Two-Stage Autoignition Dynamics of N-dodecane Droplets Under Normal Gravity at High Pressures

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Background

- The study of autoignition of an isolated, single droplet is important from the spray combustion point of view, which is quite complex

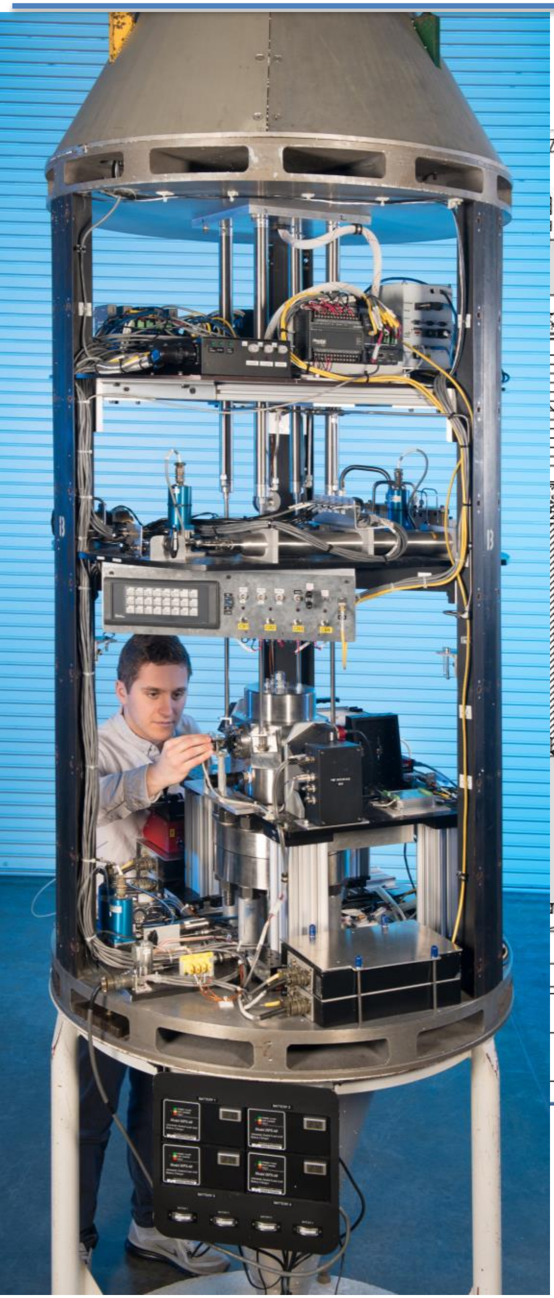
- Earlier experimental and numerical simulations with detailed chemistry
  - Tanabe et al. (1994, 1995, 1996)
  - Moriue et al. (2000)
  - Eigenbrod et al. (2016)
  - Cuoci et al. (2015) ⇐ *Numerical simulation*

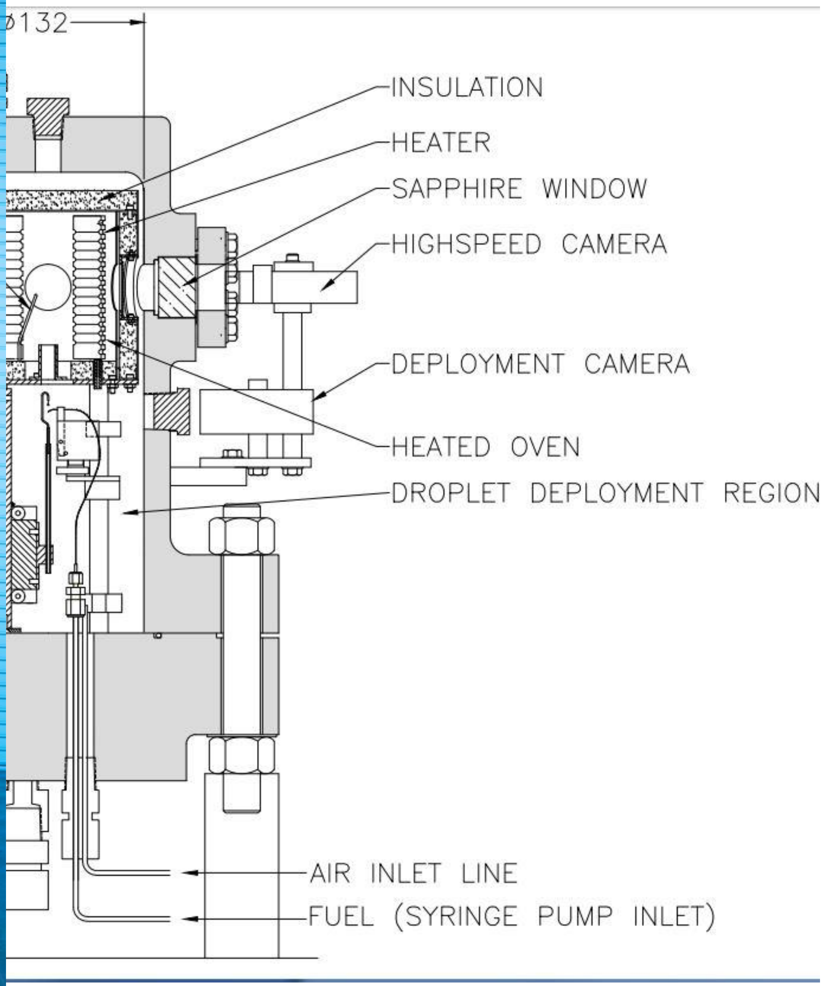
- Many aspects of single, isolated fuel droplet autoignition still remains to be thoroughly investigated, particularly at high pressures (both chemical and physical processes are important)

- A new experimental hardware is being developed at NASA Glenn to study high pressure droplet ignition and combustion

- Preliminary results using the newly developed apparatus is presented here

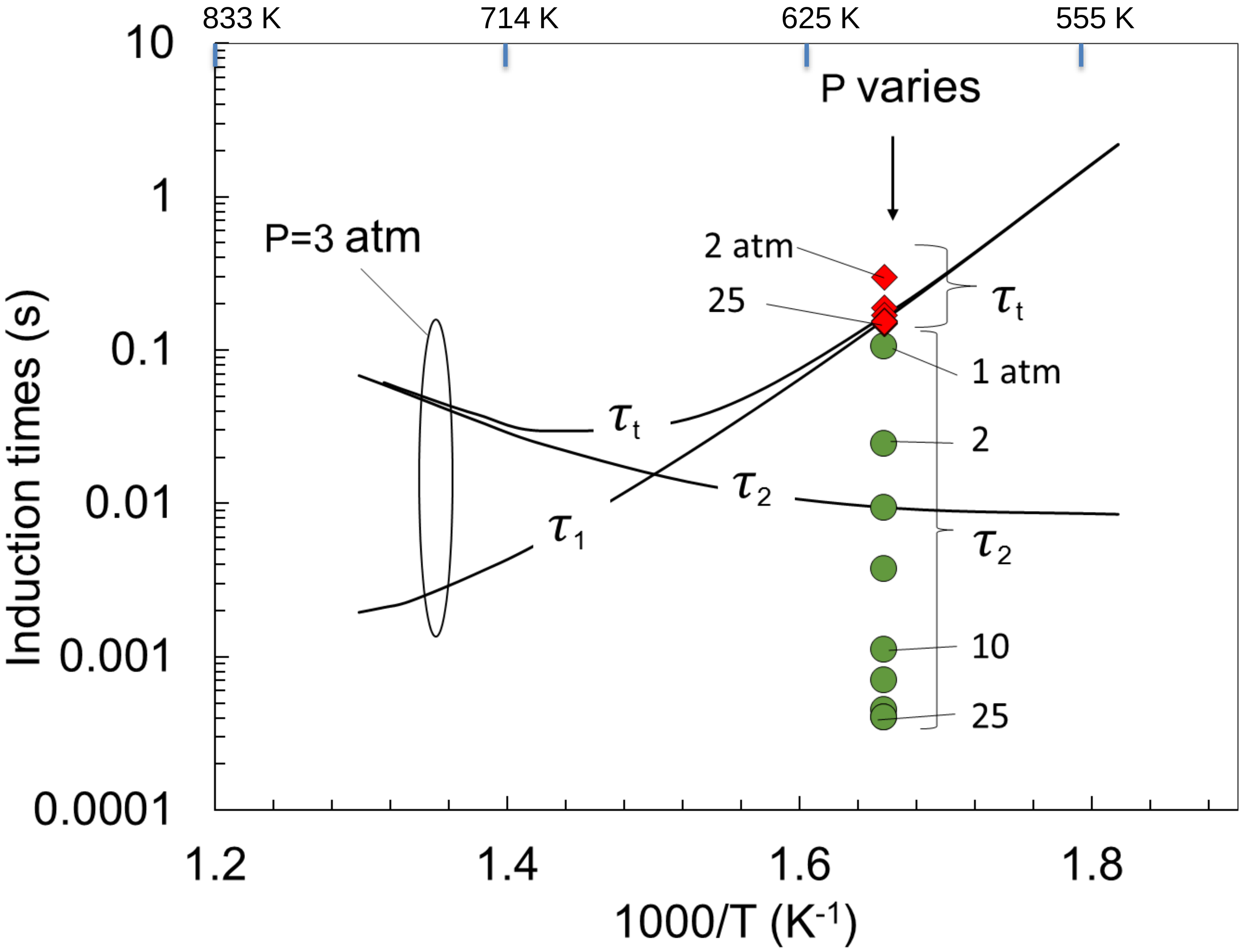
NASA Glenn High Pressure Experimental Hardware





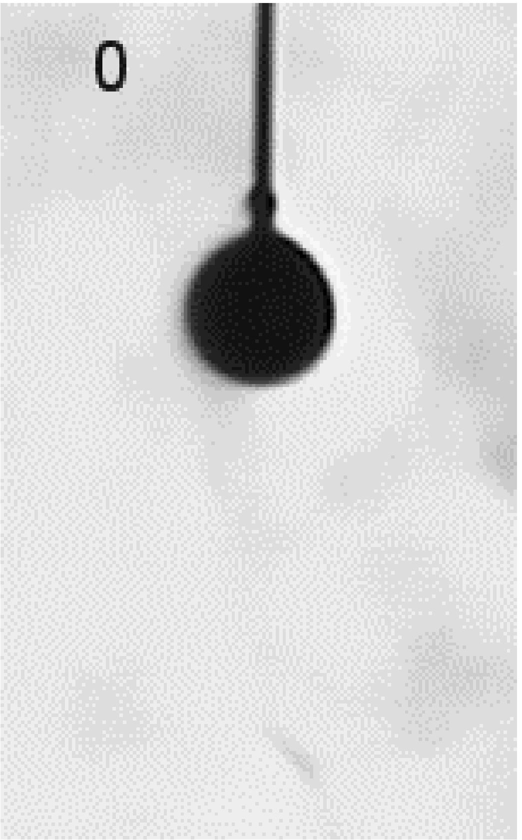
- Combustion chamber rated up to 100 bar and 1000 K
- High speed shadowgraph imaging – 3000 frames per second
- Color camera images at 300 frames per second
- PMT tube recorded at 1000 Hz
- 3-thermocouples (close to the droplet, oven and deployment)

Test matrix shown on homogeneous mixture induction time map (CANTERA)



- Homogeneous stoichiometric n-dodecane/air mixture
- Experimental conditions:
  - P=3 atm T= 560 to 780 K
  - T=603 K and P = 2 to 25 atm
- T varying case NTC behavior
- P varying case remains in Low-T region: τ_1/τ_2 varies (~1 to 400) as P increases from 1 to 25 atm

High speed video



n-dodecane droplet in air
autoignition

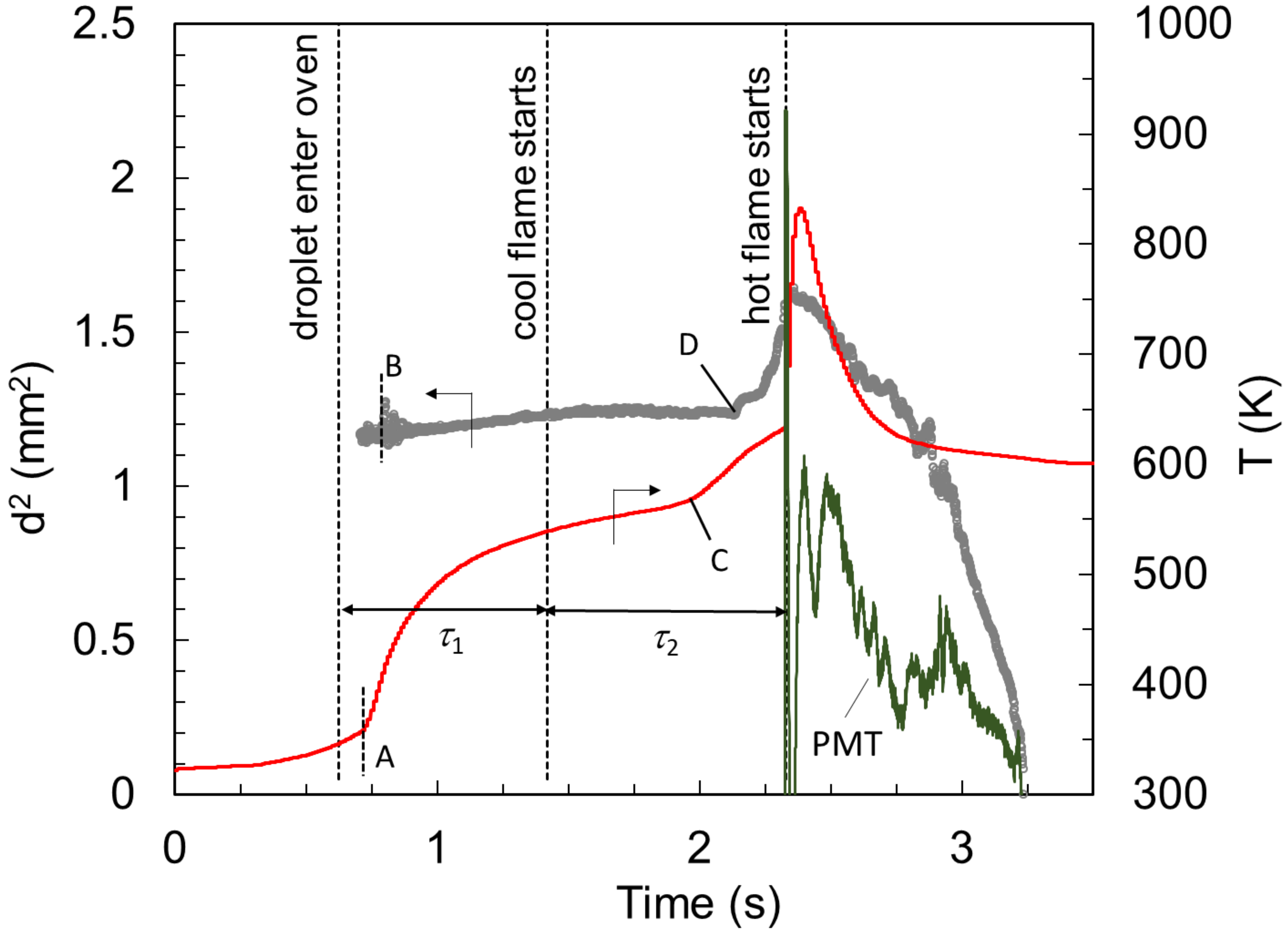
$P = 20$ atm
$T = 603$ K
$D_0 = 1.1$ mm

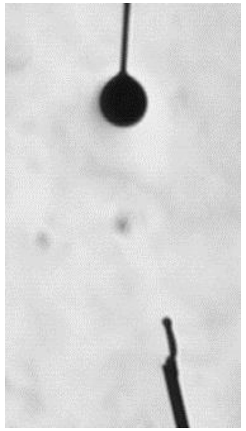
captured at 3000 fps
playback at 30 fps

$P_c = 18.1$ atm
$T_c = 658.2$ K

Temperature and diameter histories

P=3 atm
T=623 K





Four different ignition scenarios

1. Cool flame only mode (CFO):
   Observed at low pressures and low temperatures (e.g., P=2 atm T=603) droplet lifetime is shorter than second induction time

2. Cool flame followed by hot flame mode (CF-HF):
   Cool flame propagates and surrounds the droplet, followed by hot flame in its wake. Observed at higher pressures and temperatures (e.g., P=3 atm and T =643 K)

3. Cool flame and hot flame mode (CF&HF):
   As the cool flame propagates, hot flame kernel appears before the CF reaches the droplet. Both cool and hot flame structures appear for a brief period.

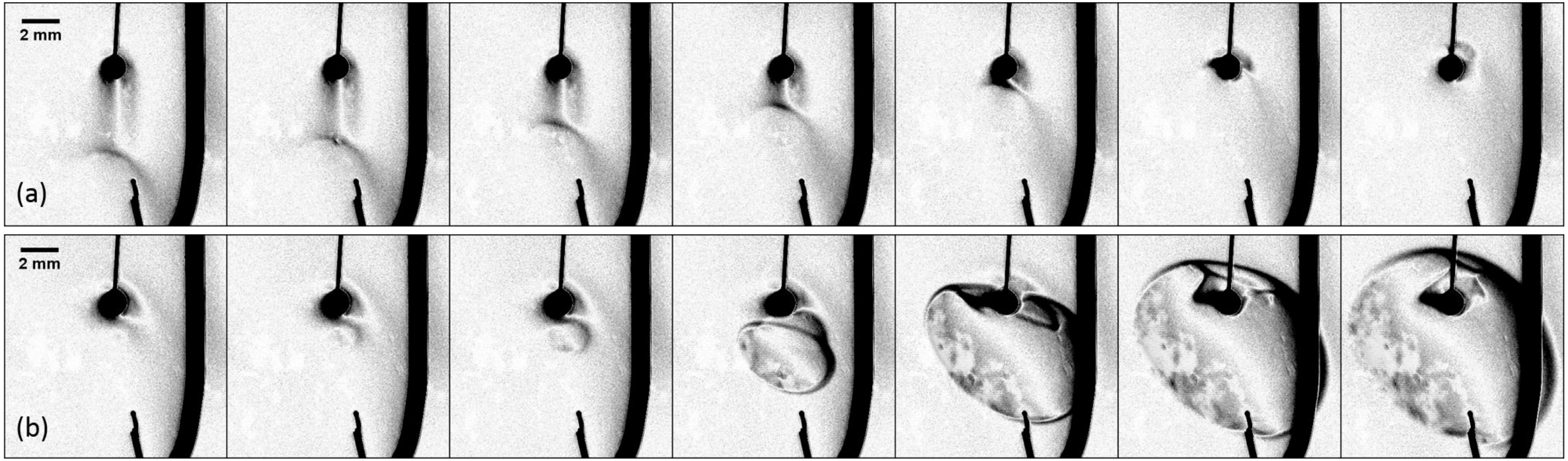
4. Hot flame only mode (HF):
   Observed at high temperatures. Cool flame never forms. The temperature is above the “upper-turnover” temperature (e.g, P=3 atm T=783 K)

Autoignition modes

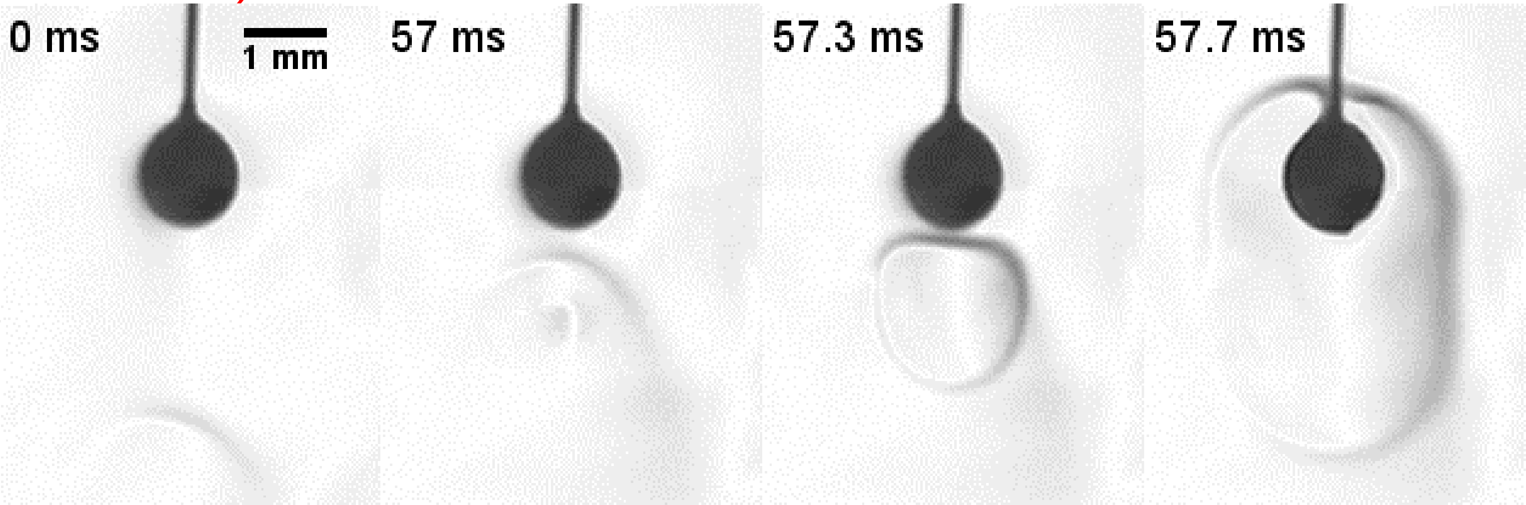
CF-HF mode: (3 atm 623 K)

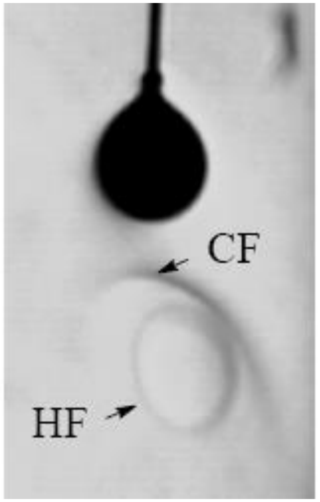
1/3 s time step

2/3 ms time step



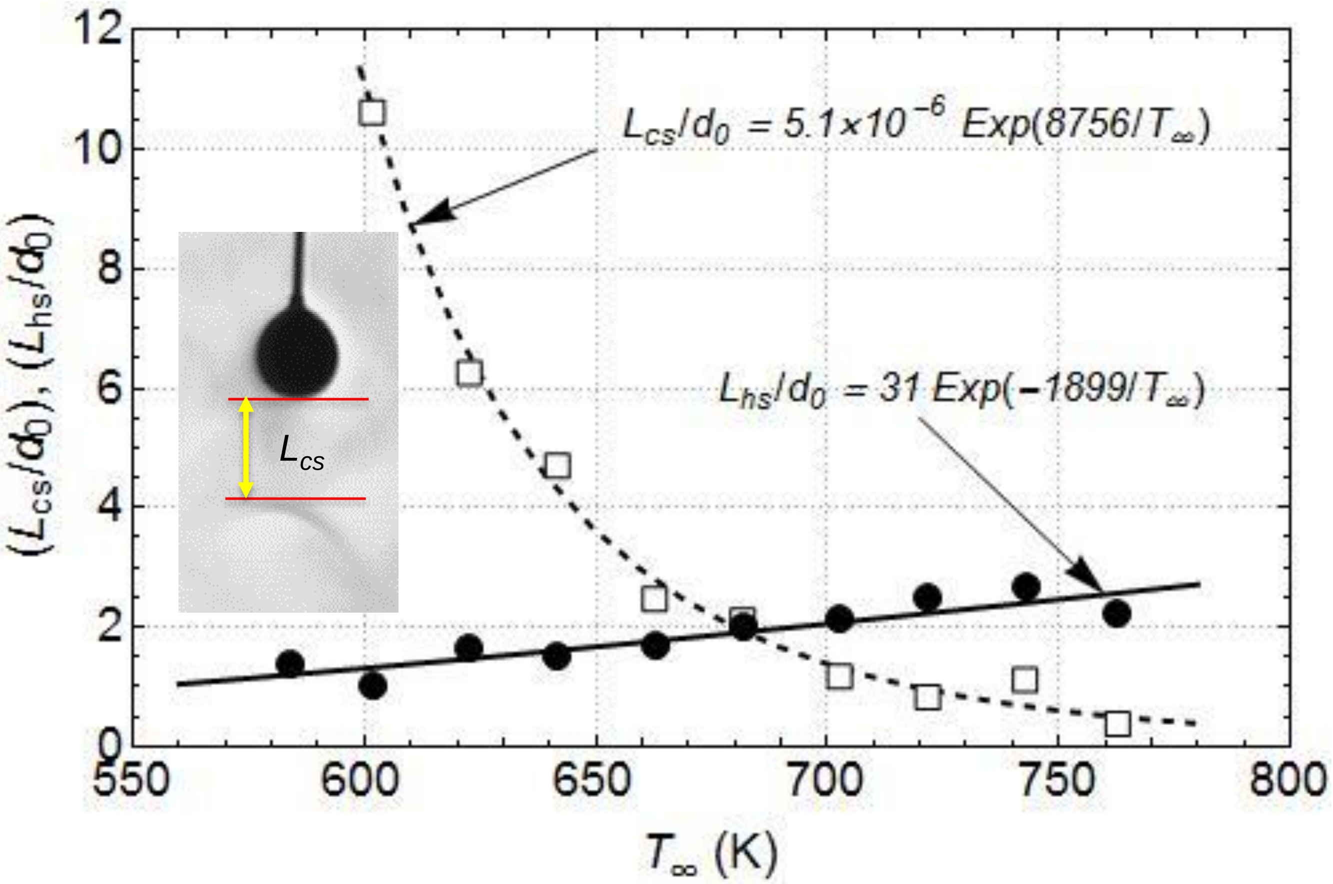
CF&HF mode: (10 atm 600 K)





Cool and hot flame starting locations:

P = 3 atm and 584 K < T < 780 K



Cool flame forms closer to the droplet as
The temperature is increased

$L_{cs} \sim U\,t_c$; $t_c \sim t_1$

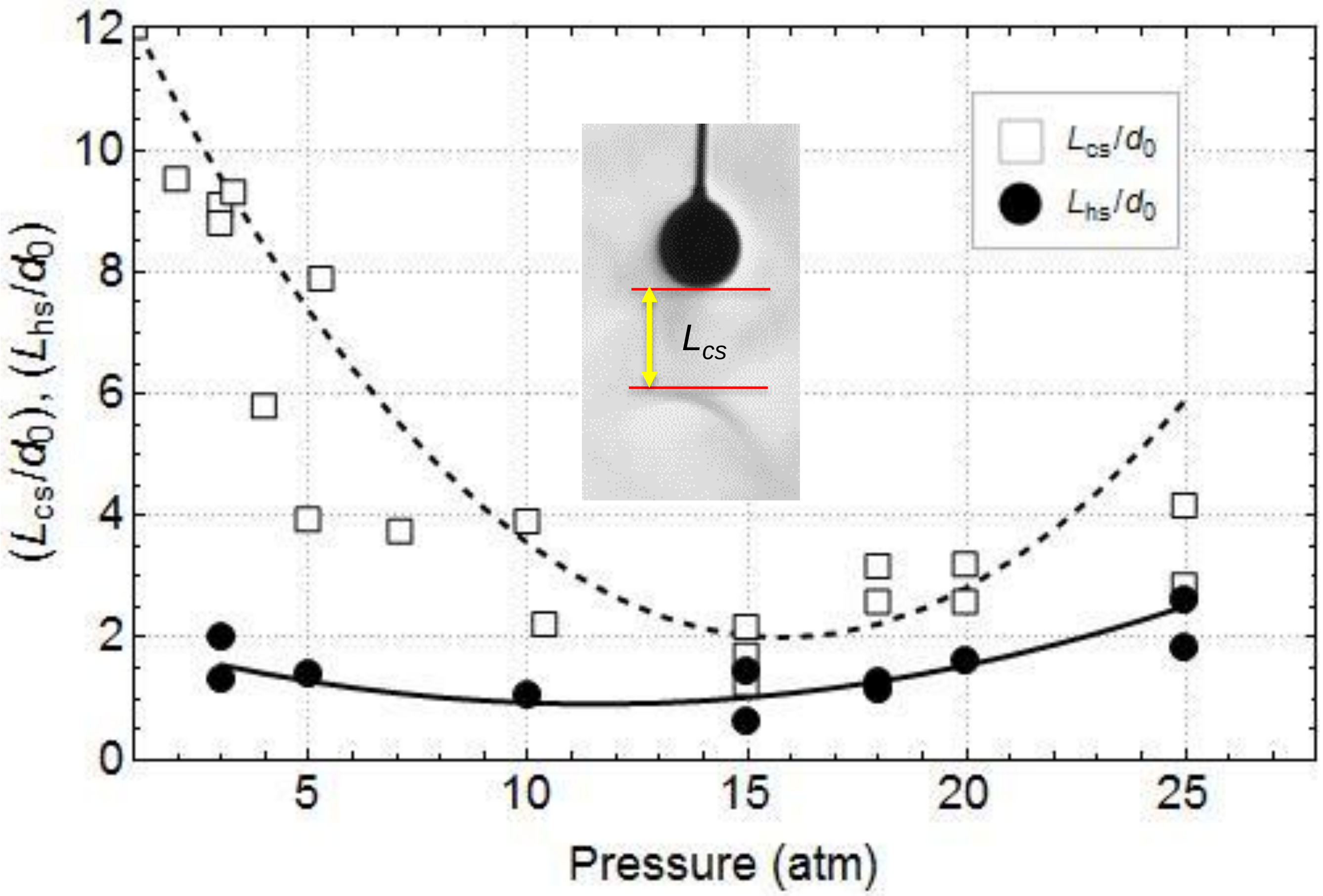
$E_c \sim 17.4$ kcal/mole
Compared to 28 kcal/mole for homogeneous mixture. Physical delay is important

L_{hs} – controlled by second induction time

$E_h \sim -4$ kcal/mole
t_2 increase with T in the NTC region

Cool and hot flame starting locations:

T = 603 K;   2 atm < P < 25 atm

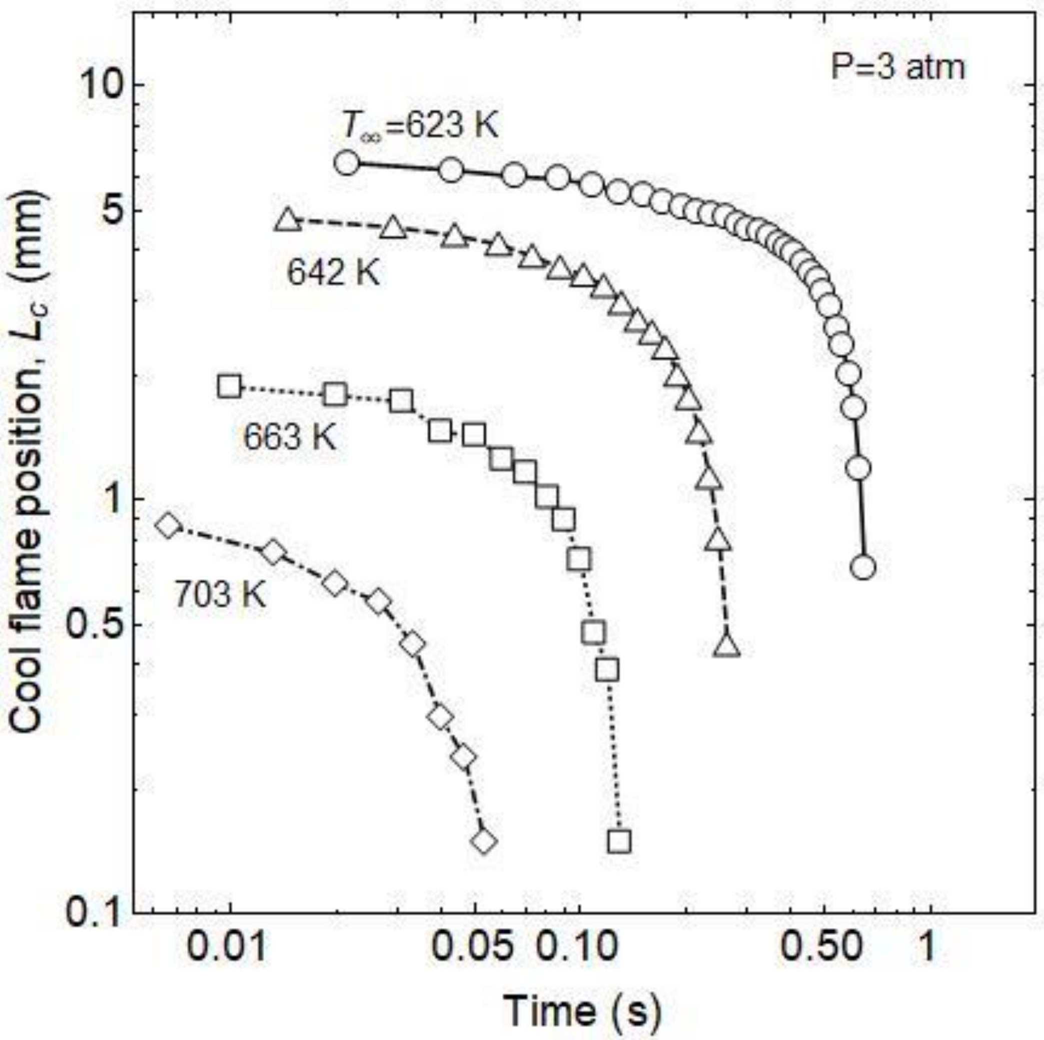


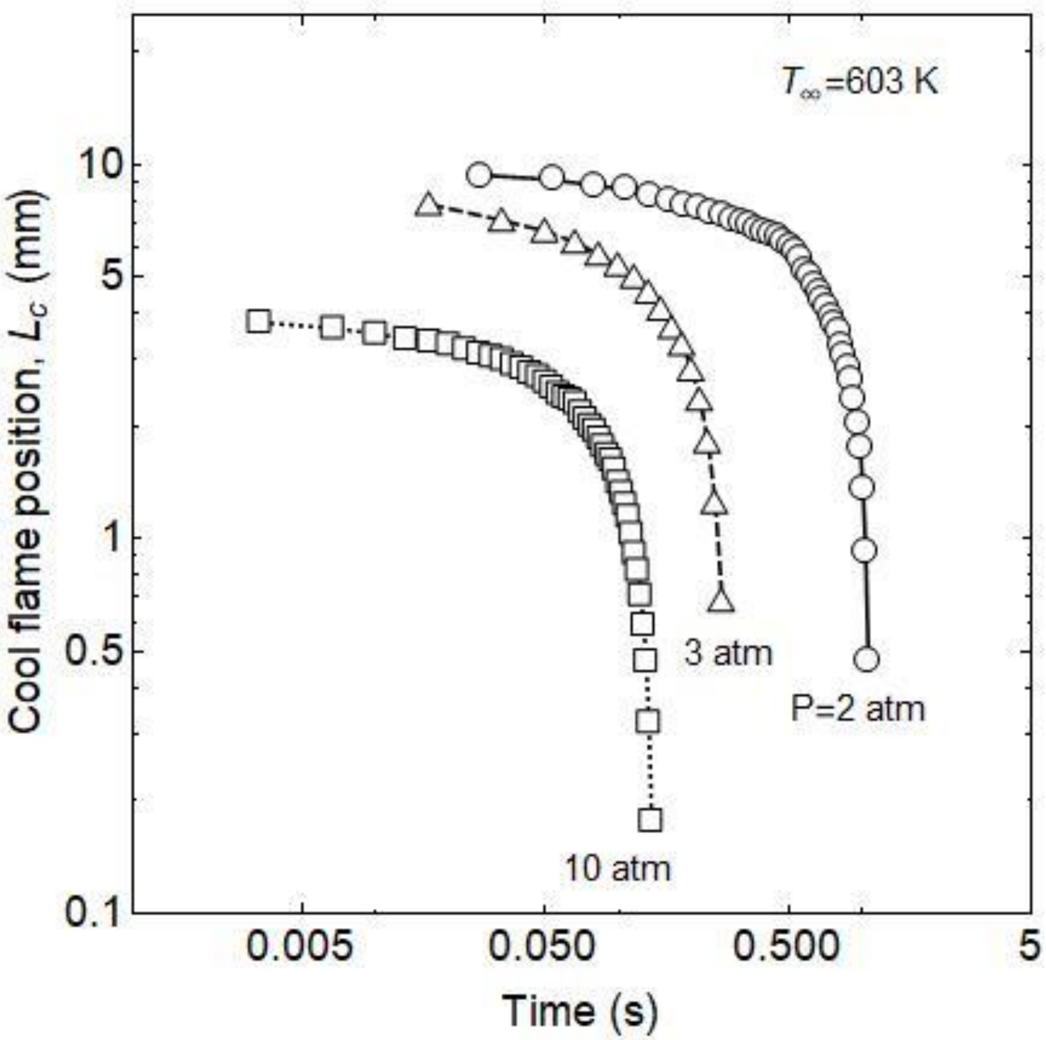
Non-Monotonic Pressure Dependence

Initial decrease in L_{cs} is caused by increased reactivity

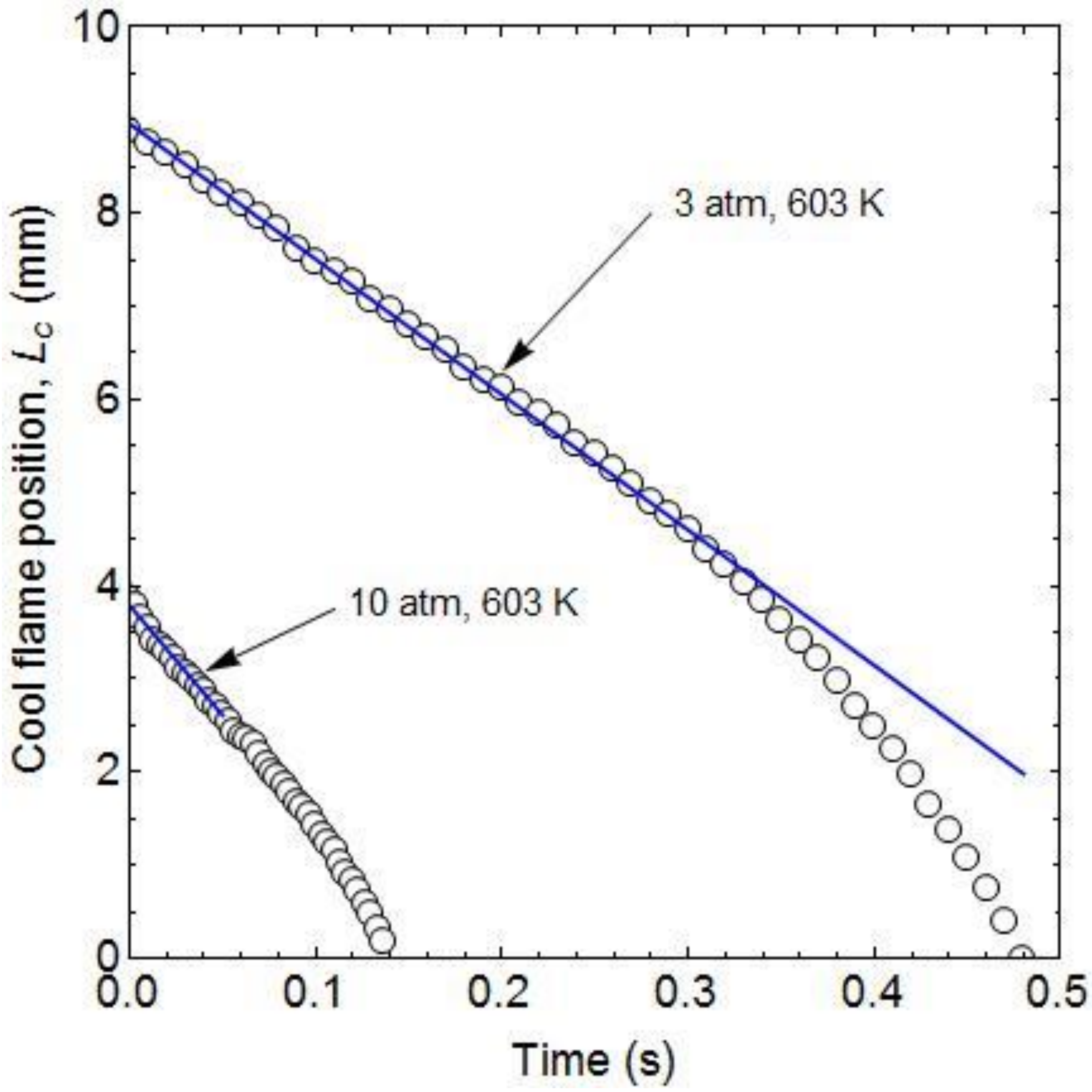
Buoyancy induced flow dominates above 15 atm (Gr – increases)

Cool-flame front position as function of time





Cool-flame speed



Initially a constant speed is observed

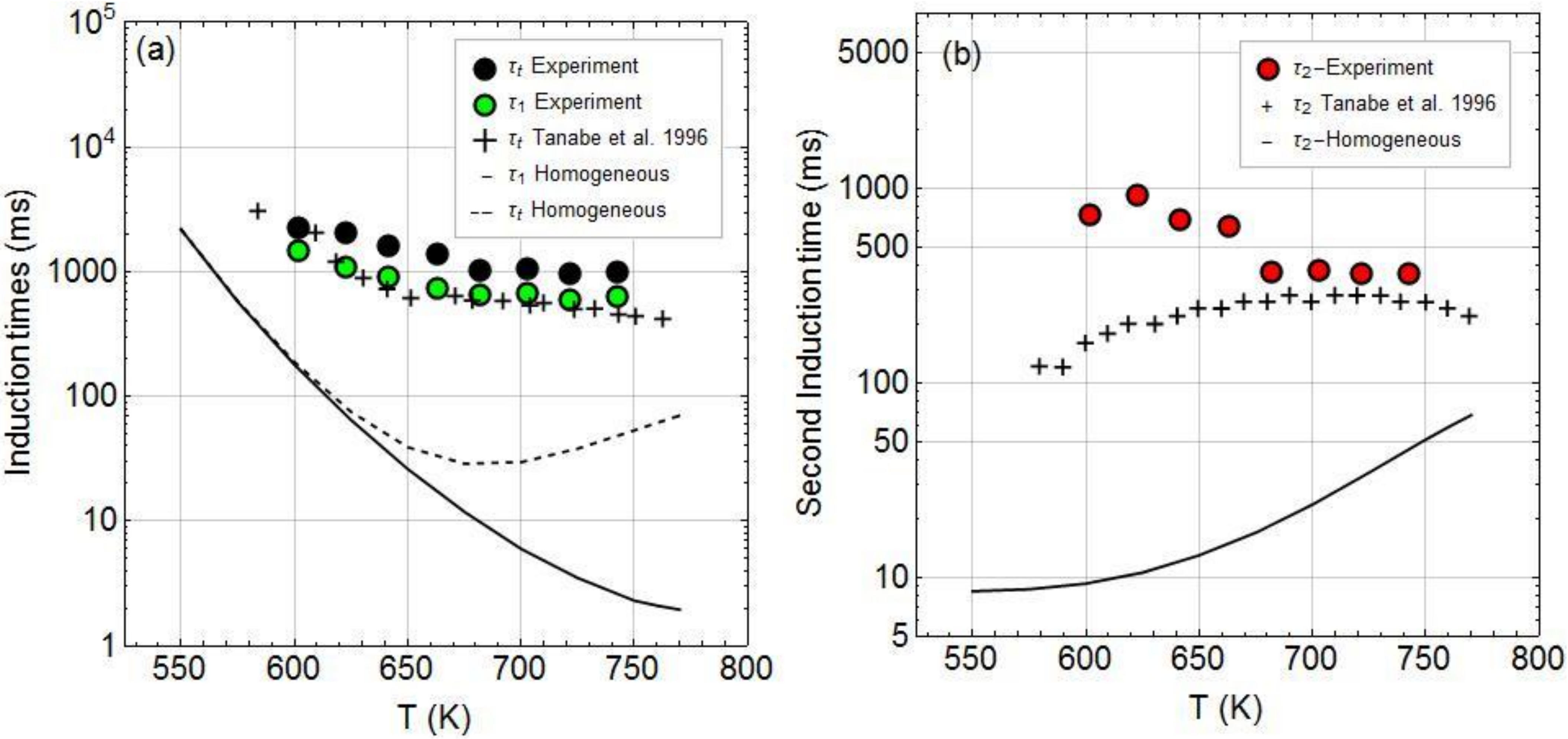
3 atm and 603K => 14.5 mm/s
10 atm and 603 K => 23.5 mm/s

Constant-speed duration decreases as ambient T or P is increased

Theories of cool-flame propagation are needed

Induction times

P = 3 atm and 584 K < T < 780 K



Induction times

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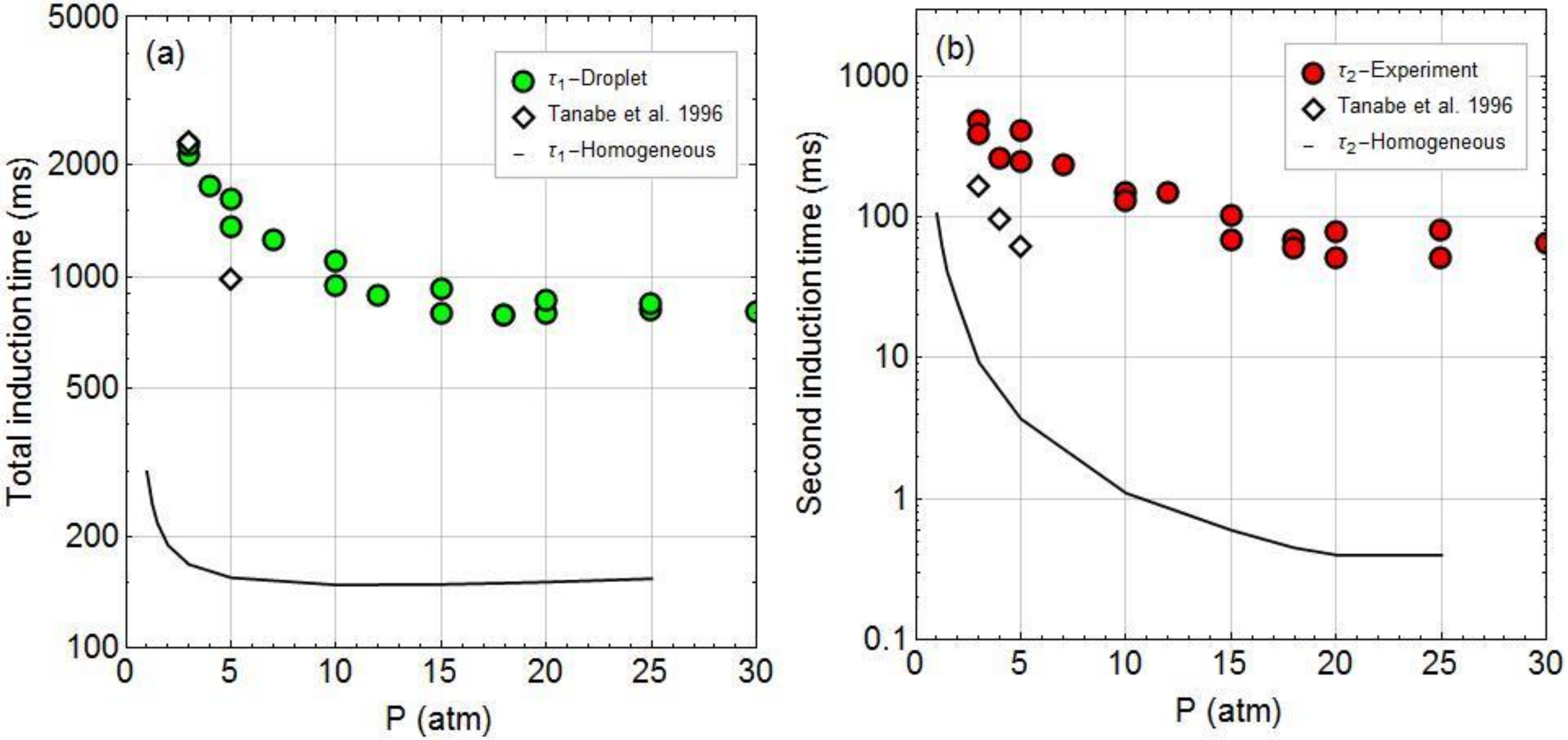

Physical Delays Dominant at High Pressures and at Low Temperatures.

Conclusions and Future Work

- Ignition dynamics at normal gravity are much more complex than in microgravity because of the downward moving buoyant plume.
- Physical ignition delays are most important for the first-stage at high temperatures and low pressures, and for the Second Stage at low temperatures and high pressures.
- Quasi-steady Cool-Flame Propagation appears to occur in these experiments at measurable velocities of a few centimeters per second, calling for calculations to be made for comparison.
- Diffusion and heat conduction around the droplet cause subcritical conditions to persist at supercritical pressures and temperatures.

Questions?