Ignition of *n*-Hexane-Air Mixtures by Moving Hot Spheres

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Summary

1. Motivation
    - Accidental Ignition
    - Hot Surface Ignition
2. Previous Work
3. Materials and Methods
4. Results
5. Conclusions/Future Work

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

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

China Air Flight 120 caught fire in Okinawa Japan (BBC News, August 20, 2007)

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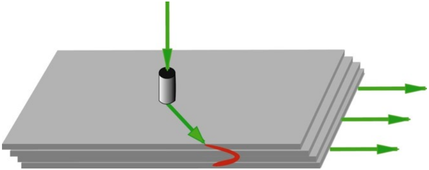

- Lightning attaching to conductor
- Current flows through composite material
- Heating of material
- Ejection of hot particles ($V_{particle} > 0$)

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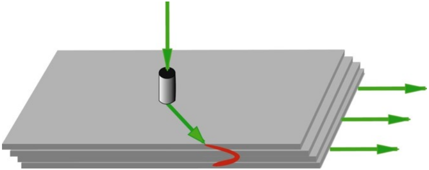

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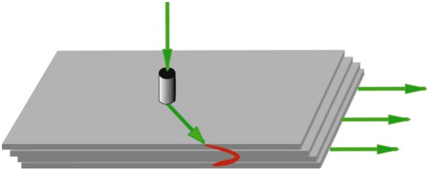

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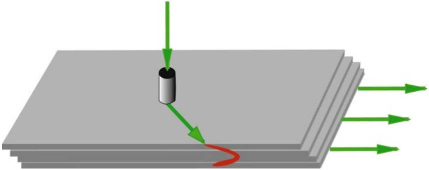

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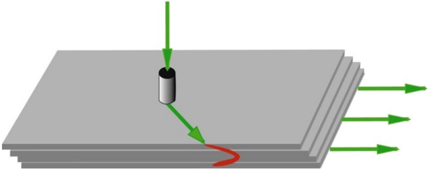

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Ignition of *n*-hexane-air mixtures using moving hot particles

Summary

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   - Results

3. Materials and Methods

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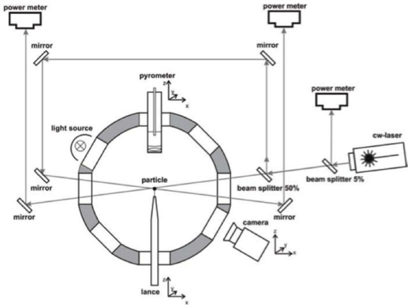
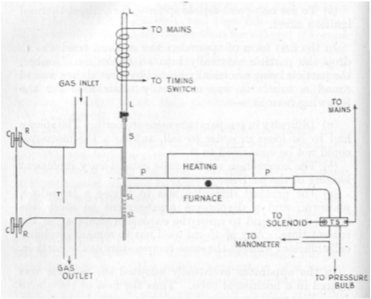
Experimental Setups : Stationary vs Moving Particles

Stationary particles heated via IR laser : Beyer et al. (2010), Dubaniewicz et al. (2000), Homan et al. (1981)

Moving heated particles introduced into a flammable environment : Silver (1937)

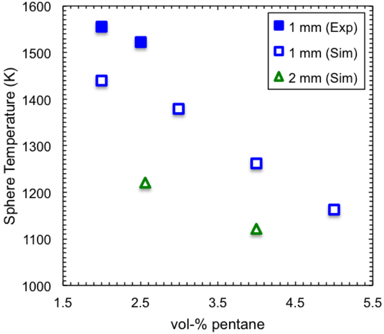


Experimental Setup, Beyer et al. (2010)



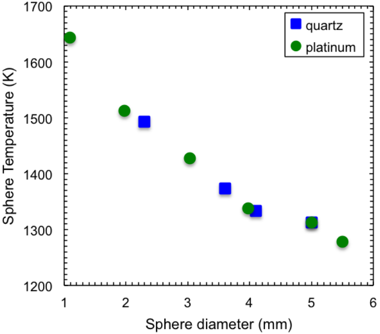
Experimental Setup, Silver (1937)

Results : Stationary vs Moving Particles



Stationary

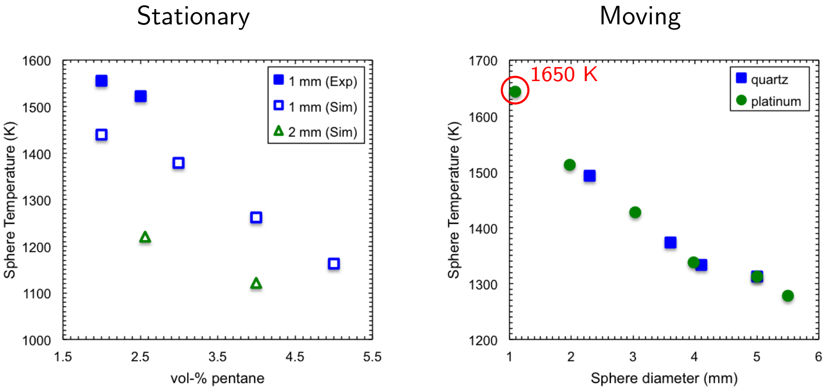
Pentane/air ignition results, Beyer et al. (2010)



Moving

3 vol-% pentane/air ignition, Silver (1937)

Results : Stationary vs Moving Particles



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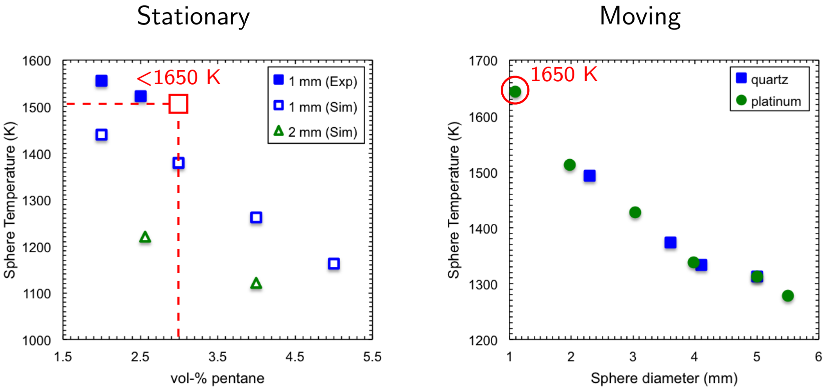

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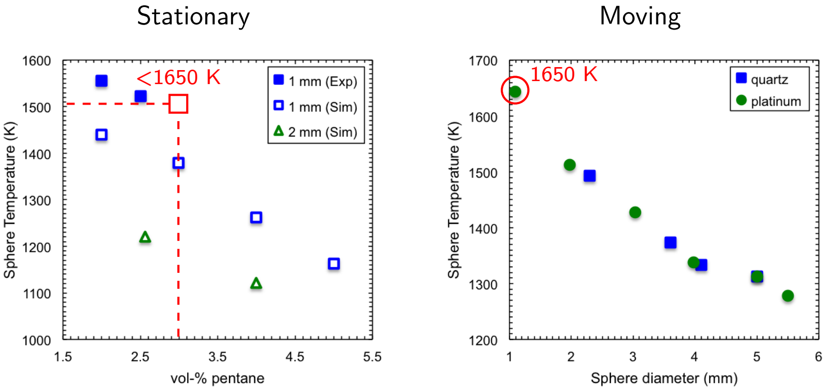

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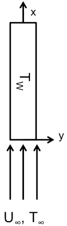
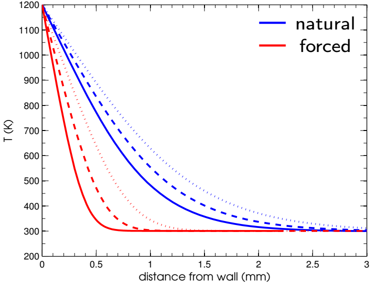
$$T_{stationary} < T_{moving}$$
$$D_{sphere} \uparrow T_{ignition} \downarrow$$

Natural and Forced Convection

- Parallel flow past a vertical plate :
  - → $U_\infty = 0$ m/s and $U_\infty = 2.5$ m/s
  - → $T_\infty = 300$ K
- Adiabatic plate : $T_w = 1200$ K





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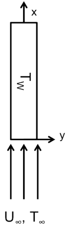

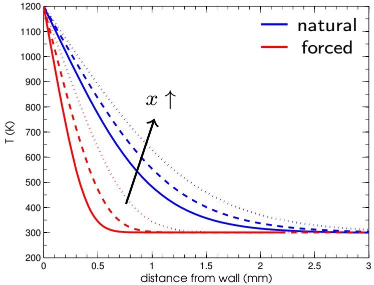

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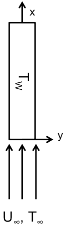

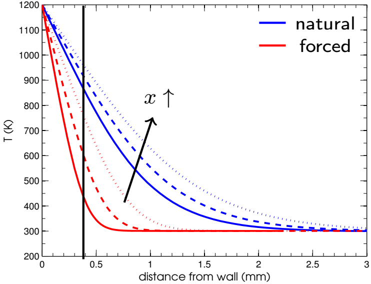

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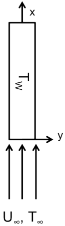

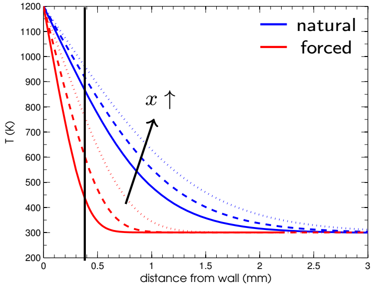

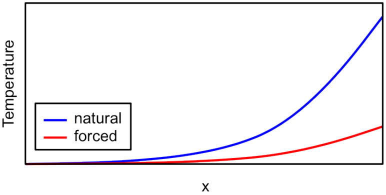

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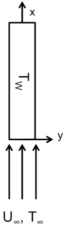

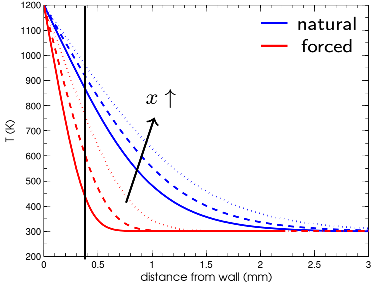

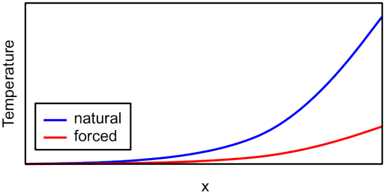

$$\rho c_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) - k \frac{\partial^2 T}{\partial y^2} = -q_c A e^{\frac{-E_a}{RT}}$$

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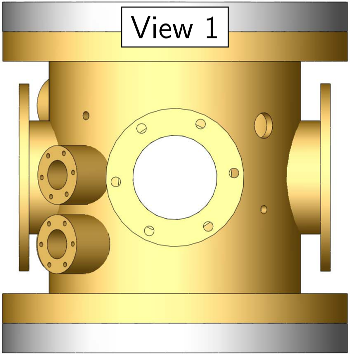

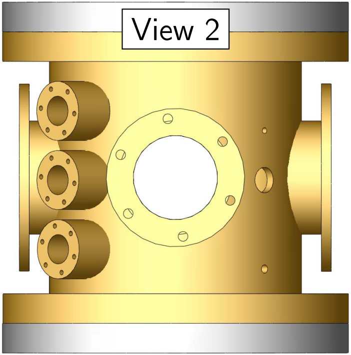

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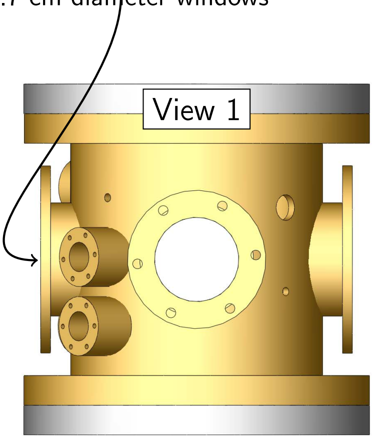
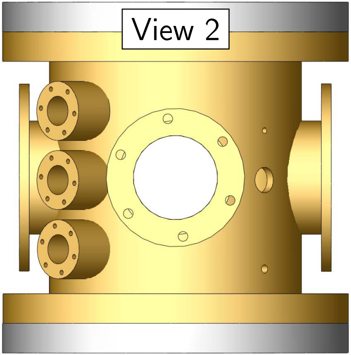

11.7 cm diameter windows



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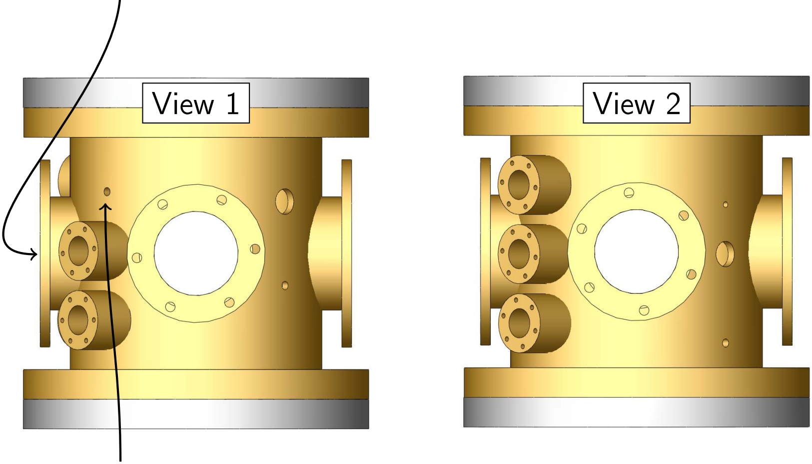

pressure manometer

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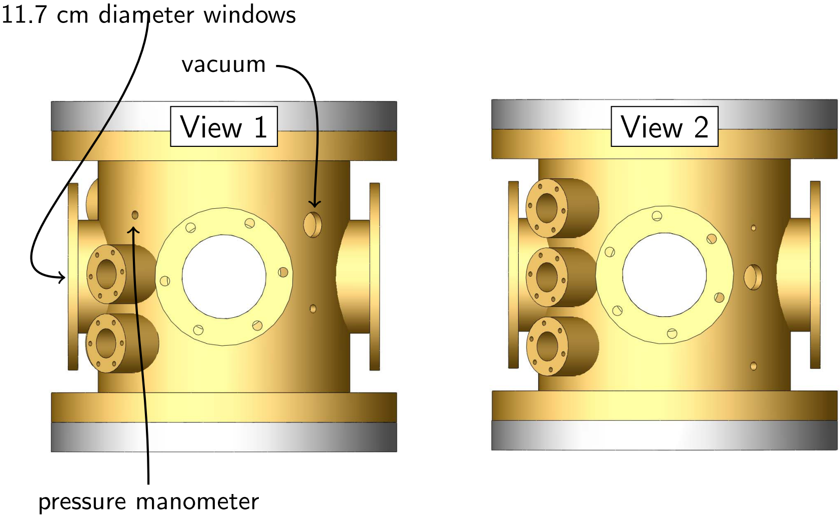

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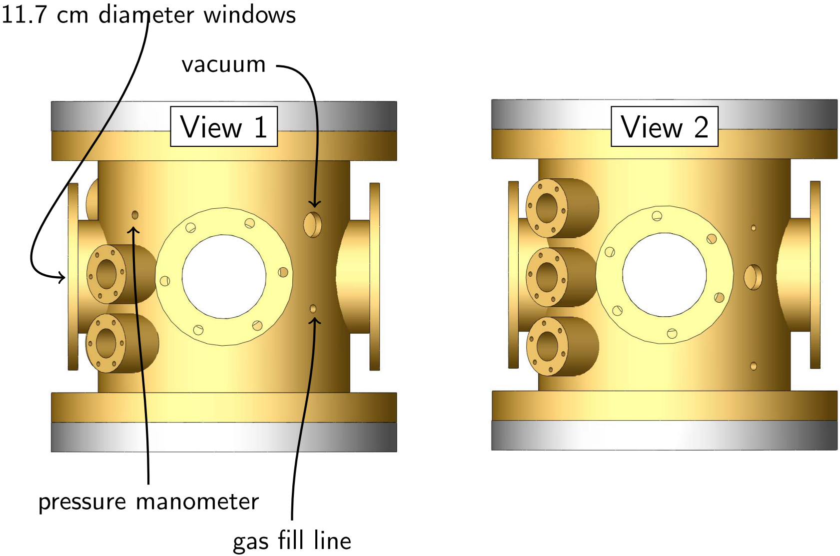

11.7 cm diameter windows

vacuum

pressure manometer

gas fill line

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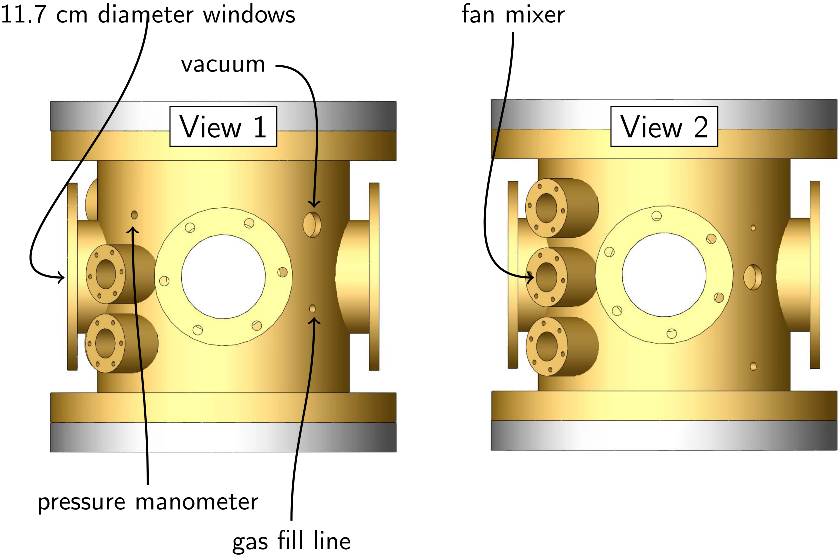

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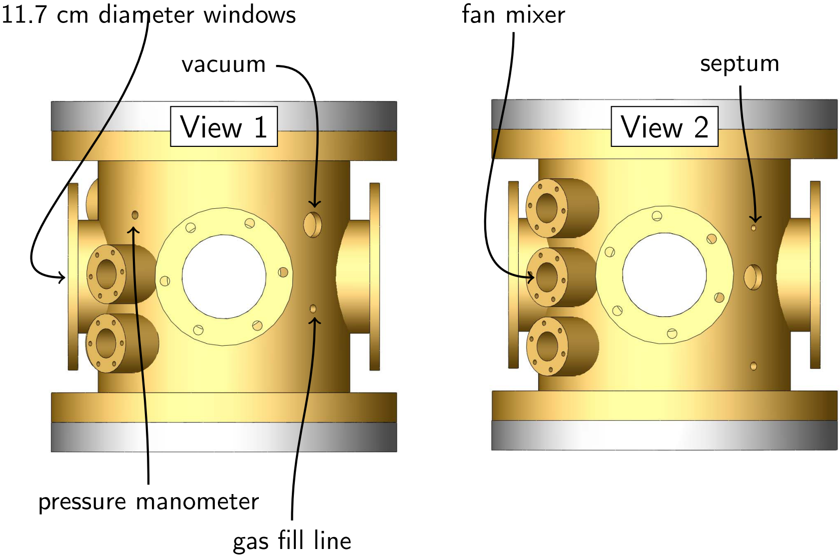

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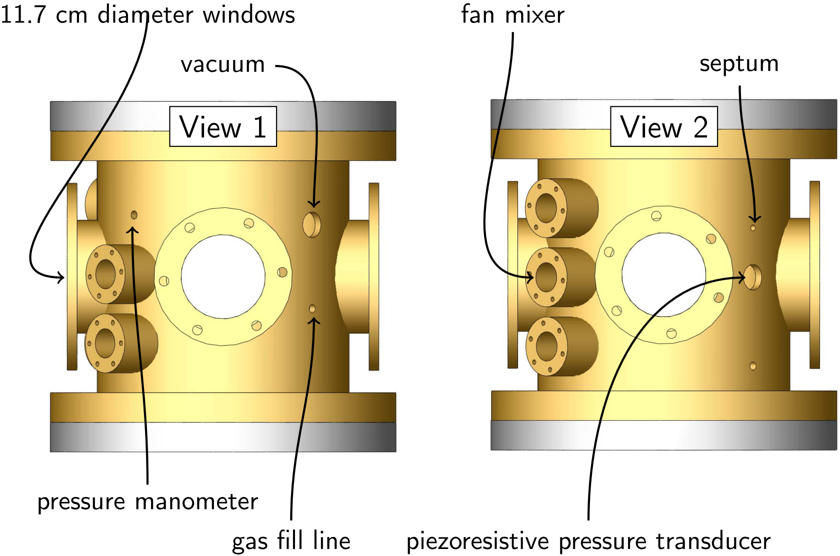

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fan mixer

septum

pressure manometer

gas fill line

piezoresistive pressure transducer

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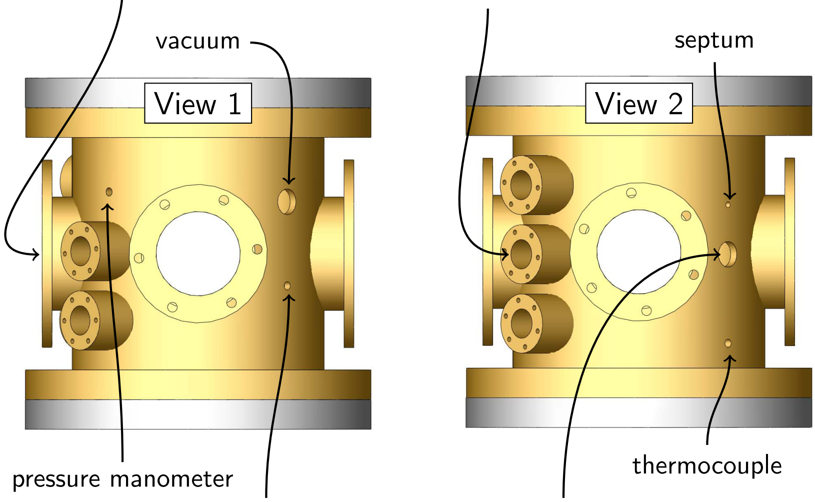

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thermocouple

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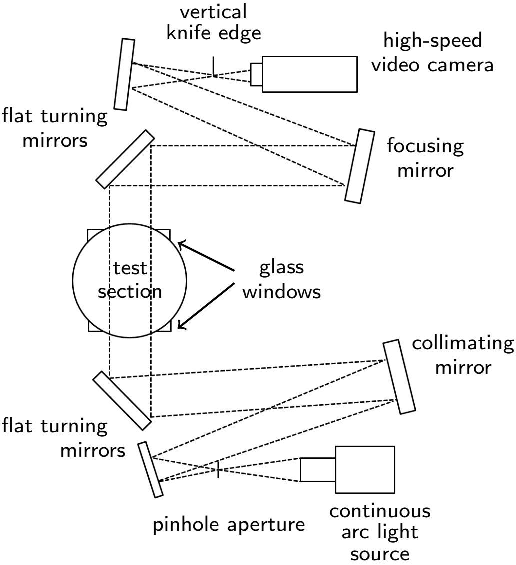
Experimental Setup : Schlieren Setup

- 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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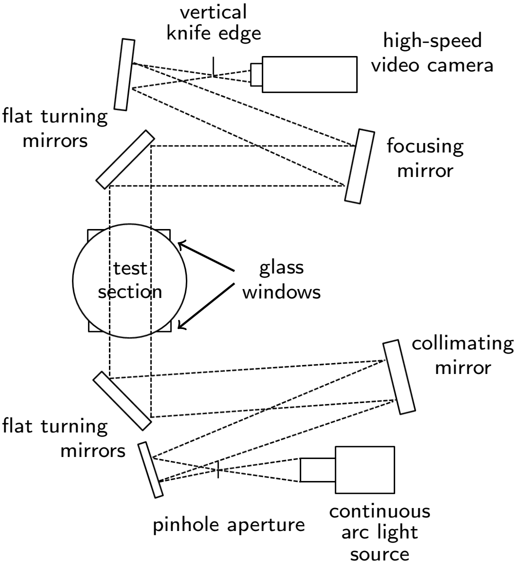

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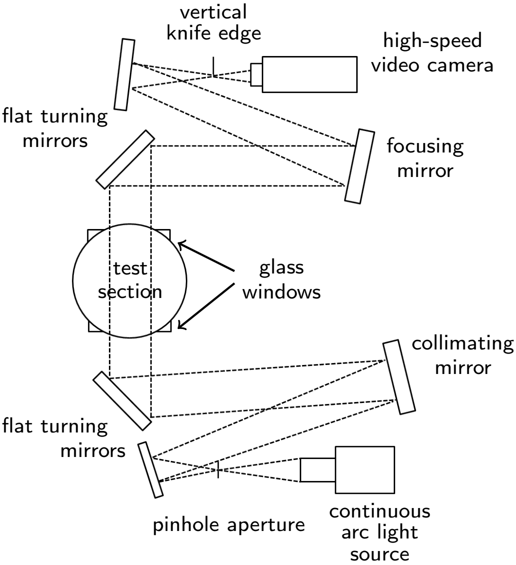

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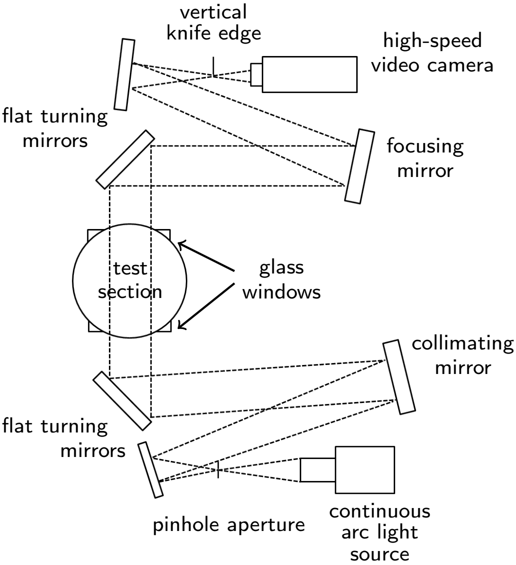

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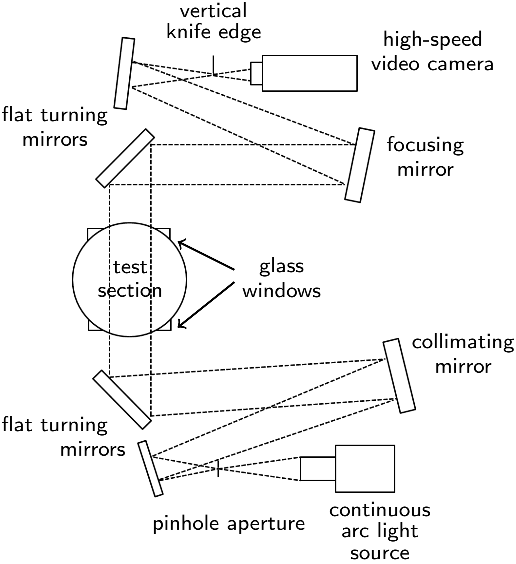

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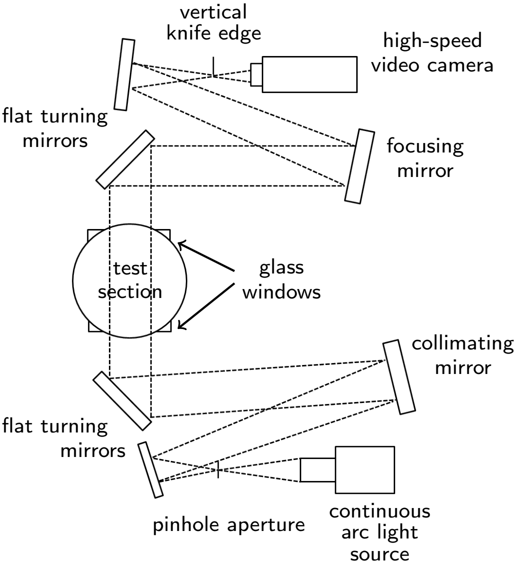
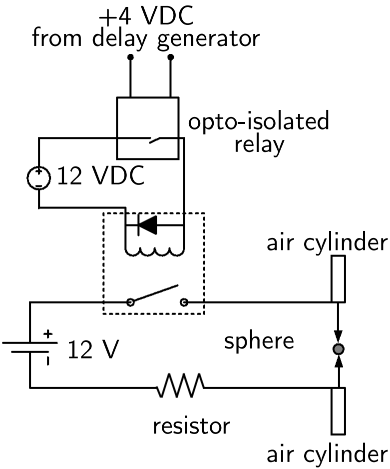
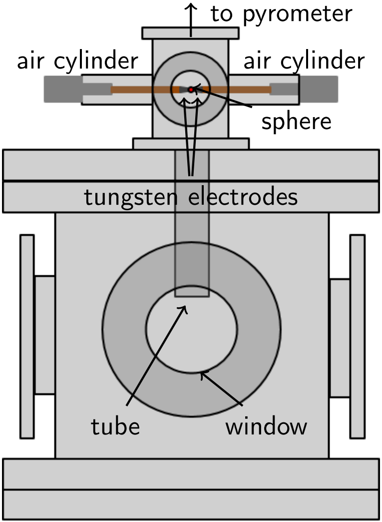


Experimental Setup : High Current Particle Heater

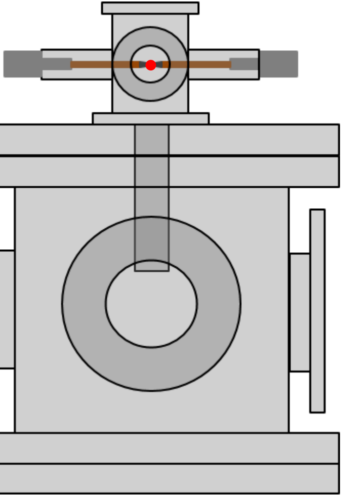


Heating circuit schematic

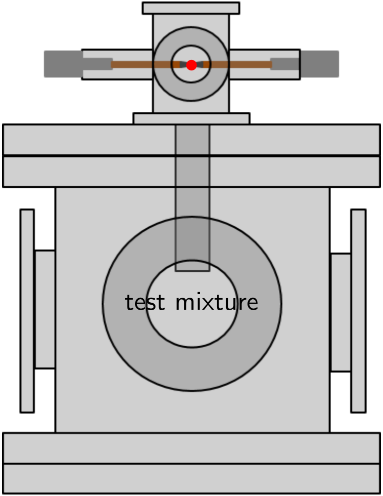


Particle heater chamber (top) and combustion vessel (bottom)

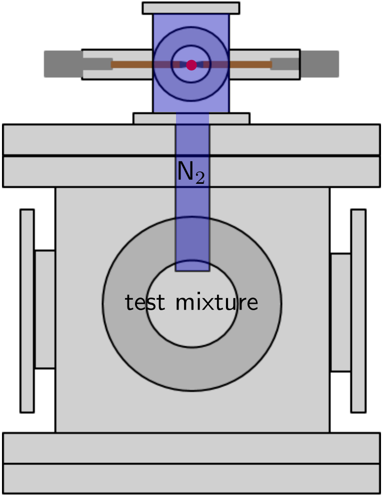
Experimental Setup : High Current Particle Heater



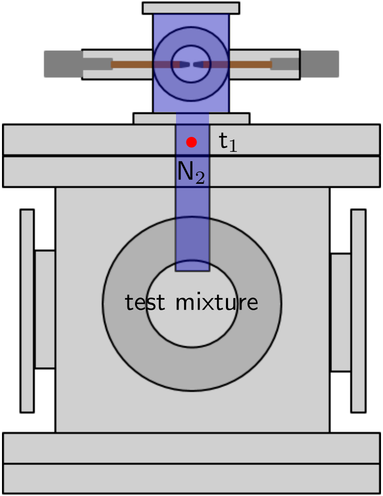
Experimental Setup : High Current Particle Heater



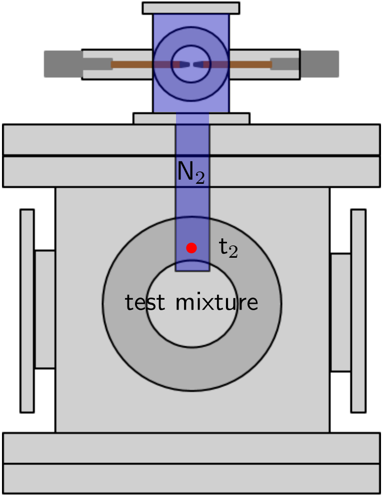
Experimental Setup : High Current Particle Heater



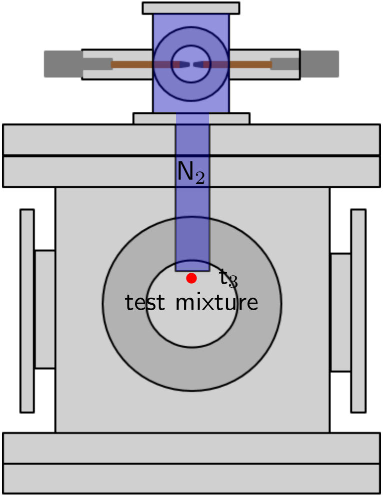
Experimental Setup : High Current Particle Heater



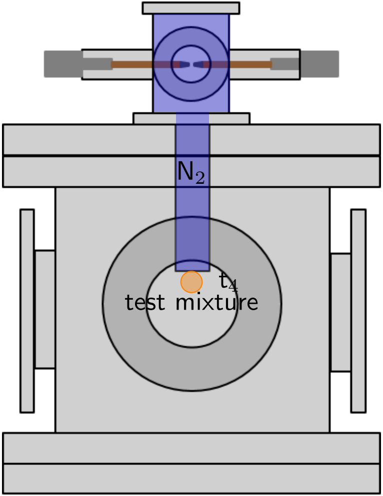
Experimental Setup : High Current Particle Heater



Experimental Setup : High Current Particle Heater



Experimental Setup : High Current Particle Heater



Summary

1. Motivation

2. Previous Work

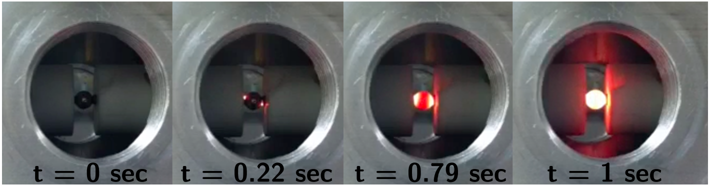
3. Materials and Methods

4. Results
    - Heating in Air
    - Ignition Results
    - Simulation Results
    - Comparison

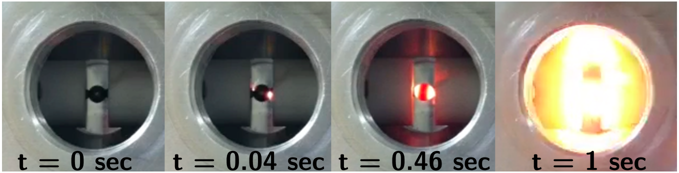
5. Conclusions/Future Work

Results : High Current Heating in Air

Heating in air, $R = 17$ mΩ, $d = 4$ mm, heating time $\approx$ 1 sec



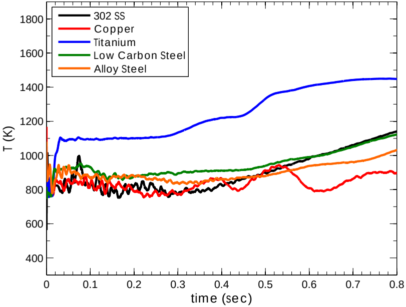
Titanium (Ti-6Al-4V) → $T_{max} \approx$ 1200 K



Titanium (Ti-6Al-4V) → $T_{max} \approx$ 1300 K

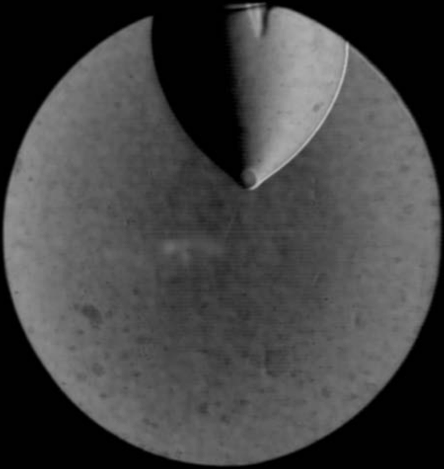
Results : High Current Heating in Air

Heating in air, $R = 13$ mΩ, $d = 4$ mm



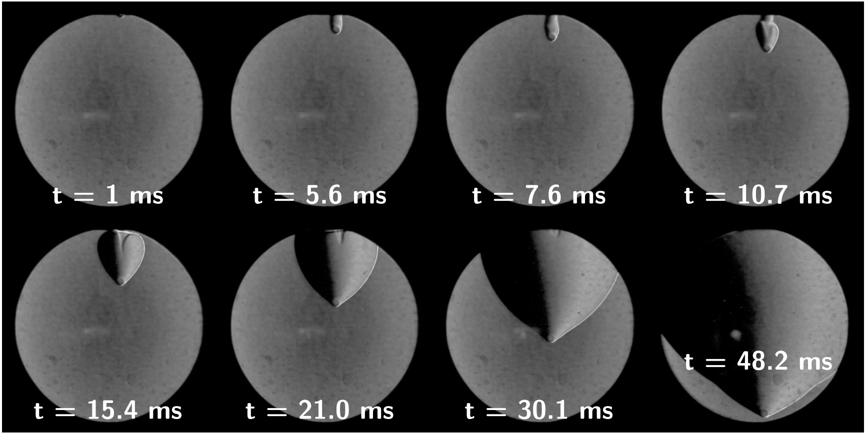
Material	$T_{melting}$ (K)
Copper	1350
Carbon steel, alloy steel, 302 SS	1700-1800
Titanium	1950

n-Hexane–air : $P_0 = 100$ kPa, $T_0 = 300$ K, $\Phi = 0.9$
$d = 4$ mm, material : titanium, $V \approx 2.3$ m/s



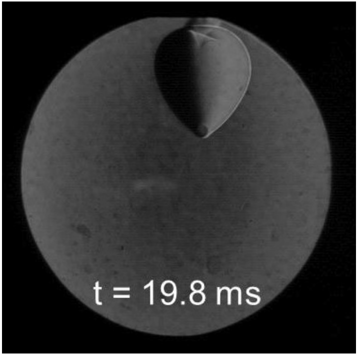
Results : Ignition Test

$$T_{surface} = 1199 + 42\ \text{K}/\text{-}10\ \text{K}$$



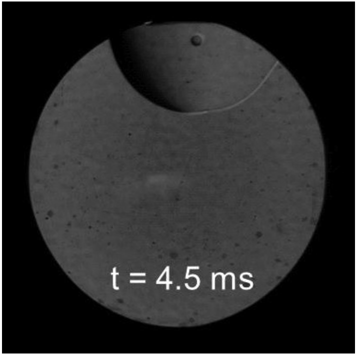
Results : Flame Geometry

n-Hexane–Air, $\Phi = 0.9$
$P = 100$ kPa



$V_S^0 = 2.6$ m/s
$V_P \approx 2.3$ m/s

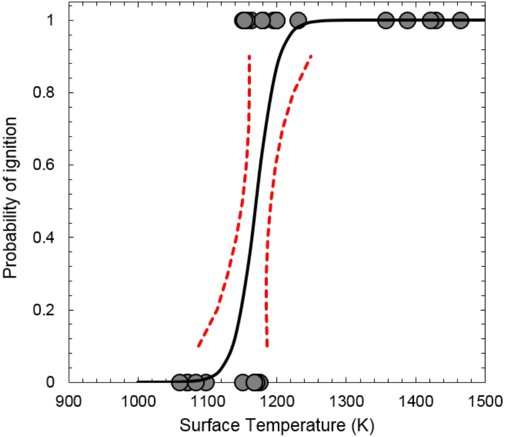
n-Hexane–O$_2$–40% N$_2$, $\Phi = 0.9$
$P = 50$ kPa



$V_S^0 = 23$ m/s
$V_P \approx 2.3$ m/s

Results : Ignition Tests

Probability distribution : $P_0 = 100$ kPa, $T_0 = 300$ K and $\Phi = 0.9$
# of tests : 26



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Probability distribution : $P_0 = 100$ kPa, $T_0 = 300$ K and $\Phi = 0.9$
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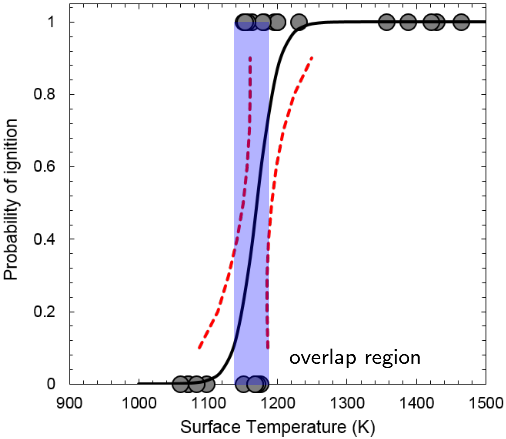

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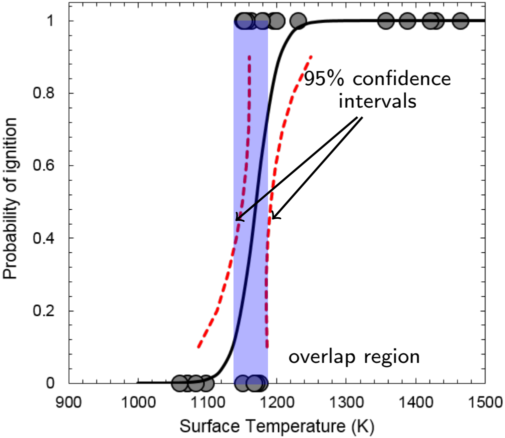

Results : Ignition Tests

Probability distribution : $P_0 = 100$ kPa, $T_0 = 300$ K and $\Phi = 0.9$
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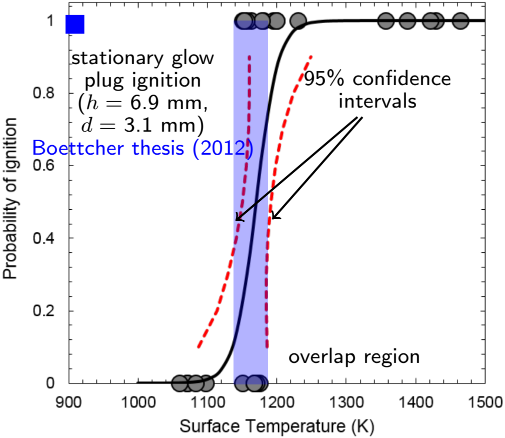
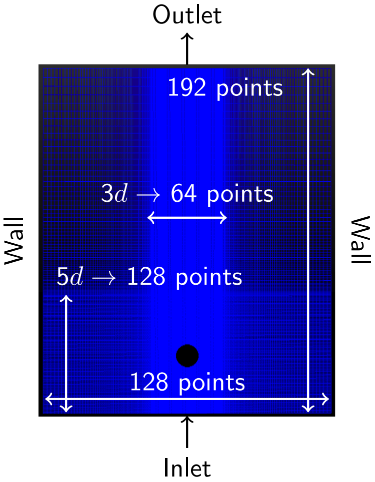


Simulation Setup

- Grid
  - → Axisymmetric
  - → Locally refined around stationary hot particle
  - → 192x128 mesh points
- Boundary conditions
  - → Constant particle temperature
  - → Wall temperature : 300 K
  - → Inert surfaces
  - → Neumann boundary condition for species
- Initial conditions
  - → $P_0 = 100$ kPa, $T_0 = 300$ K and $\Phi = 0.9$
  - → Flow N_2 at $t =$ 0-200 ms and *n*-heptane[1]–air at $t > 200$ ms



- Low Mach number Navier-Stokes equations and detailed chemistry calculations

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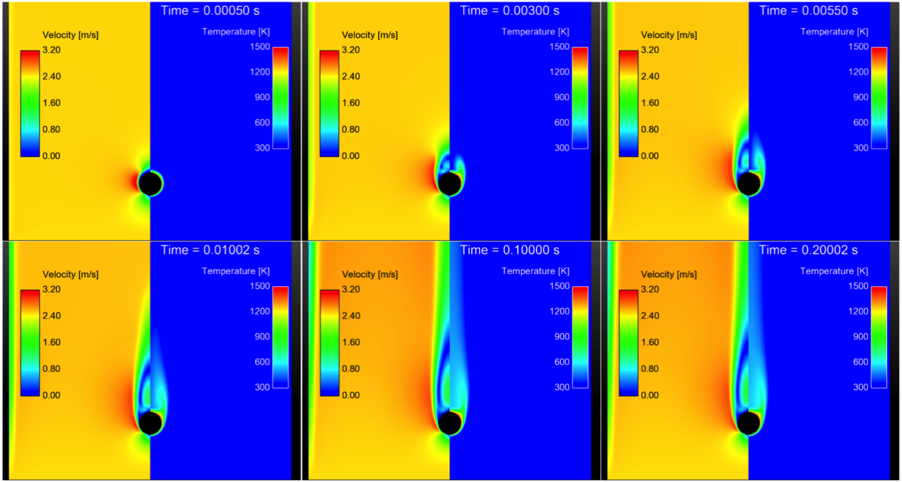
[1] Blanquart G., Pepiot-Desjardins P., and Pitsch H. (2009). Combustion and Flame. 156 : 588-607.

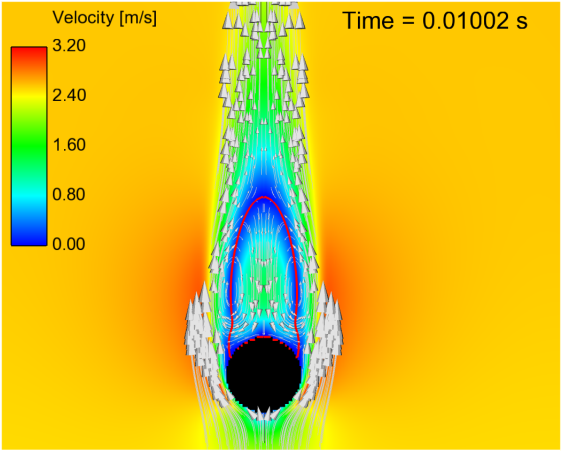
Results : Simulations (N_2 Hot Wake)

N_2 velocity and thermal boundary layers, stabilized at $t > 100$ ms,
$T_{surface} = 1500$ K

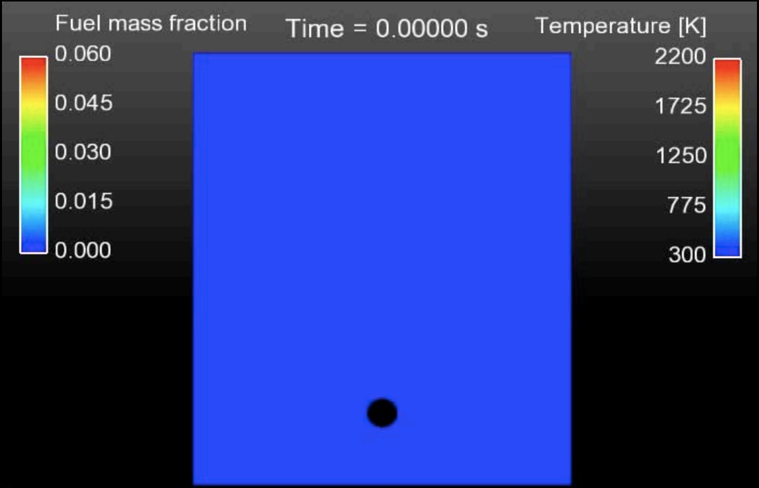


Results : Simulations (N_2 Hot Wake)

$T_{surface}$ = 1500 K

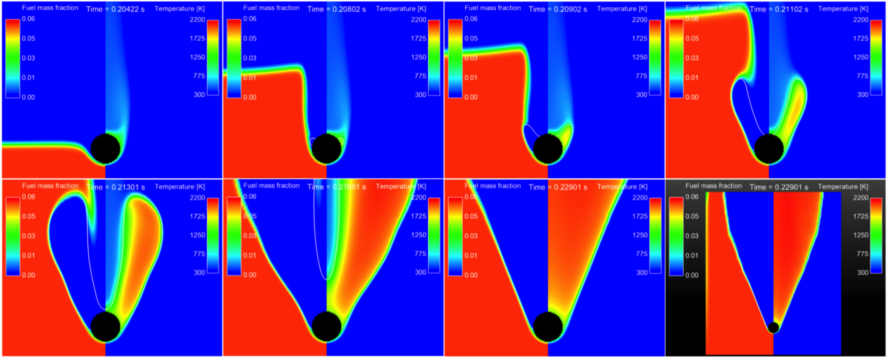


n-Heptane–air : $P_0 = 100$ kPa, $T_0 = 300$ K, $\Phi = 0.9$
$d = 4$ mm, $V = 2.5$ m/s, $T_{surface} = 1450$ K



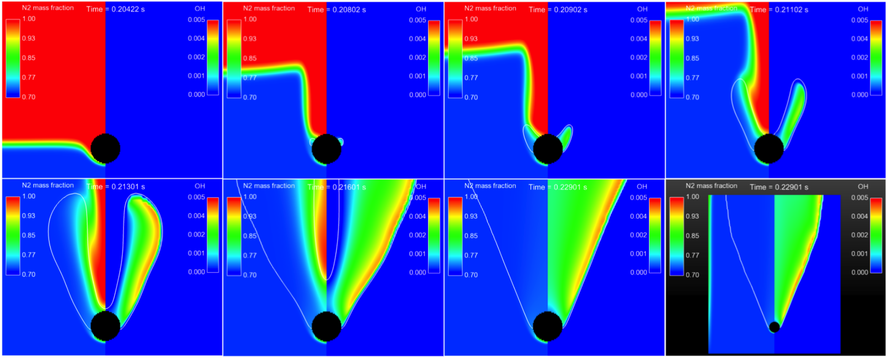
Results : Ignition Simulations

$T_{surface}$ = 1450 K, fuel mass fraction and temperature



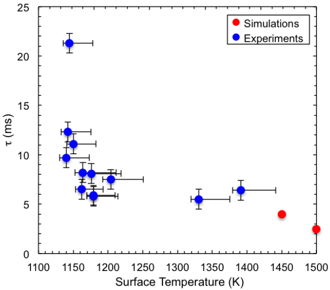
Results : Ignition Simulations

$T_{surface} = 1450$ K, N_2 mass fraction and OH*



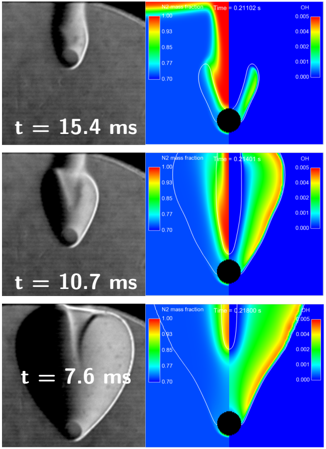
Results : Experiments and Simulations

Ignition delay time



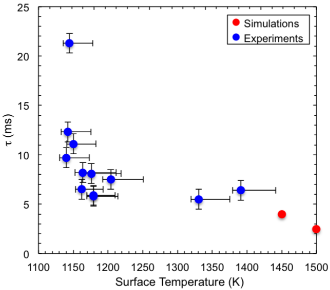
- Ignition delay time ≈ 5 ms
- Increase in ignition delay time while approaching minimum ignition temperature

Experiment : $T_{surface} = 1199$ K,
Simulation : $T_{surface} = 1450$ K



Results : Experiments and Simulations

Ignition delay time



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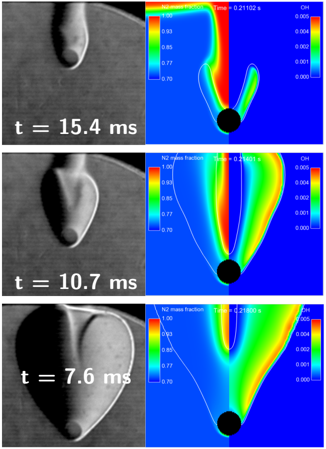

Summary

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Conclusions/Future Work

Conclusions

- Ignition of *n*-hexane–air mixtures using moving heated particles ($P_0 = 100$ kPa, $T_0 = 300$ K, $\Phi = 0.9$) with $V_P \approx 2.3$ m/s
  - → 50% probability of ignition with $T_{surface} = 1170$ K using 4 mm diameter titanium spheres
  - → Interaction of flame and sphere for mixtures with flame speeds comparable to the particle velocity
- Qualitative agreement between experiments and simulation
  - → Nitrogen recirculation region that leads to a particular flame propagation behaviour
  - → Ignition close to sphere surface near flow separation region
- Comparable ignition delay times between experiments and simulations
  - → 35-60% difference at $T_{surface} > 1400$ K

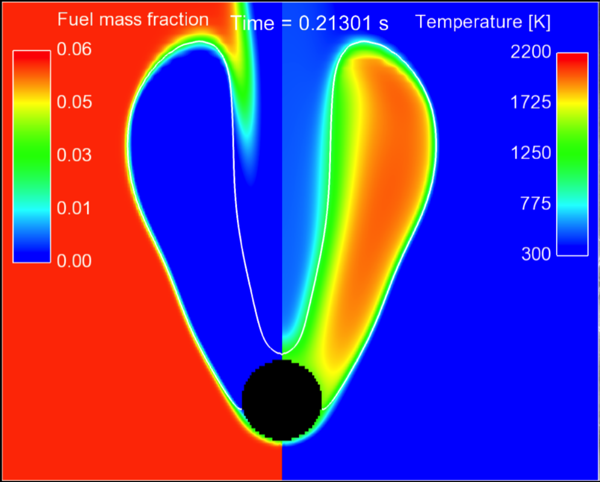
Future Work

- New particle heating method : CO_2 laser
  - → Repeatable surface temperatures
  - → Use of metallic or non-metallic materials
  - → Easy switch to larger or smaller particles

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.

Thank You



David Marxer photography