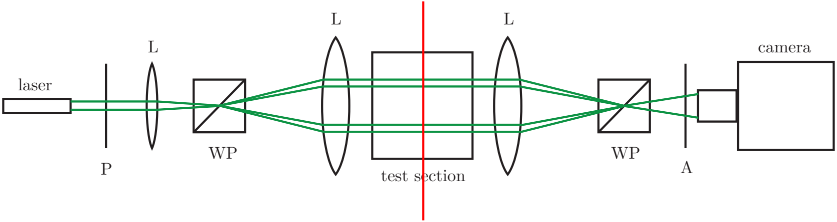

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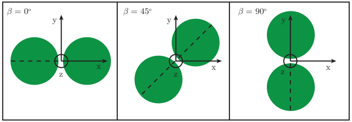

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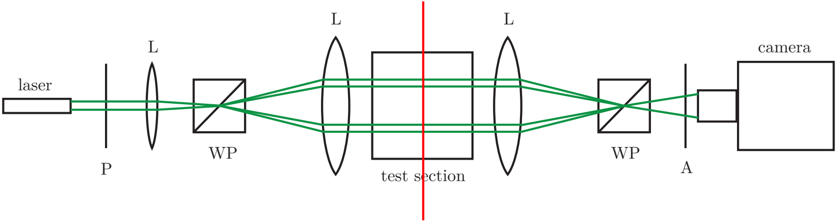

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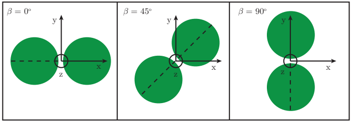
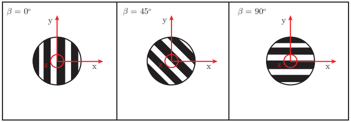




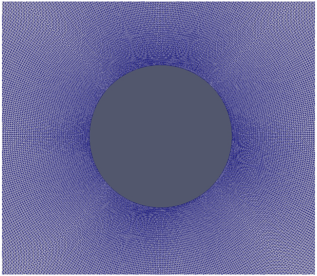
Finite fringe configurations

Simulation Setup

- Grid
  - → 2D axisymmetric
  - → Square of size $20d$
  - → $300,000$ cells
  - → Sphere vicinity ($40\ \mu$m cell size)
- Boundary conditions
  - → T_{sphere} = constant
  - → $T_{wall} = 300$ K
  - → Inert surface
  - → Neumann boundary condition for species
- Initial conditions
  - → $P_0 = 100$ kPa, $T_0 = 300$ K and $\Phi = 0.9$
  - → Flow N_2 at $t = 0 - 250$ ms and $\mathbf{u} = (0, gt, 0)$
  - → One-step n-hexane[1]–air ($R \rightarrow P$) at $t > 250$ ms

Outlet

↑



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Inlet

- OpenFOAM: Variable-density reactive Navier-Stokes equations

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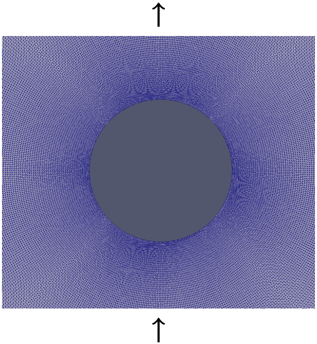

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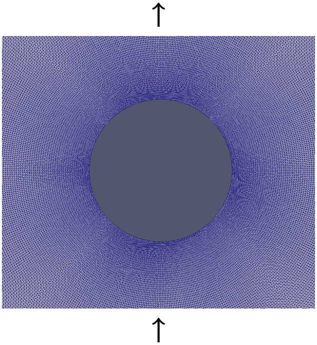

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[1] H. P. Ramirez et al. (2011). Proceedings of the Combustion Institute, 33

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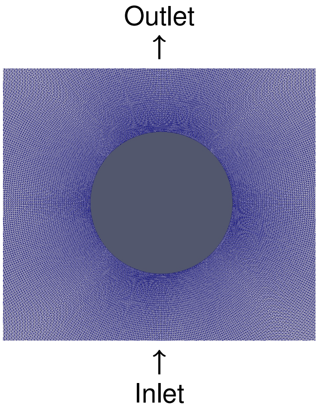

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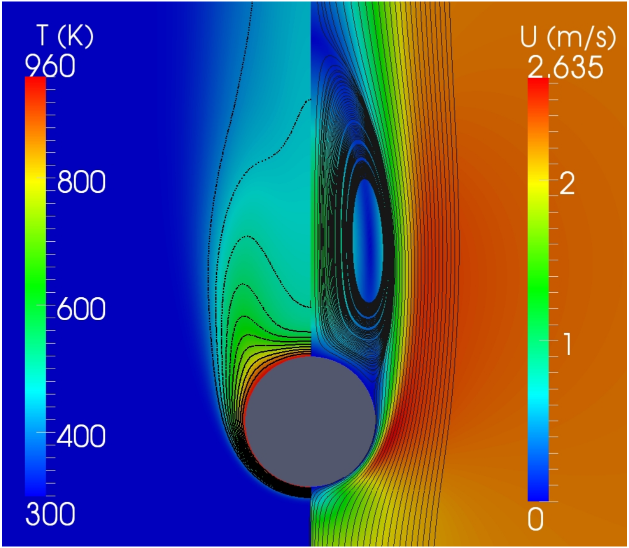
N_2 Hot Particle Wake (Simulation)



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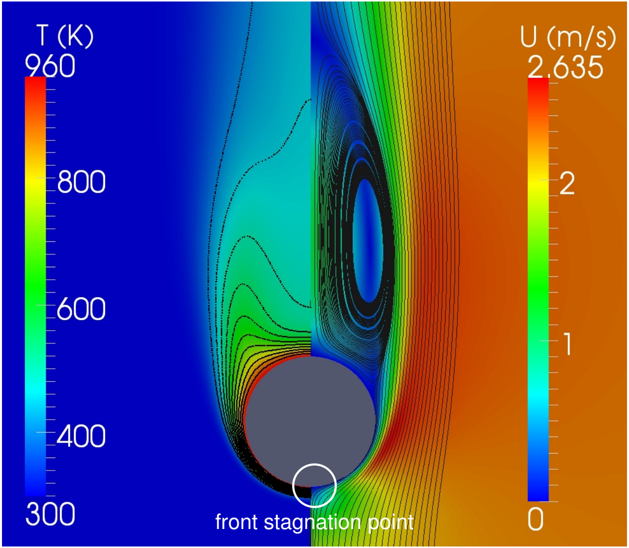

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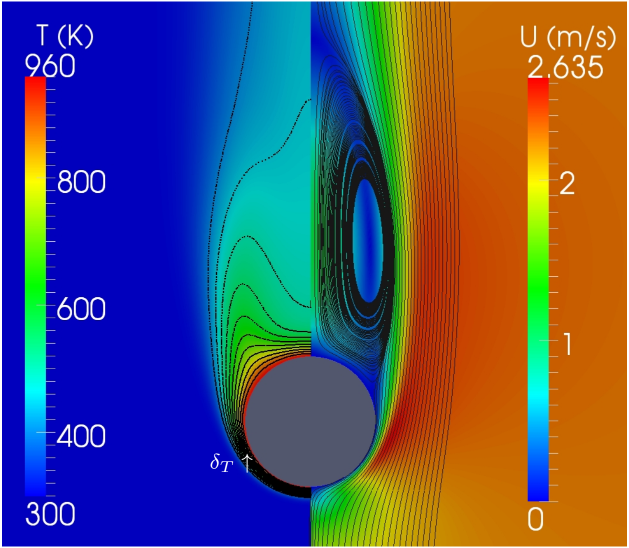

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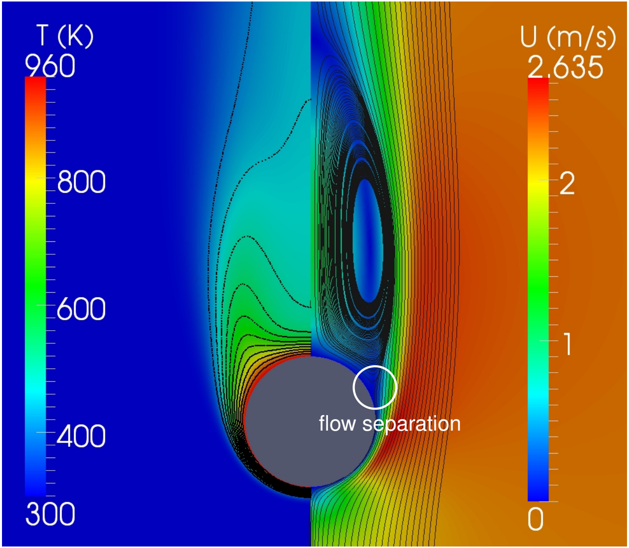

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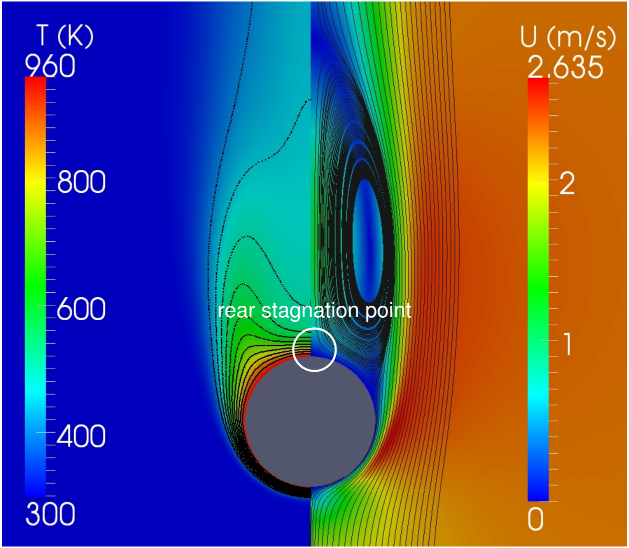

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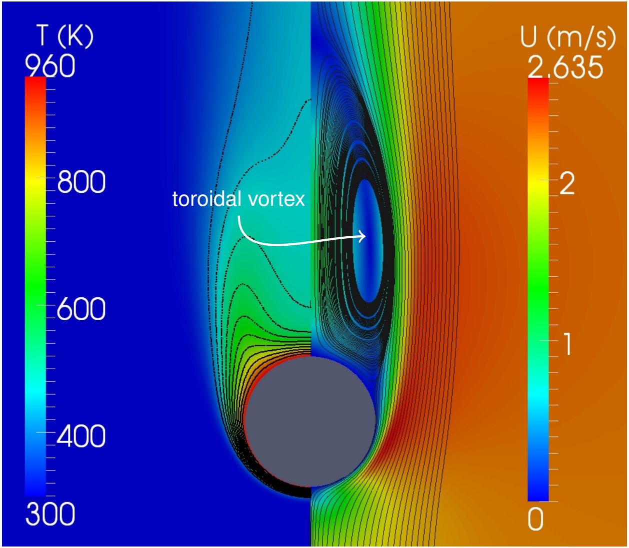
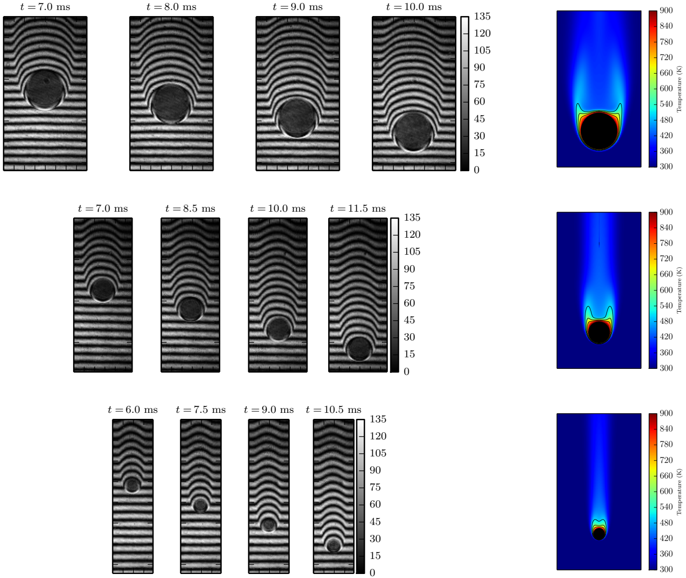


Unreacted Hot Particle Wake: ≈ 900 K (Exp. and Sim.)

$d = 6.0$ mm

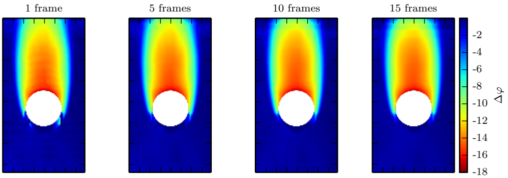
$d = 3.5$ mm

$d = 1.8$ mm



Unreacted Hot Particle Wake (Experiment)

Time averaged unwrapped optical phase



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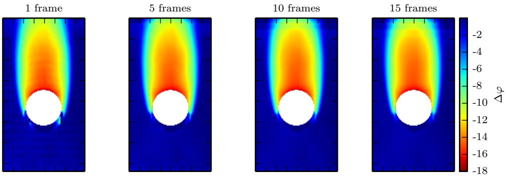

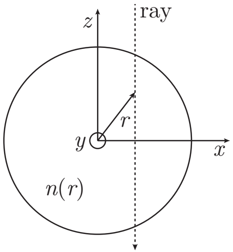

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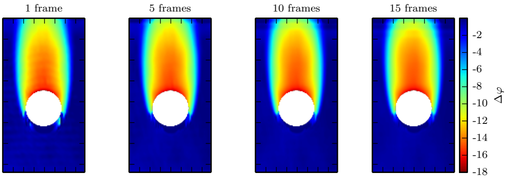

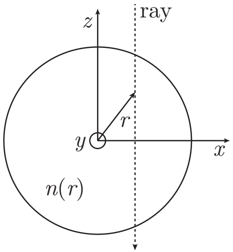

Abel transform

$$F(x) = 2\int_x^\infty \frac{f(r)r}{(r^2 - x^2)^{1/2}}\,\mathrm{d}r. \tag{1}$$

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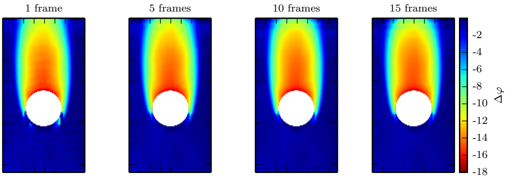

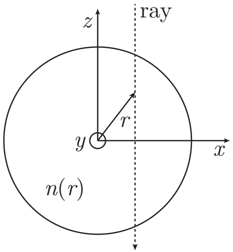

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$$f(r) = -\frac{1}{\pi}\int_r^\infty \frac{\mathrm{d}F}{\mathrm{d}x}\frac{\mathrm{d}x}{(x^2 - r^2)^{1/2}}, \tag{2}$$

Unreacted Hot Particle Wake (Experiment)

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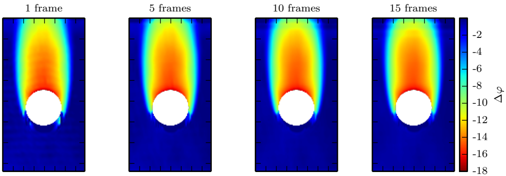

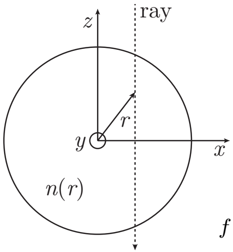

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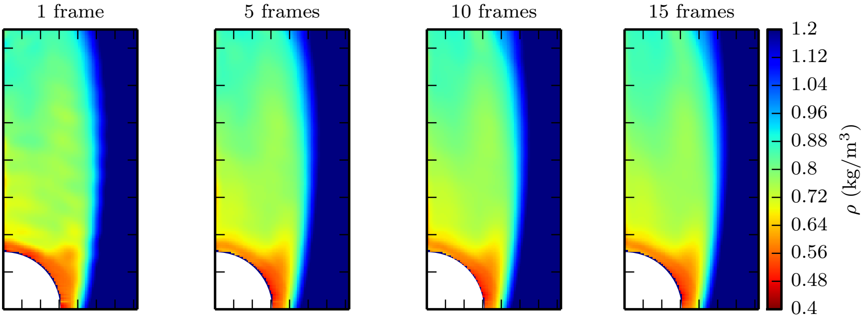
$$f(r) = \frac{2\pi}{\lambda}[n(r) - n_o(r)] \quad \text{and} \quad F(x) = \Delta\varphi \tag{3}$$

Unreacted Hot Particle Wake (Experiment)

Gladstone-Dale relation $n - 1 = K\rho$



Unreacted Hot Particle Wake (Experiment)

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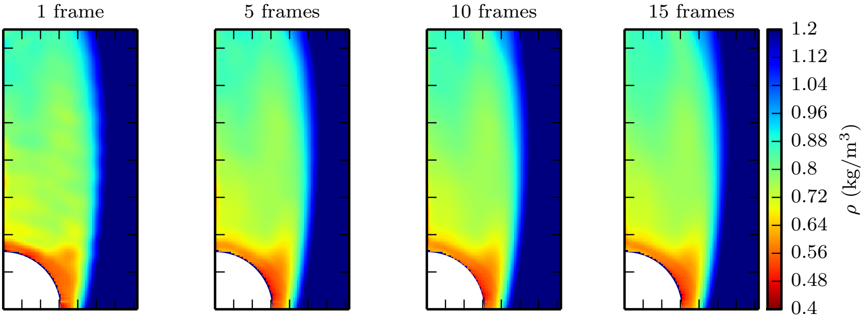
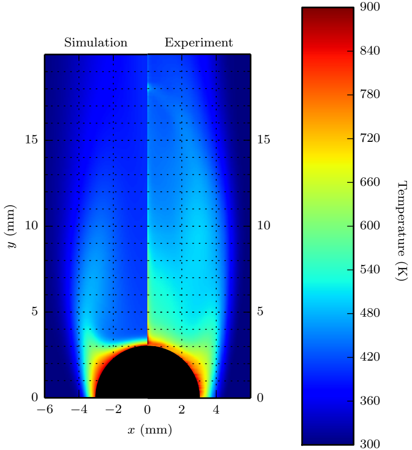


$$P = \rho R T$$

Unreacted Hot Particle Wake: Validation



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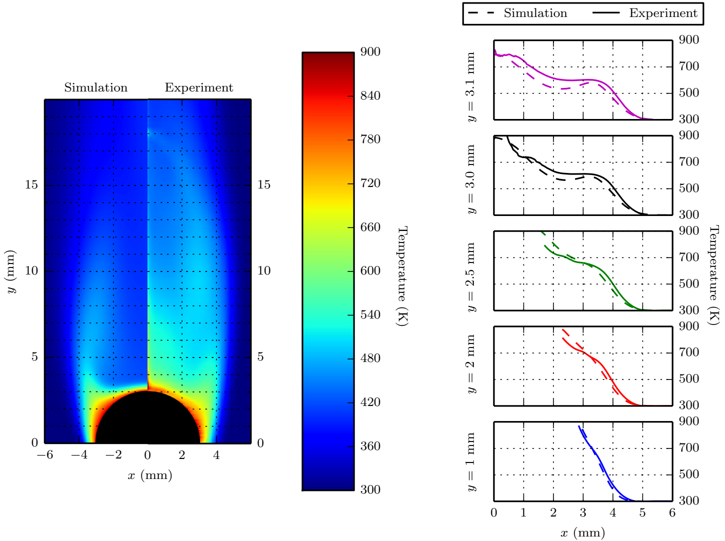
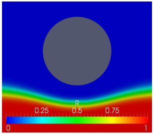


Ignition (Experiment)

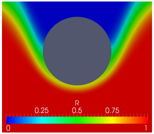
1.8 mm

Ignition (Simulation)

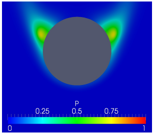
$t = 1.25$ ms



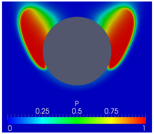
$t = 5.00$ ms



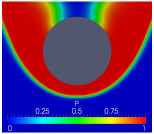
$t = 15.0$ ms



$t = 15.5$ ms

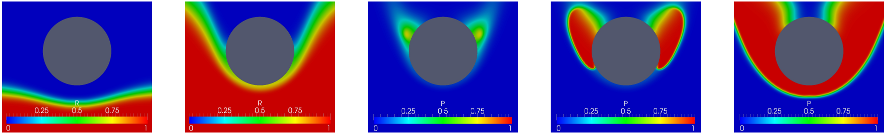


$t = 16.25$ ms



Ignition (Simulation)

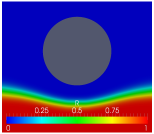
$t = 1.25$ ms | $t = 5.00$ ms | $t = 15.0$ ms | $t = 15.5$ ms | $t = 16.25$ ms



Arrival of reactive mixture (R)

Ignition (Simulation)

$t = 1.25$ ms



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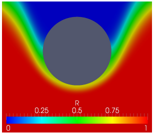
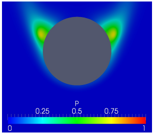
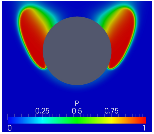


Contact of reactive mixture (R) with hot sphere

$t = 15.0$ ms



$t = 15.5$ ms



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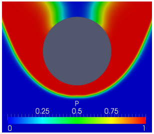
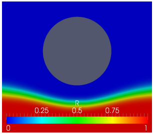


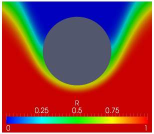
Ignition (Simulation)

$t = 1.25$ ms



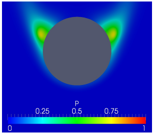
Arrival of reactive mixture (R)

$t = 5.00$ ms



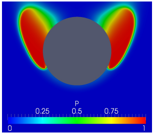
Contact of reactive mixture (R) with hot sphere

$t = 15.0$ ms

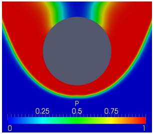


Creation of products (P)

$t = 15.5$ ms

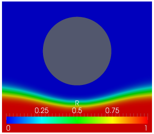


$t = 16.25$ ms



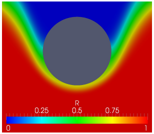
Ignition (Simulation)

$t = 1.25$ ms



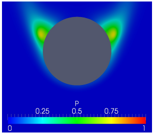
Arrival of reactive mixture (R)

$t = 5.00$ ms



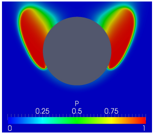
Contact of reactive mixture (R) with hot sphere

$t = 15.0$ ms



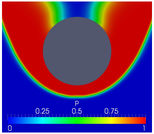
Creation of products (P)

$t = 15.5$ ms



Flame propagation

$t = 16.25$ ms



Flame propagation

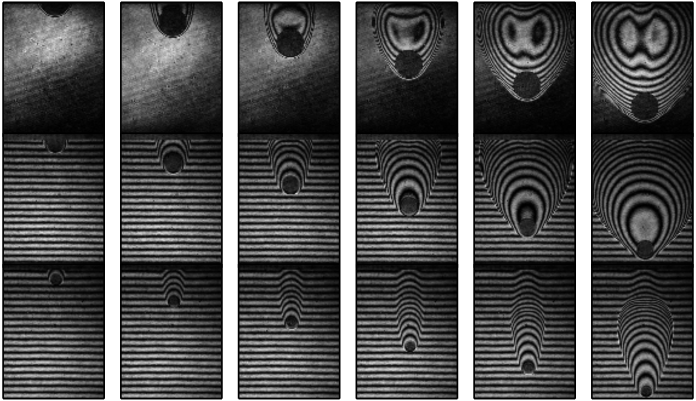
Flame Propagation (Experiment)

Recall: $\Phi = 0.9$ Current flame: $S_b = 2.6$ m/s Particle speed: $V_p = 2.3 - 2.4$ m/s

$d = 6.0$ mm

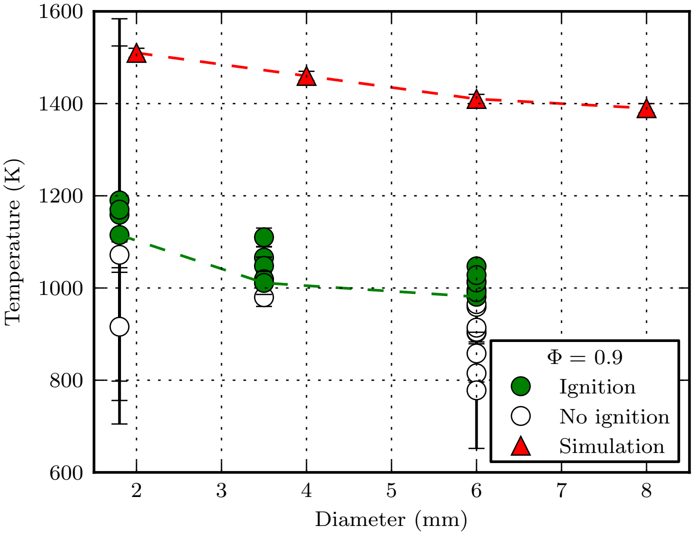
$d = 3.5$ mm

$d = 1.8$ mm

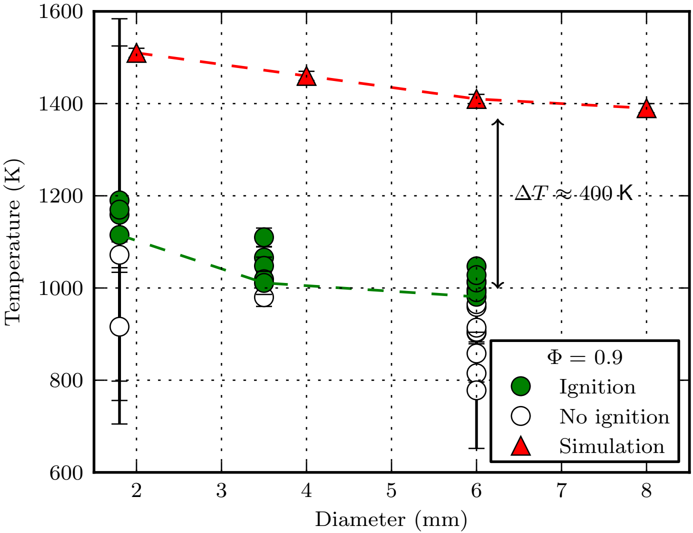


1.5 ms 3.5 ms 5.5 ms 7.5 ms 9.5 ms 11.5 ms

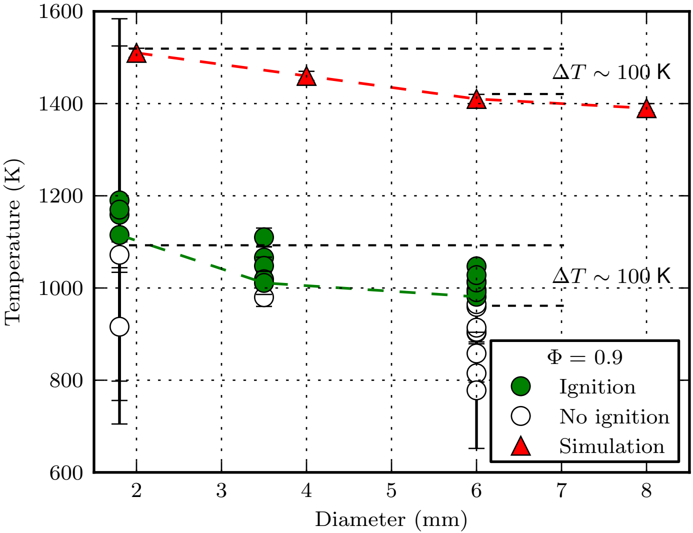
Ignition Thresholds (Exp. and Sim.)



Ignition Thresholds (Exp. and Sim.)

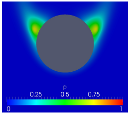


Ignition Thresholds (Exp. and Sim.)



Conclusions

- Simulation predicts ignition to occur in the flow separation region



- The ignition threshold was found to be 981 ± 10 K, 1010 ± 25 K, and 1159 ± 10 K, for sphere diameters of 6.0 mm, 3.5 mm and 1.8 mm, respectively at $V_p = 2.3 - 2.4$ m/s for alumina spheres
- Simulations using a one-step model predicted an ignition temperature 400 K higher than the experimental thresholds
  - → Similar trends predicted
  - → Use of one-step model not sufficient to capture ignition behavior
  - → Have not accounted for surface reactions
  - → Have not accounted for species diffusion to the surface
  - → Further understanding of the low-temperature oxidation of *n*-hexane needed
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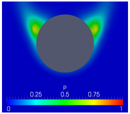

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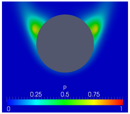

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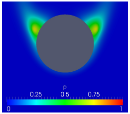

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Acknowledgements

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Thank You