The effect of reduced pressure on the characteristics of spreading flames

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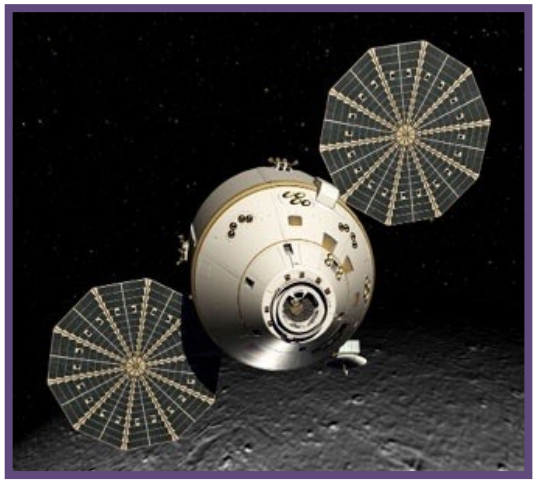
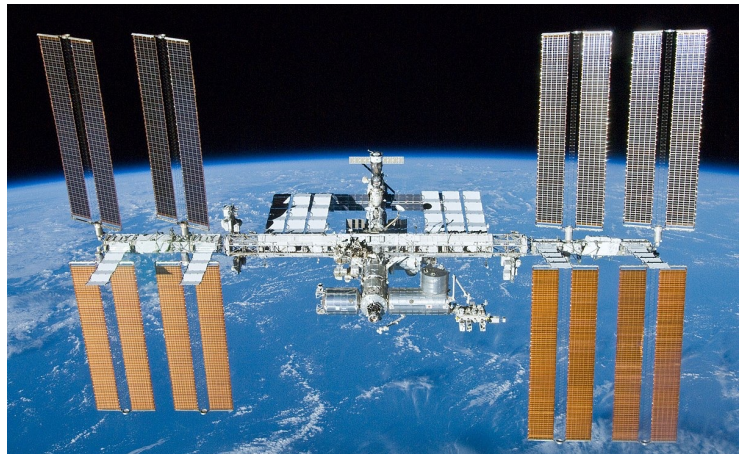
Understanding flame spread in different conditions

- Improve safety procedures, especially in enclosed habitats

- NASA's interest for future space exploration vehicles:
  - low pressure, increased oxygen
  - low velocity flows
  - different gravity levels



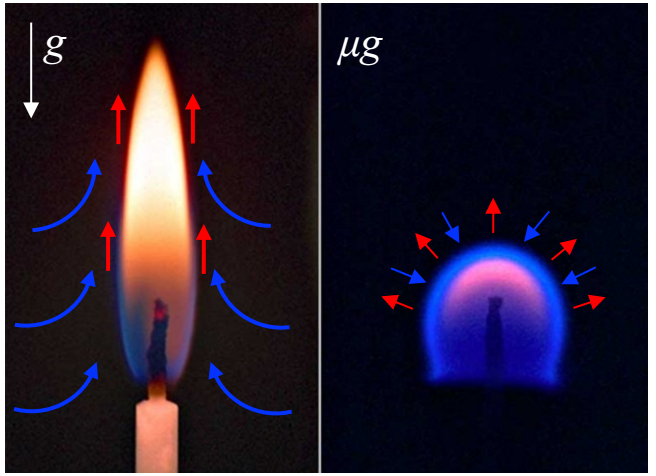
- These environmental conditions affect flame spread and material flammability, and can lead to unexpected events

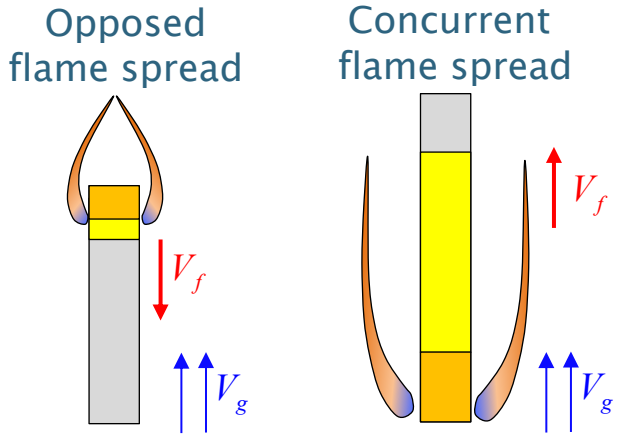


- Testing real fire scenarios in space is not always feasible

Can we mimic low gravity flames by reducing pressure?

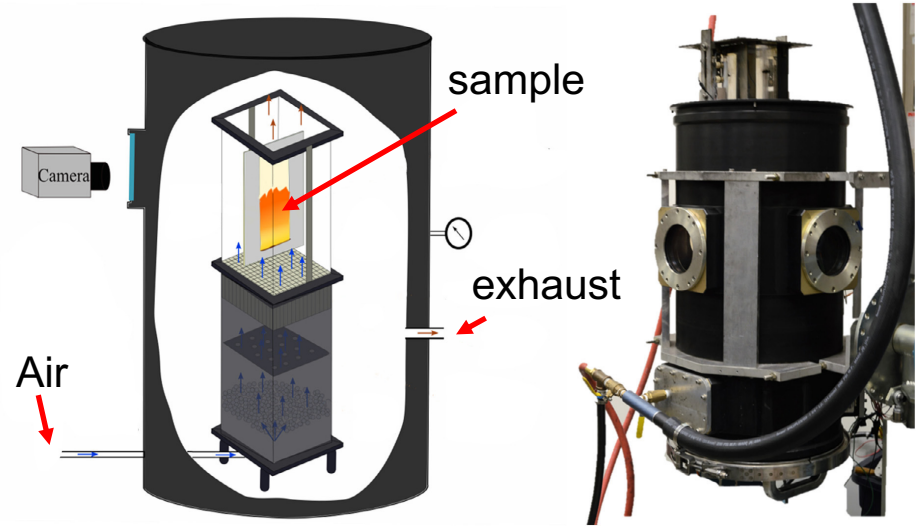
- Sub-atmospheric pressures offer an alternative to reduced gravity
- Reduced buoyancy in partial gravity, implications on heat and mass transfer mechanisms
- How does low pressure affect flame characteristics and spread?
- Two flame spread configurations

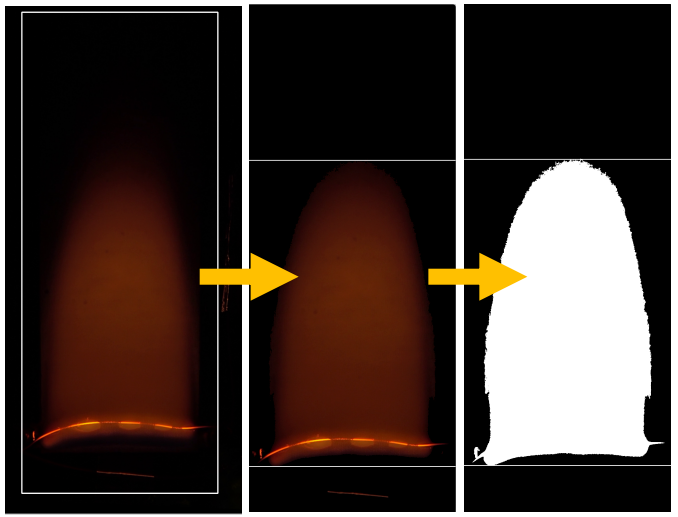




Experimental parameters

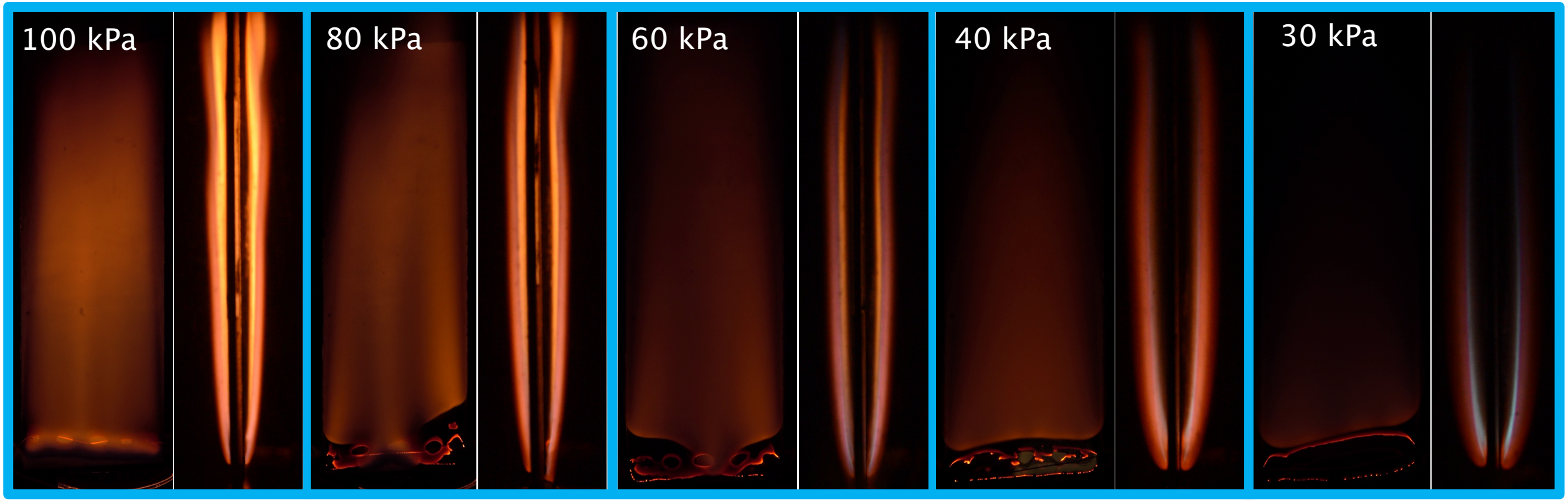
- Thin cotton samples (5x15 cm)
- Ambient pressure: 30–100 kPa
- Forced velocity (upward): 20 cm/s
- Front and side view cameras
- Videos processed with Flame Tracker*





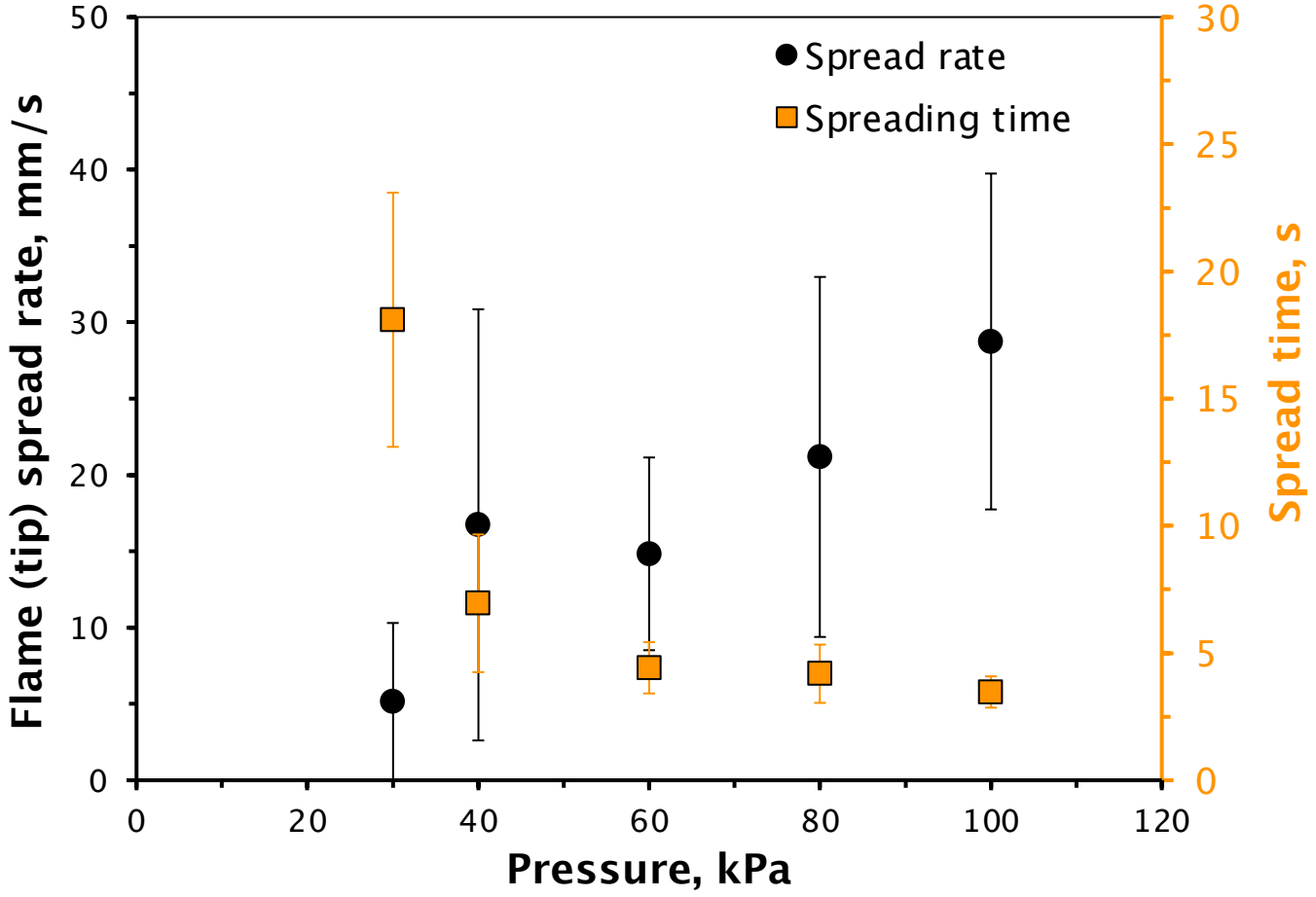
* https://github.com/combustionTools/flameTracker

Experimental results: Concurrent flame spread

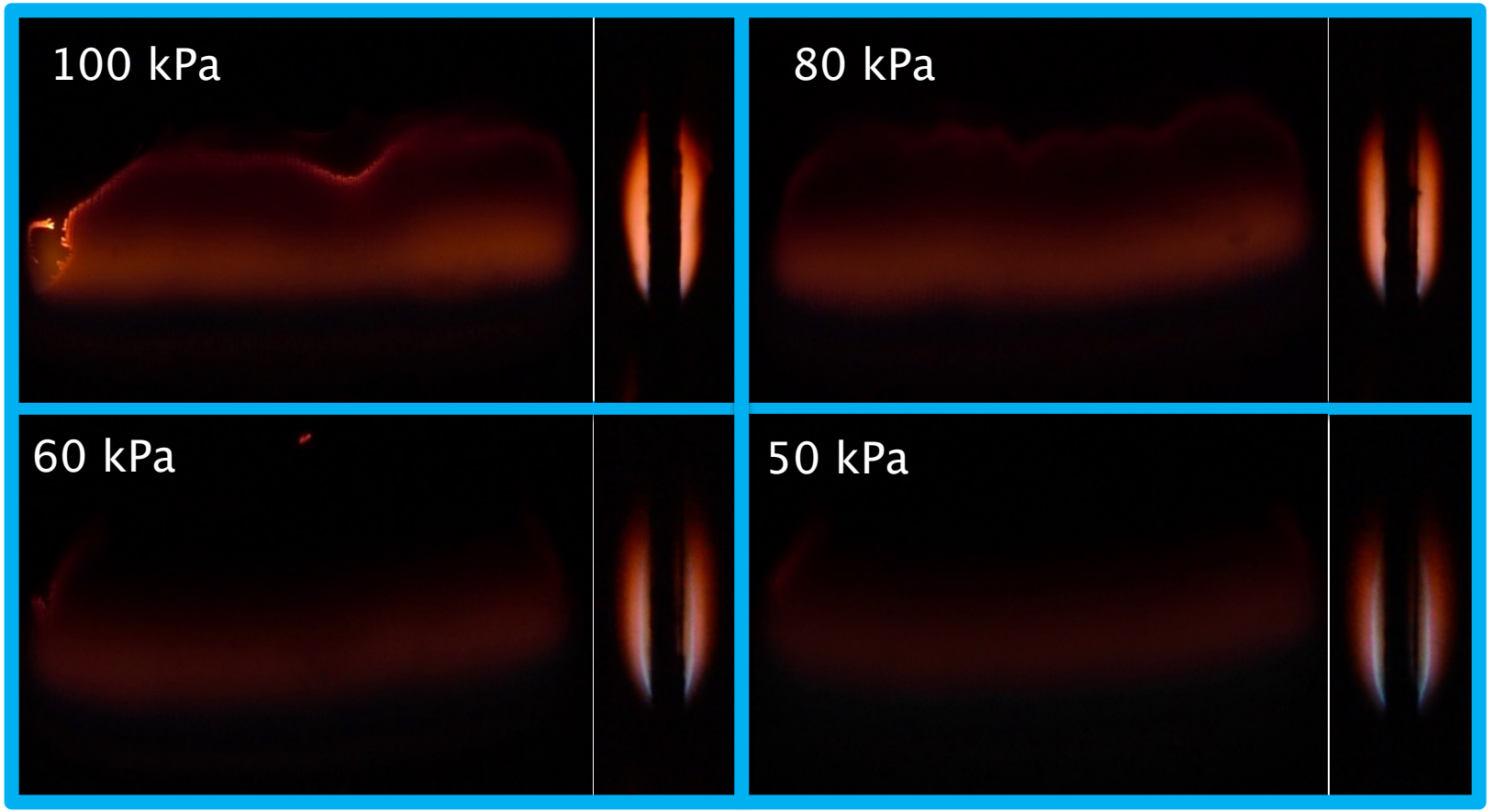


Experimental results: Concurrent flame spread

- These flames (and their spread rates), initially grow in time
- Instantaneous spread rates averaged over spread time
- Large increase of spread time (and slower ignition) at low pressures

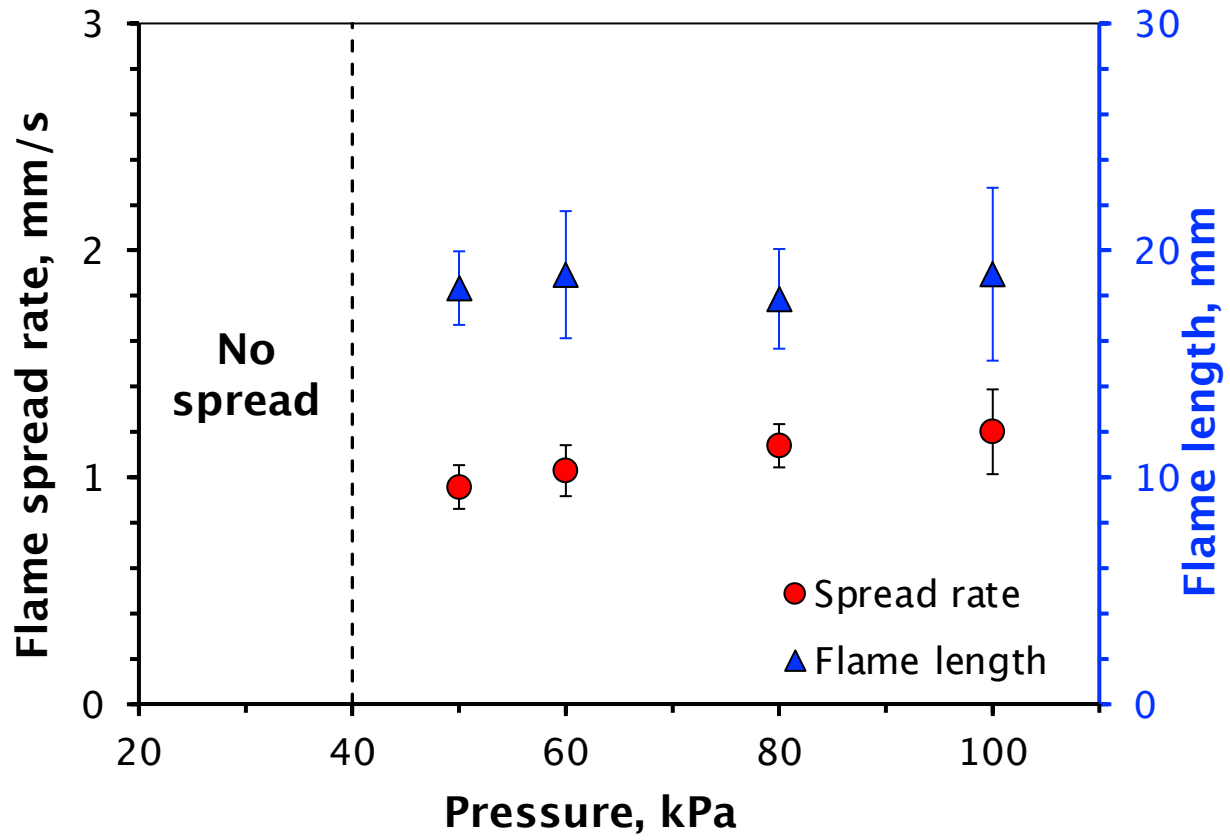


Experimental results: Opposed flame spread



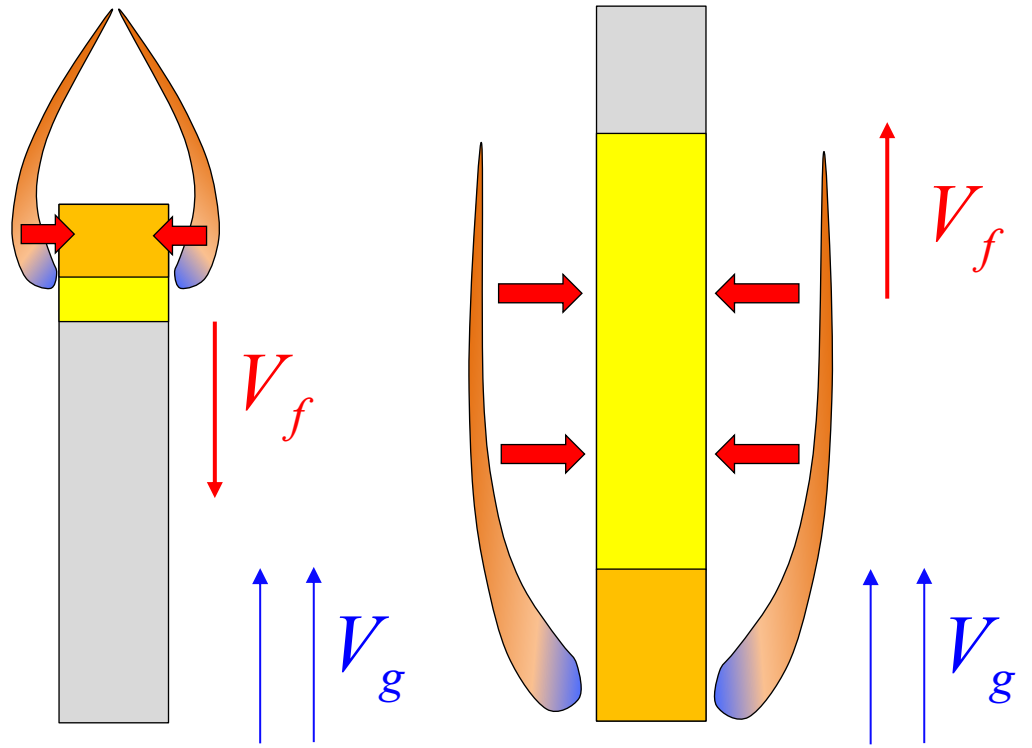
Experimental results: Opposed flame spread

- Steady-state conditions
- Low decrease of V_f (~20%)
- No spread at p ≤ 40 kPa
- Flame length did not vary with pressure



Experimental results: Flame standoff distance

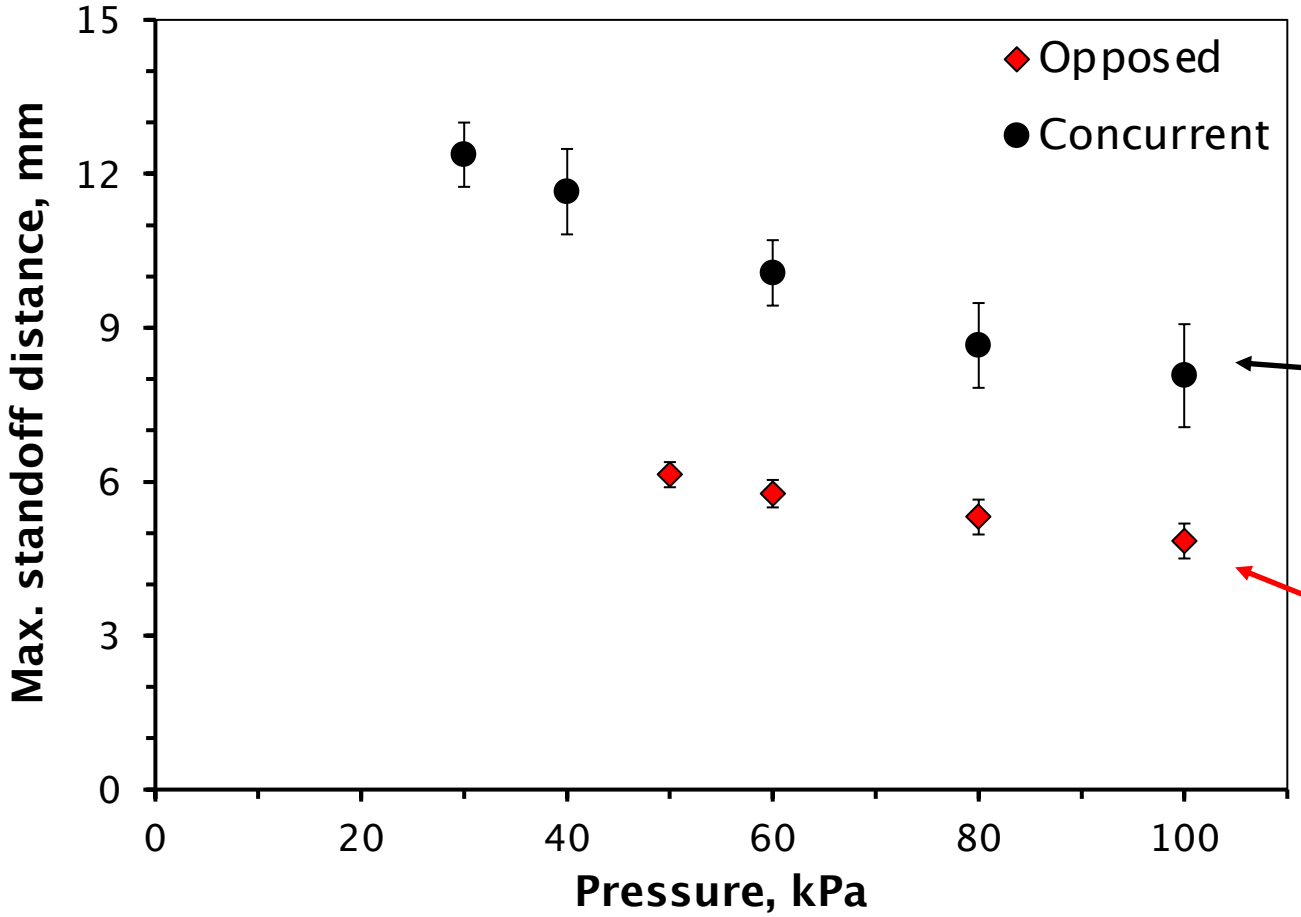
- Distance between flame and fuel surface
- Controls heat transfer to the solid fuel
- Importance depending on flame spread configuration
- Affected by flow field around the flame

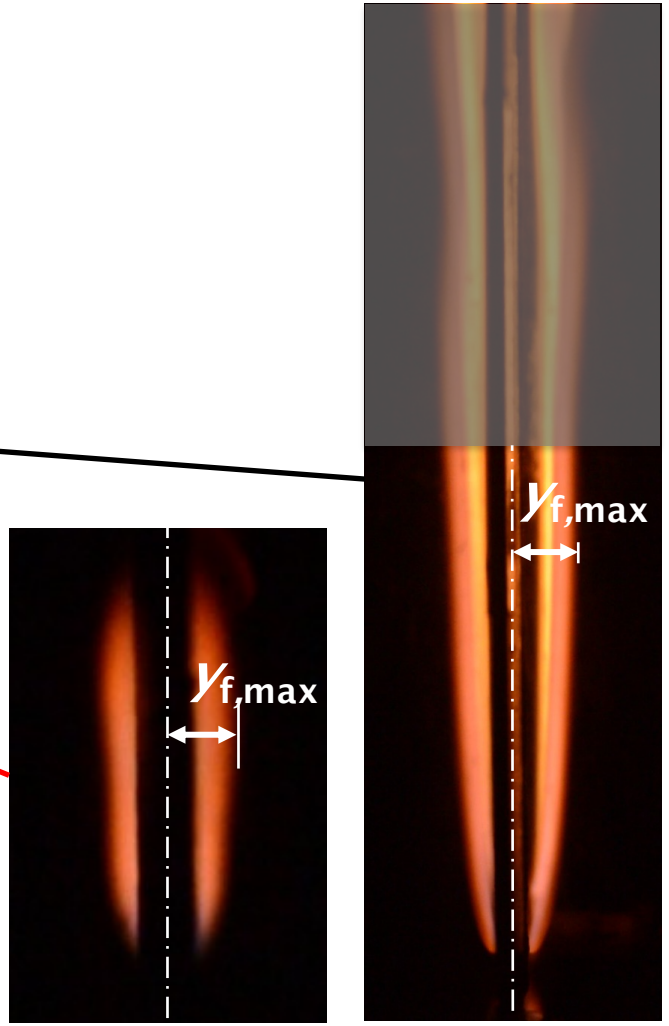


Opposed flame spread

Concurrent flame spread

Experimental results: Flame standoff distance





Standoff distance (mixed flow)

- The flow facing the flames has a forced and a natural components (mixed flow)
- From previous studies, the standoff distance can be expressed as [1–3]:

$$y_f = \left(\mathrm{Re}^4 + \mathrm{Gr}^2\right)^{-1/8} x \int_0^{\eta_f} \left[1 + \theta\left(\frac{T_w}{T_\infty} - 1\right)\right] d\eta$$

Where θ = non-dimensional temperature, x = local coordinate along the fuel, and:

$$\mathrm{Re} = \frac{V_g x}{\nu} \;;\; \mathrm{Gr} = \frac{g\beta\Delta T x^3}{\nu^2}$$

[1] A.C. Fernandez-Pello, “A Theoretical Model for the Upward Laminar Spread of Flames Over Vertical Fuel Surfaces," *Combustion and Flame*, **31**, 135-148, 1978.
[2] A.C. Fernandez-Pello, "Flame Spread in a Forward Forced Flow," *Combustion and Flame*, **36**, 63-78, 1979.
[3] C.P. Mao, A. C. Fernandez-Pello, and P.J. Pagni, "Mixed Convective Burning of a Fuel Surface with Arbitrary Inclination," *Journal of Heat Transfer*, **106**, 2, 304-309, 1984

Standoff distance (mixed flow)

If we neglect the integral term (order of 1), and assume x = constant = L :

$$y_f = \left(\mathrm{Re}^4 + \mathrm{Gr}^2\right)^{-1/8} x \int_0^{\eta_f} \left[1 + \theta\left(\frac{T_w}{T_\infty} - 1\right)\right] d\eta \longrightarrow \boxed{y_f \sim \left(\mathrm{Re}^4 + \mathrm{Gr}^2\right)^{-1/8} L}$$

Buoyant flow driven by density difference between flame and surroundings:

$$\mathrm{Gr} = \frac{g\rho\Delta\rho\, L^3}{\mu^2}\,; \quad \text{where} \quad \rho\Delta\rho = \rho_\infty\left(\rho_\infty - \rho_f\right)$$

Standoff distance: Pressure dependence

Re and Gr depend on the ambient density (and pressure):

$$\mathrm{Gr} = \frac{g\rho\Delta\rho L^3}{\mu^2} \longrightarrow \rho\Delta\rho = \rho_\infty\left(\rho_\infty - \rho_f\right) \propto p_\infty^2 \quad \left(\text{with } \frac{\rho_\infty}{\rho_f} \gg 1\right)$$

$$\mathrm{Re} = \frac{\rho V_g L}{\mu} \propto p_\infty$$

The dependence of standoff distance on pressure becomes:

$$y_f \sim \left(\mathrm{Re}^4 + \mathrm{Gr}^2\right)^{-1/8} L \longrightarrow \boxed{y_f \propto p_\infty^{-0.5}}$$

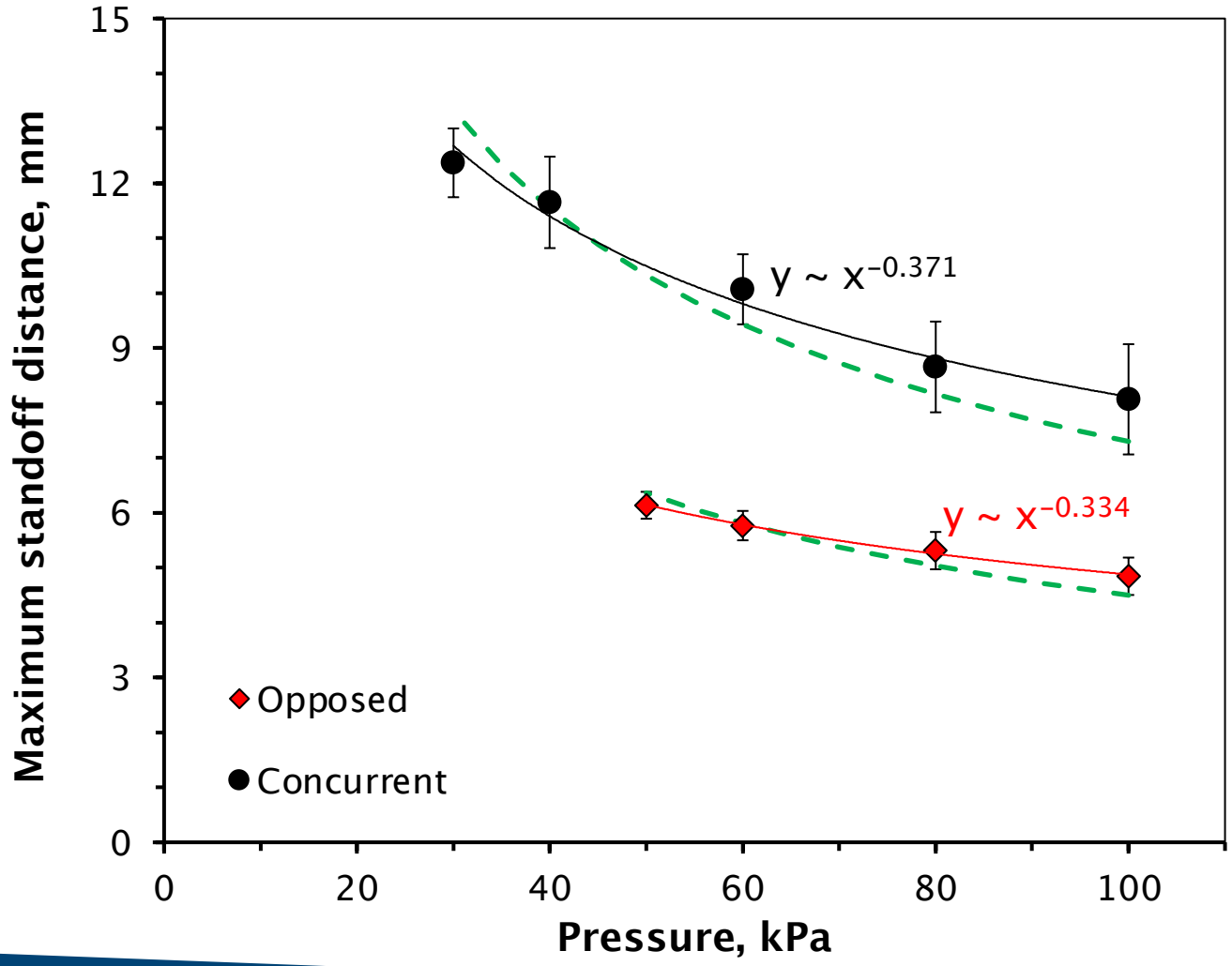
Standoff distance: Pressure dependence

From the experiments:

- Opposed: $y_f \propto p_\infty^{-0.334}$
- Concurrent: $y_f \propto p_\infty^{-0.371}$

From the scale analysis:

$$y_f \propto p_\infty^{-0.5}$$



Importance of the length scale

By using the pyrolysis length L_p as the scale of the problem:

$$y_f \sim \left(\mathrm{Re}^4 + \mathrm{Gr}^2\right)^{-1/8} L \longrightarrow \boxed{y_f \sim \left(\frac{L_p \mu_\infty}{\rho_\infty}\right)^{1/2} \left(V_g^4 + g^2 L_p^2 \frac{\Delta\rho^2}{\rho_\infty^2}\right)^{-1/8}}$$

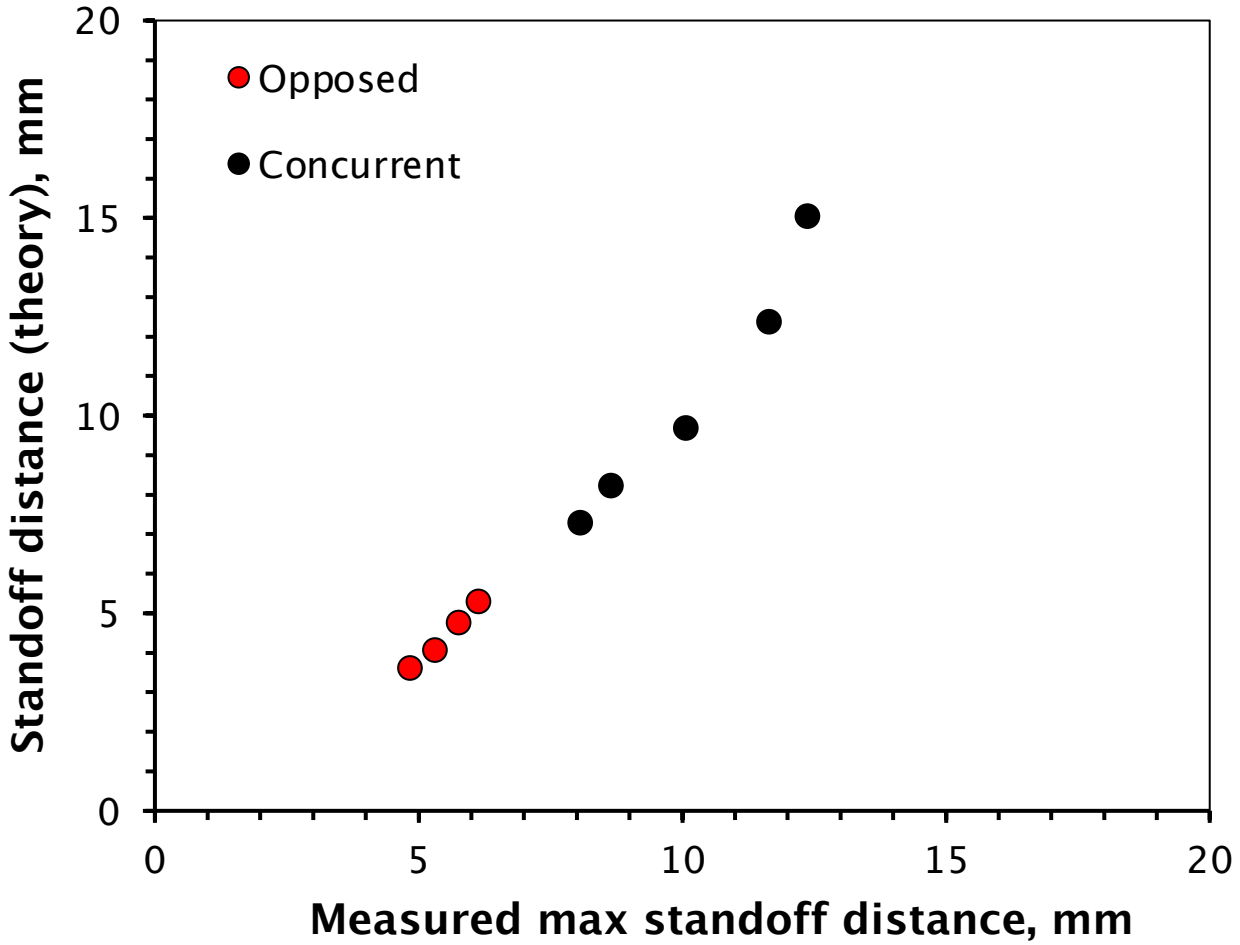
The *constant* length scale L_p depends on the spreading configuration:

- Opposed flame spread: $L_p \sim 10\,\mathrm{mm}$
- Concurrent flame spread: $L_p \sim 150\,\mathrm{mm}$

Opposed and Concurrent comparison

$$y_f = 5 \cdot \left(\frac{L_p \mu_\infty}{\rho_\infty}\right)^{1/2} \left(V_g^4 + g^2 L_p^2 \frac{\Delta\rho^2}{\rho_\infty^2}\right)^{-1/8}$$

- T_∞=300 K, T_f= 2100 K
- $L_{p,\mathrm{opp}}$ = 10 mm, $L_{p,\mathrm{con}}$ = 150 mm
- Multiplication factor of 5



Discussion

- Pressure reductions slow down the flames, and make them less bright and ”thicker” (reaction zone)
- Anomaly of blue region moving towards fuel surface at low pressures
- Theoretical dependence of flame standoff distance $y_f \propto p_\infty^{-0.5}$ close to experimental values. Differences could be due to measurement errors or additional pressure dependence of the length scale
- The standoff distance for opposed flame spread follows the same trend as for concurrent flame spread by varying ambient pressure

Acknowledgments

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Thank you for your attention!!