UCI Liquid-Film Miniature Combustor

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There is an interest in portable power systems:

Length scale – 1-10 cm (maybe 20 cm with fuel tank)

Power level – 100 watts - 1 kilowatt

Weight – 60 grams – 6 kilograms

Operational period – 1-10 hours

Overview

- Role for Miniature Combustor in
  Portable-power Opportunities
- Film Combustor Concept, Use of Swirl
- UCI Experimental Work
- UCI Theoretical Work
- Use of Secondary Air
- Use of Swirl Vanes
- Concluding Remarks


New power sources are needed to energize autonomous technologies
Portable Power Systems
power
personal microclimates
portable air reconnaissance
artificial organs
personal rob
pervasive computing and communication
ASIMO
HONDA
MITSUBISHI

Power Scales

- 10000 W – riding lawnmower ~ elephant

- 1000 W – microwave oven ~ horse

- 100 W – light bulb ~ human
- 10 W – small laptop ~ bat

Portable Power

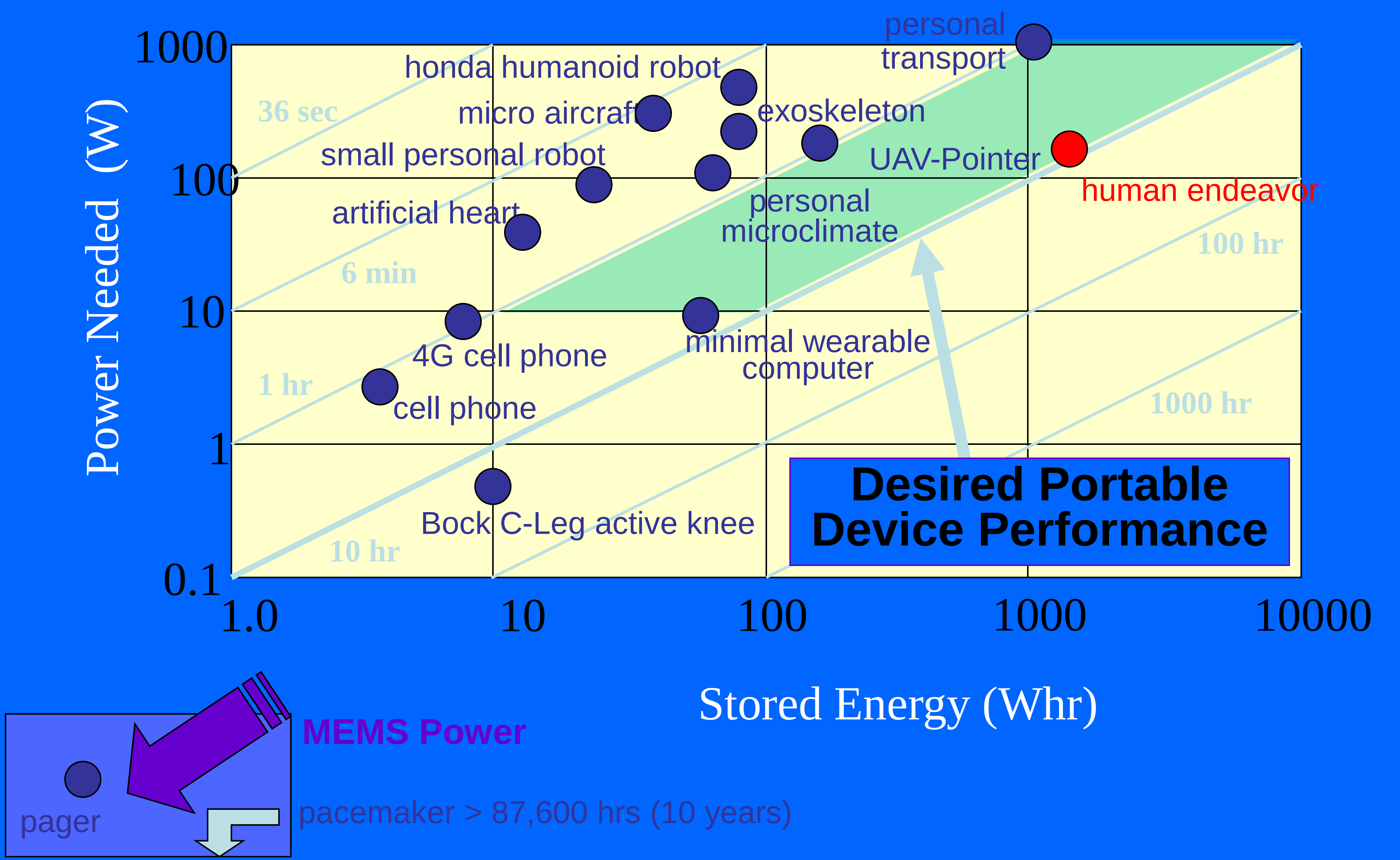
- 1 W – cell phone ~ hummingbird

- 10 mW – pager ~ blowfly

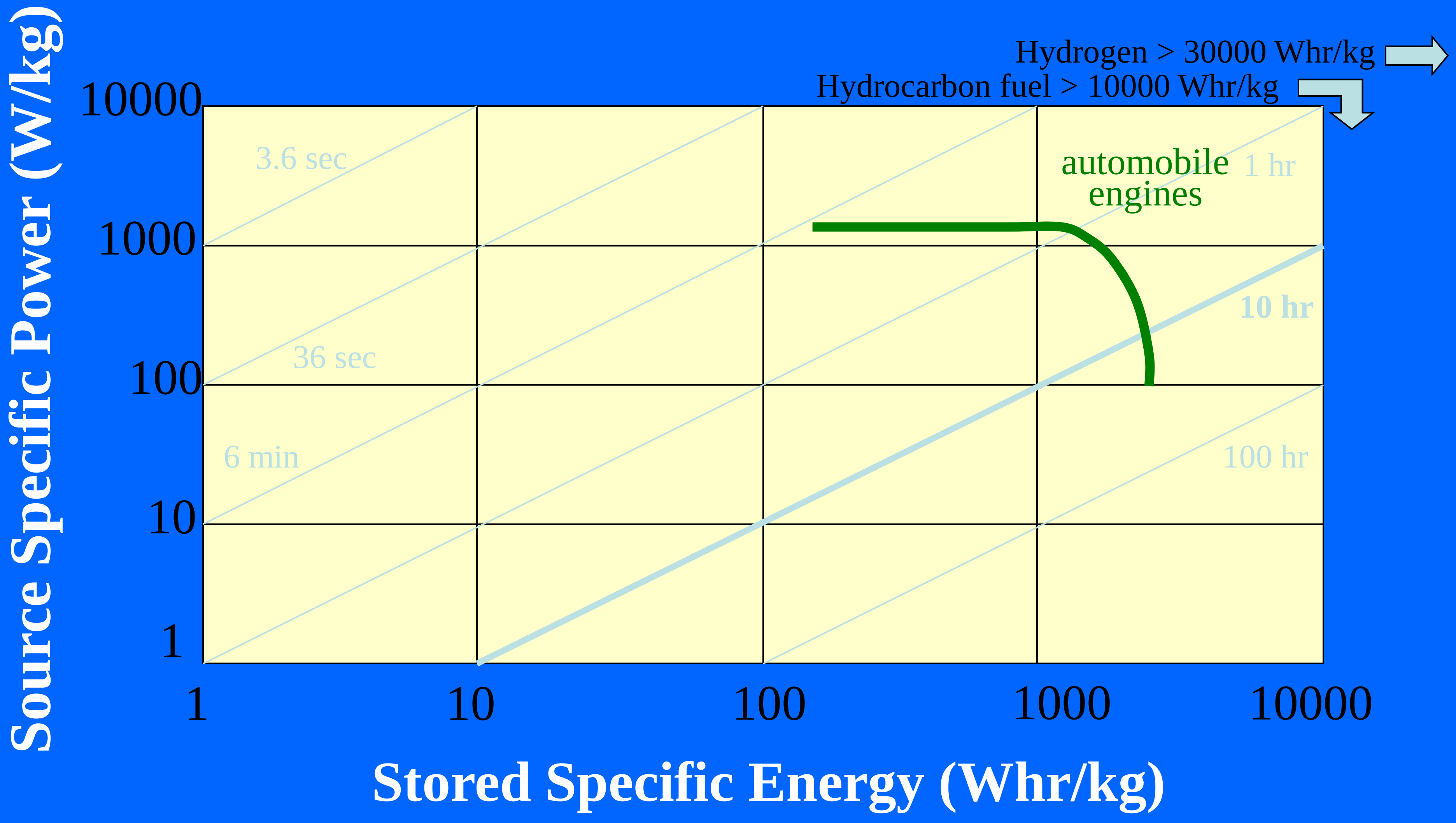
- 10 μW – pacemaker ~ fruit fly

images are not to scale

Power and Energy Performance: Current Portable Devices

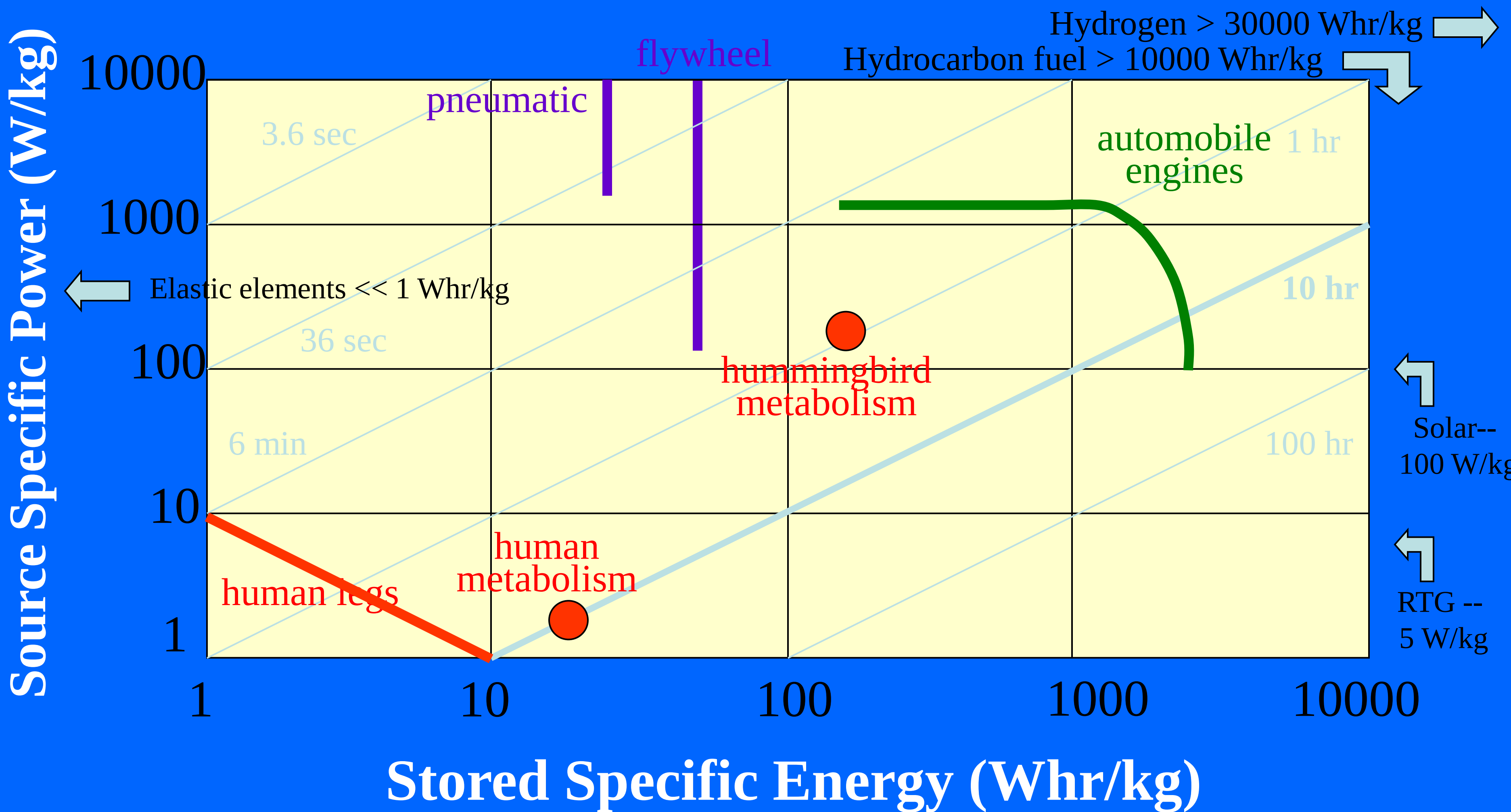


Mass Specific Power and Energy



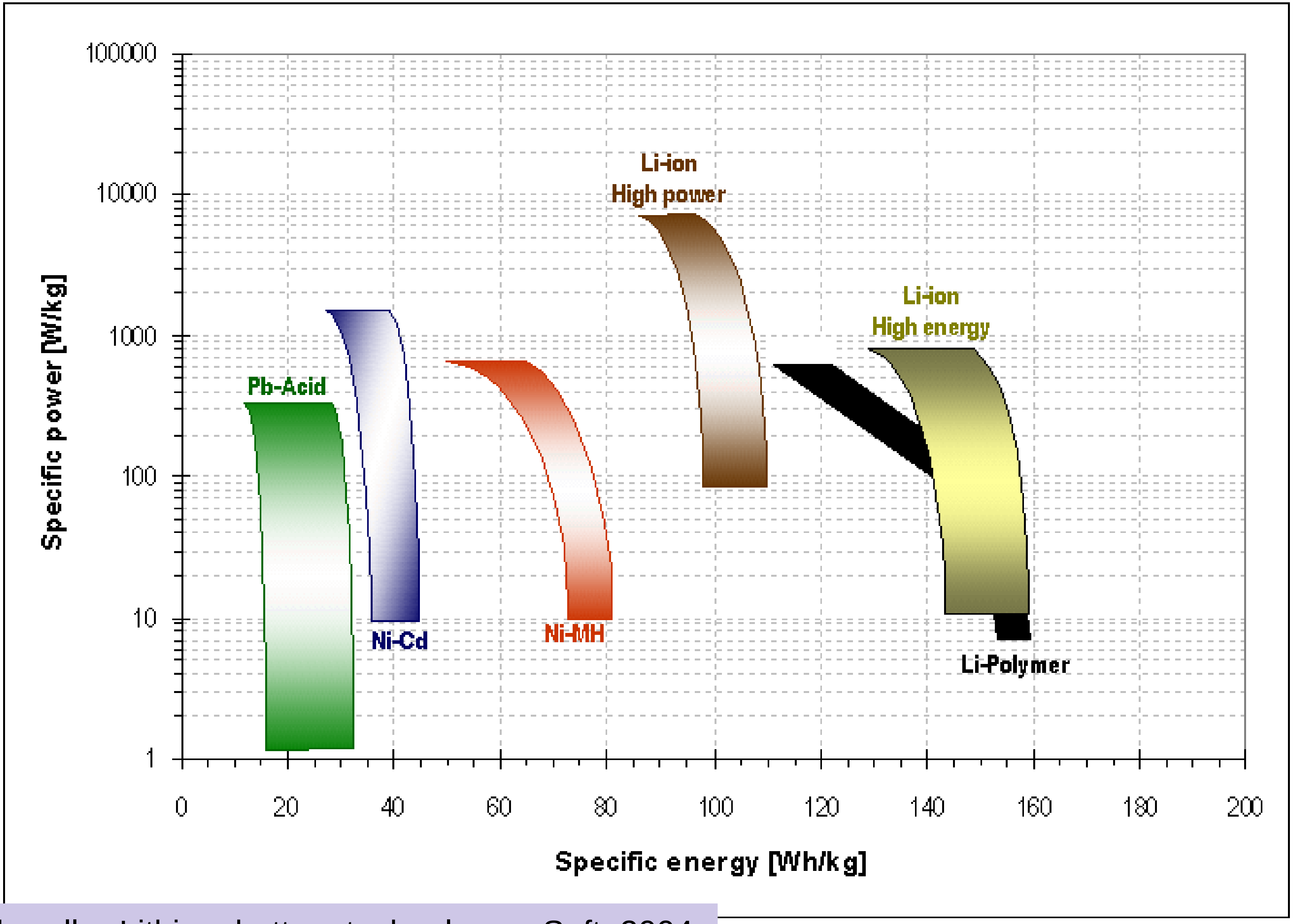
Ragone Plot

Potential Power Sources



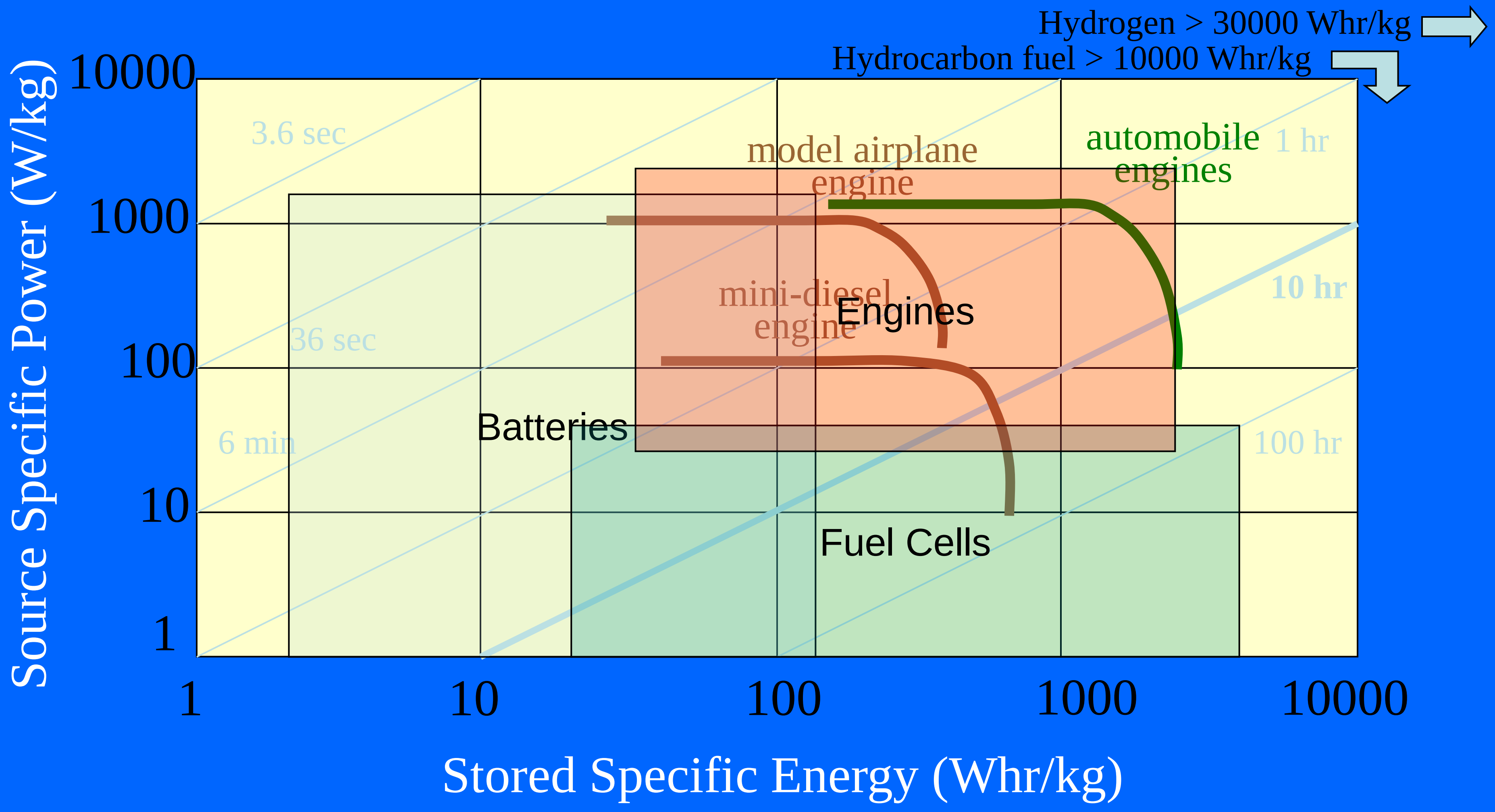
What about batteries and fuel cells?

Battery Ragone Plot



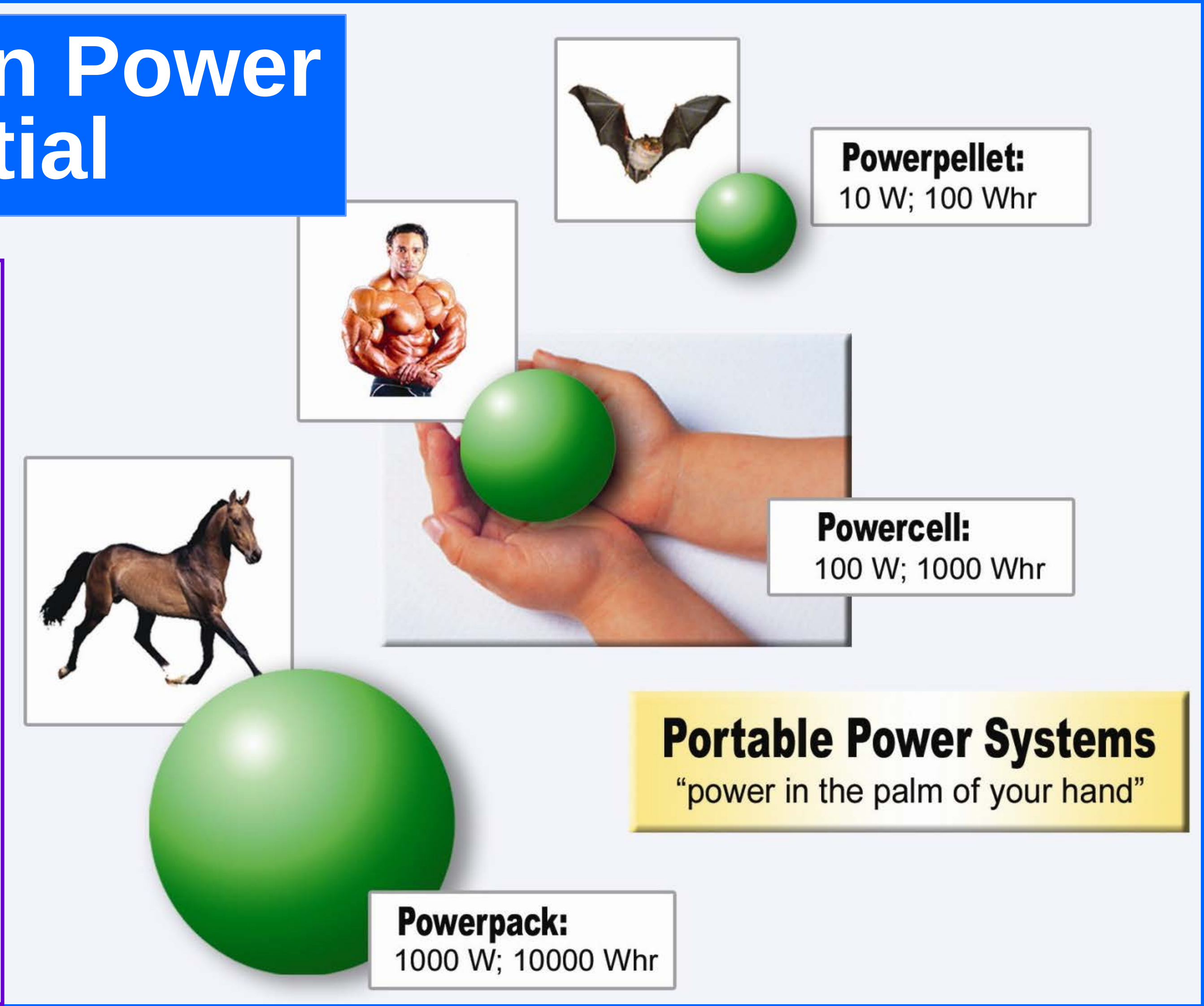
J. Mcdowall -- Lithium battery technology – Saft, 2004

Sources of Power



Combustion Power Potential

- Assumptions
  - 15% fuel/energy conversion efficiency
  - Fuel specific energy equivalent to liquid hydrocarbons (13kWhr/kg)
  - Fuel occupies 66% of system
  - Combustion can generate 100 W/cc chamber volume



- Compact Size and Low Mass
  - 60 g -- 6 kg power source weight
  - 0.01 -- 0.10 m system length scale
  - 60 cc -- 6 liter volume

- High Power and Energy
  - 10 W -- 1000 W power output
  - 1 hr -- 10 hr operation
  - 600 -- 6000 Whr/kg specific energy

Miniature Combustion Systems

- Volumetric heat release from liquid fuel will be necessary for highest power/mass ratios
- Combustion is extremely fuel tolerant
- Challenges include high surface-to-volume ratios (thermal issues, flame quenching, short residence times)
- Three miniature combustion approaches
  - Catalytic combustion
  - Fuel film combustors
  - Miniature IC engines

Film Combustion Concept

- Sprays traditionally used
- Increasing surface-to-volume ratio with decreasing combustor size lead to heat loss and quenching
- Liquid films provide adequate vaporization rates at small scales
- Films keep temperatures below fuel boiling temperature
- Liquid films are advantageous at small scales

Spray Combustion vs. Film Combustion

$$(S/V)_{drop} = 4\pi R^2 / (4\pi R^3 / 3) = 3 / R$$

$$(S/V)_{film} = \pi dL / (\pi dLt) = 1 / t$$

$$(S/V)_{film} / (S/V)_{drop} \sim (40 / 3) (\rho_l u_l / \rho_g u_g) R / d$$

As chamber diameter d decreases, film combustion gains advantage over droplet combustion in terms of total surface area

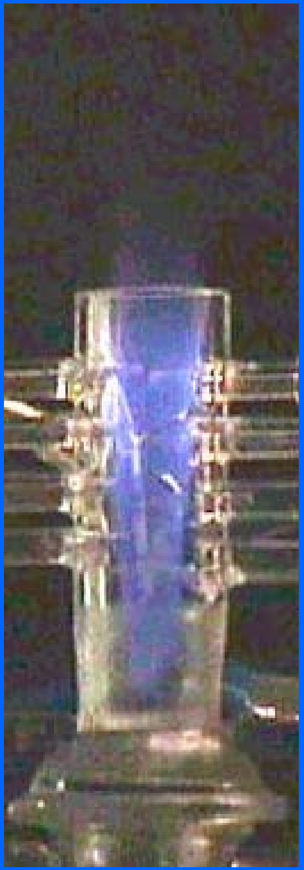
By considering laminar transport rates, the length of the film in the streamwise direction can be determined

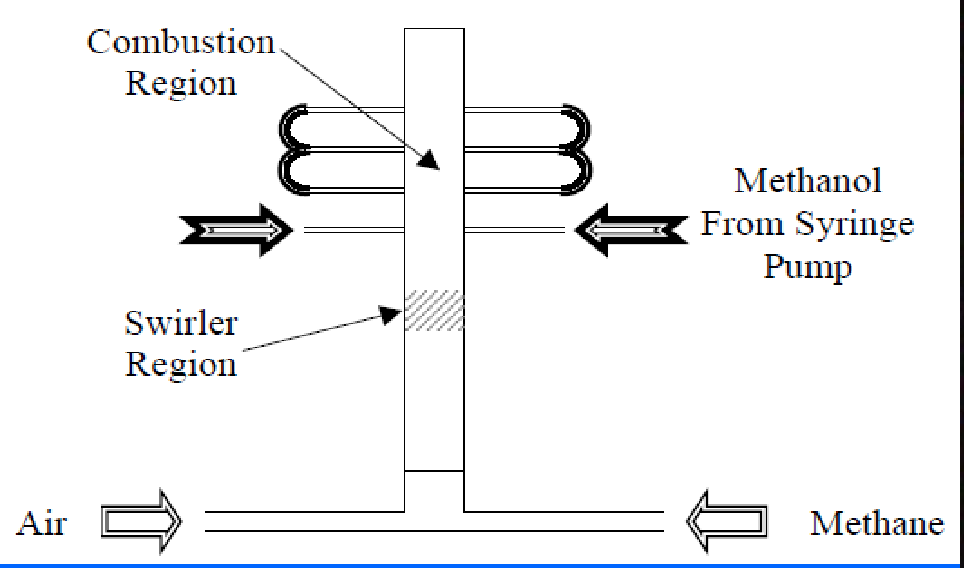
$$L / d \sim 10^{-3} Re_d$$

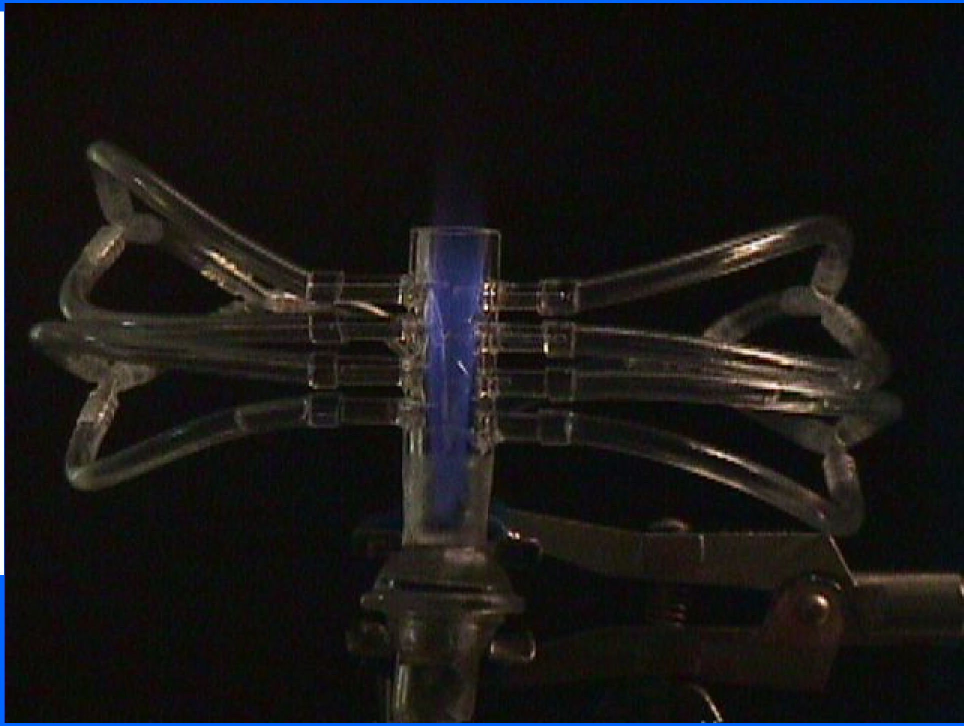
Proof of Concept

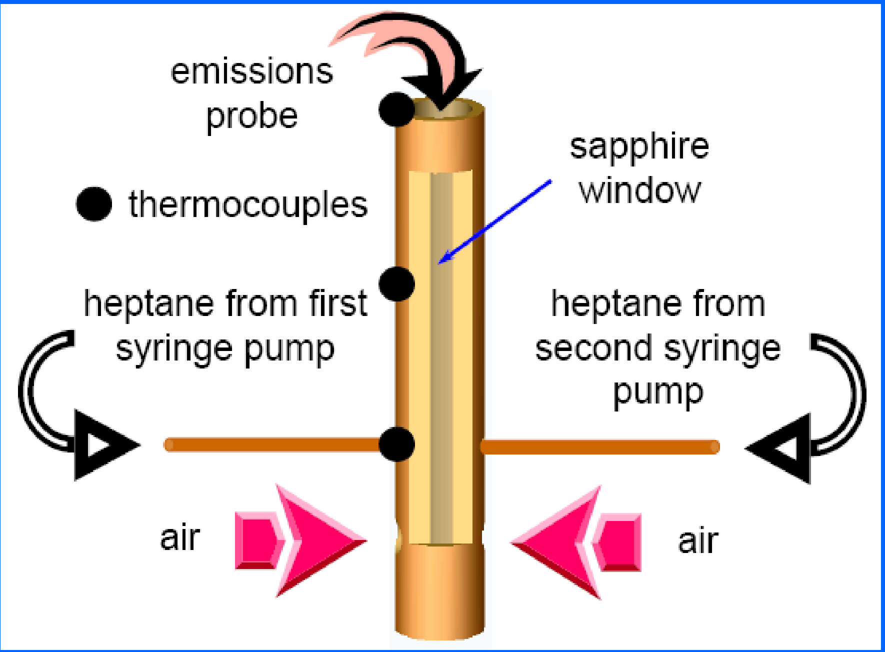
Liquid heptane or methanol injected tangentially with air injected through bottom swirl vanes. Internal flame is stable.

Methane gas and air injected at bottom through swirl vanes. Flame could not be stabilized internally.



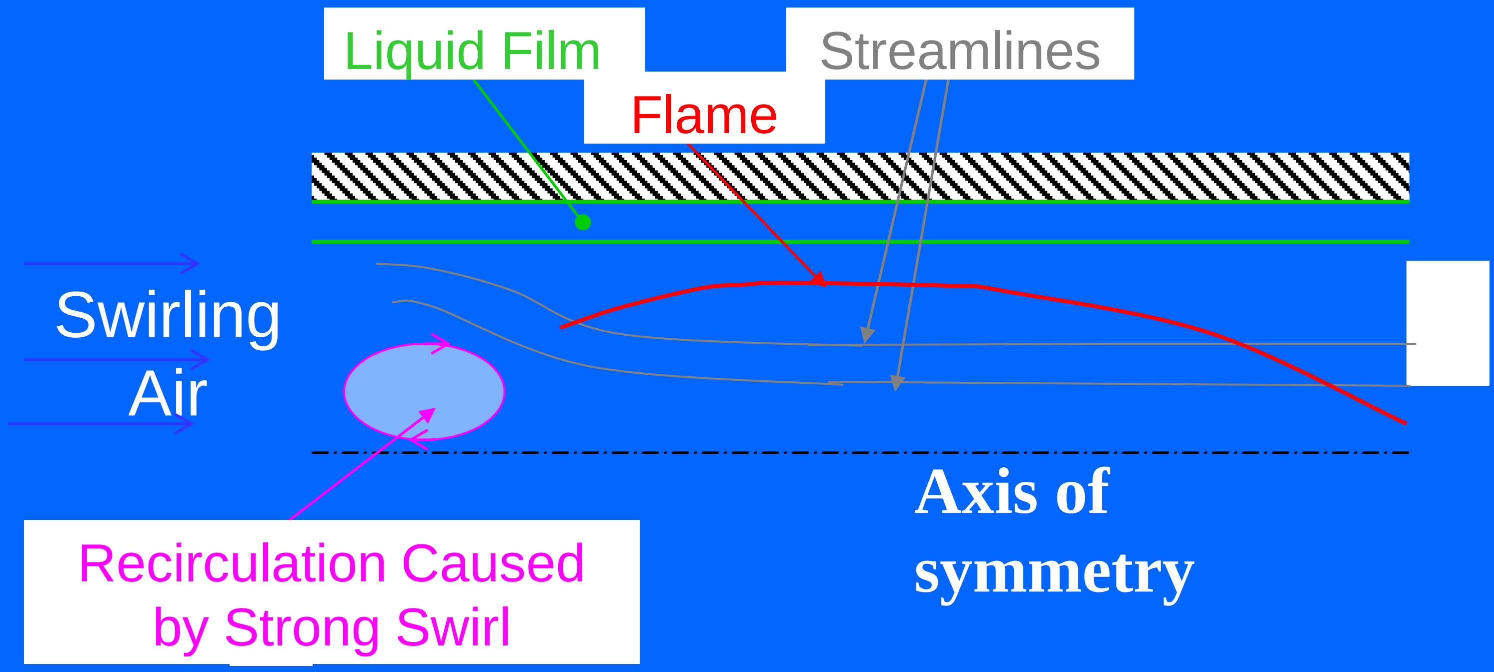


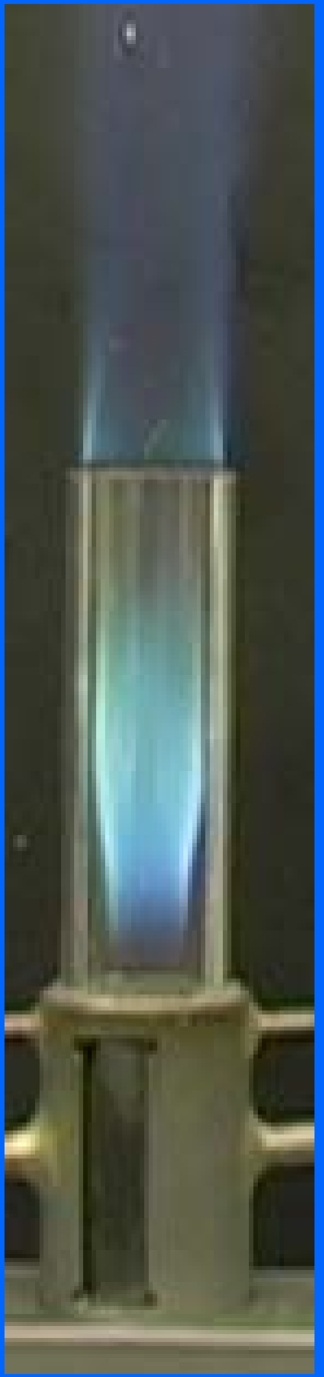




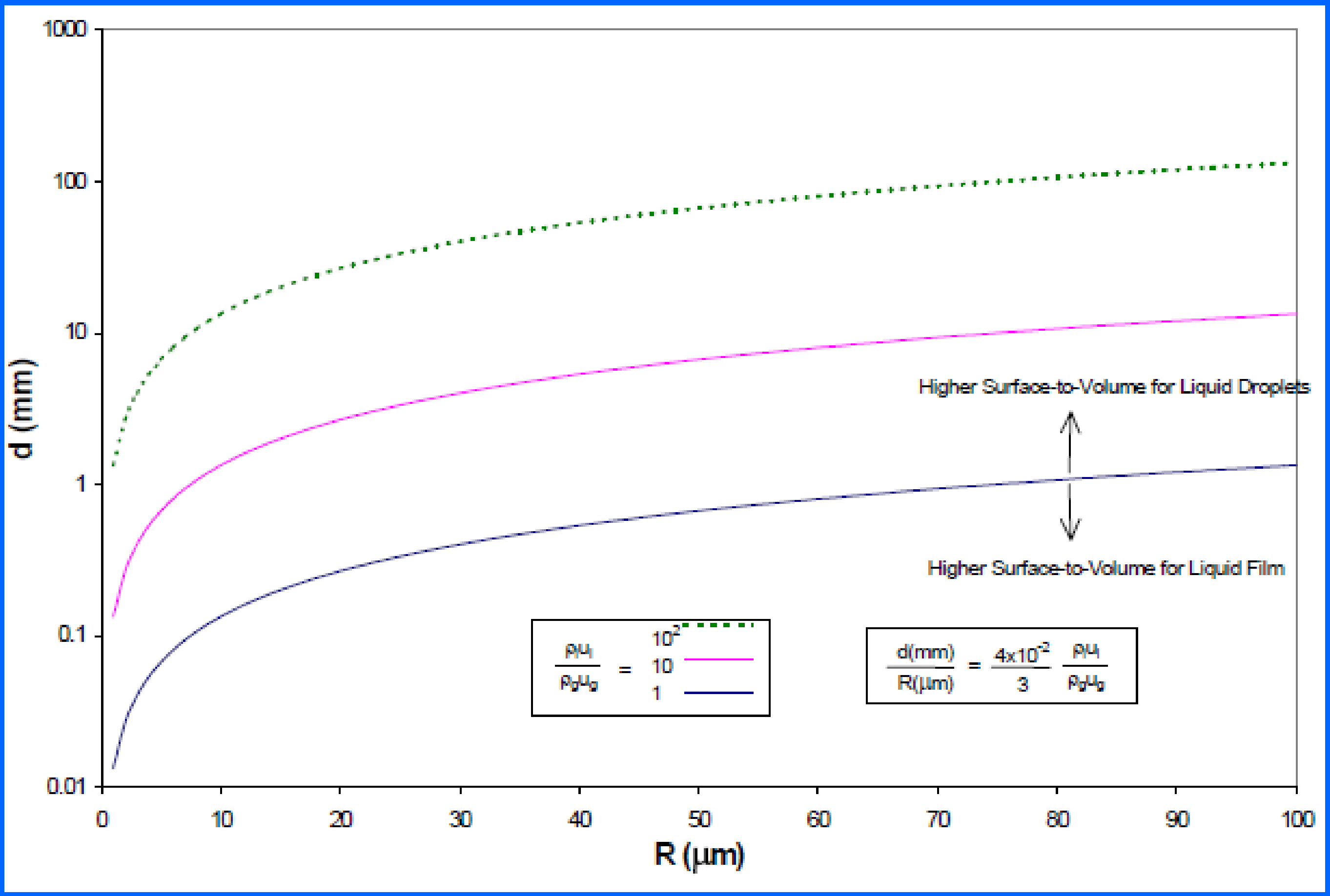
Methanol and heptane flames were stabilized in one-cm (or lower) diameter cylinders.

Swirl of both air and fuel were important.


Liquid Film
Streamlines
Flame
Swirling
Air
Recirculation Caused
by Strong Swirl
Axis of
symmetry



For small diameter chambers, wall films compete with sprays plus they keep heat loss through walls and inhibit quenching



The continuity relations for gas and liquid and the stoichiometric proportion for the mass flows determine that

$$(S/V)_{film} \; / \; (S/V)_{drop} \sim (40/3)(\rho_l u_l / \rho_g u_g) R/d$$

SCALAR ANALYSIS

$$Pe\left(1-\varepsilon^2\tilde{r}^2\right)\frac{\partial\alpha}{\partial\tilde{x}}=\frac{1}{\tilde{r}}\frac{\partial}{\partial\tilde{r}}\left(\tilde{r}\frac{\partial\alpha}{\partial\tilde{r}}\right)+\frac{\partial^2\alpha}{\partial\tilde{x}^2}$$

$$Pe=\frac{u_c R}{D}$$

$$\alpha=\Theta\left(\tilde{r}\right)e^{-k\tilde{x}}$$

$$\Theta''+\frac{1}{\tilde{r}}\Theta'+\lambda^2\left(1-\epsilon_*^2\ \tilde{r}^2\right)\Theta=0$$

$$\lambda^2\equiv Pe\,k+k^2$$

$$\varepsilon_*=\varepsilon/\left(1+k/Pe\right)^{1/2}$$

For plug flow, $\varepsilon = 0$ and Bessel functions are produced. For a parabolic velocity profile, we obtain

$$\Theta_n\left(\eta,\ \beta_n\right)\ =\ e^{-\beta_n\eta^2\ /\ 4}\sum_{m=0}^{\infty}a_{2m}\left(\beta_n\right)\eta^{2m}$$

$$\eta\equiv\frac{2\varepsilon_*\sqrt{1+\beta_n}\,\tilde{r}}{\beta_n}$$

$$a_{2m}\left(\beta_n\right)=\left(-\frac{1}{4}\right)^m\frac{\prod_{p=0}^{m-1}\left(1-2p\beta_n\right)}{\left[m!\right]^2}$$

$$\beta_n\ \equiv\ \frac{1}{\dfrac{\lambda_n}{2\varepsilon_*}-1}\ =\ \frac{1}{\dfrac{\sqrt{Pek_n+k_n^2}}{2\varepsilon_*}-1}$$

SCALAR SOLUTION

Solution for Scalar Field Variable

$$\alpha = Y_F - \nu Y_O - Y_{Fs} = \sum_{n=1}^{\infty} c_n \Theta_n(\tilde{r}) e^{-k_n \tilde{x}}$$

$$c_n = \frac{\int_0^{R_1/R} \left(\tilde{r} - \varepsilon_*^2 \tilde{r}^3\right) \alpha(\tilde{r},0) \Theta_n(\tilde{r}) d\tilde{r}}{\int_0^{R_1/R} \left(\tilde{r} - \varepsilon_*^2 \tilde{r}^3\right) \Theta_n^2(\tilde{r}) d\tilde{r}}$$

$$\Theta_n(\eta, \beta_n) = e^{-\beta_n \eta^2 / 4} \sum_{m=0}^{\infty} a_{2m}(\beta_n) \eta^{2m}$$

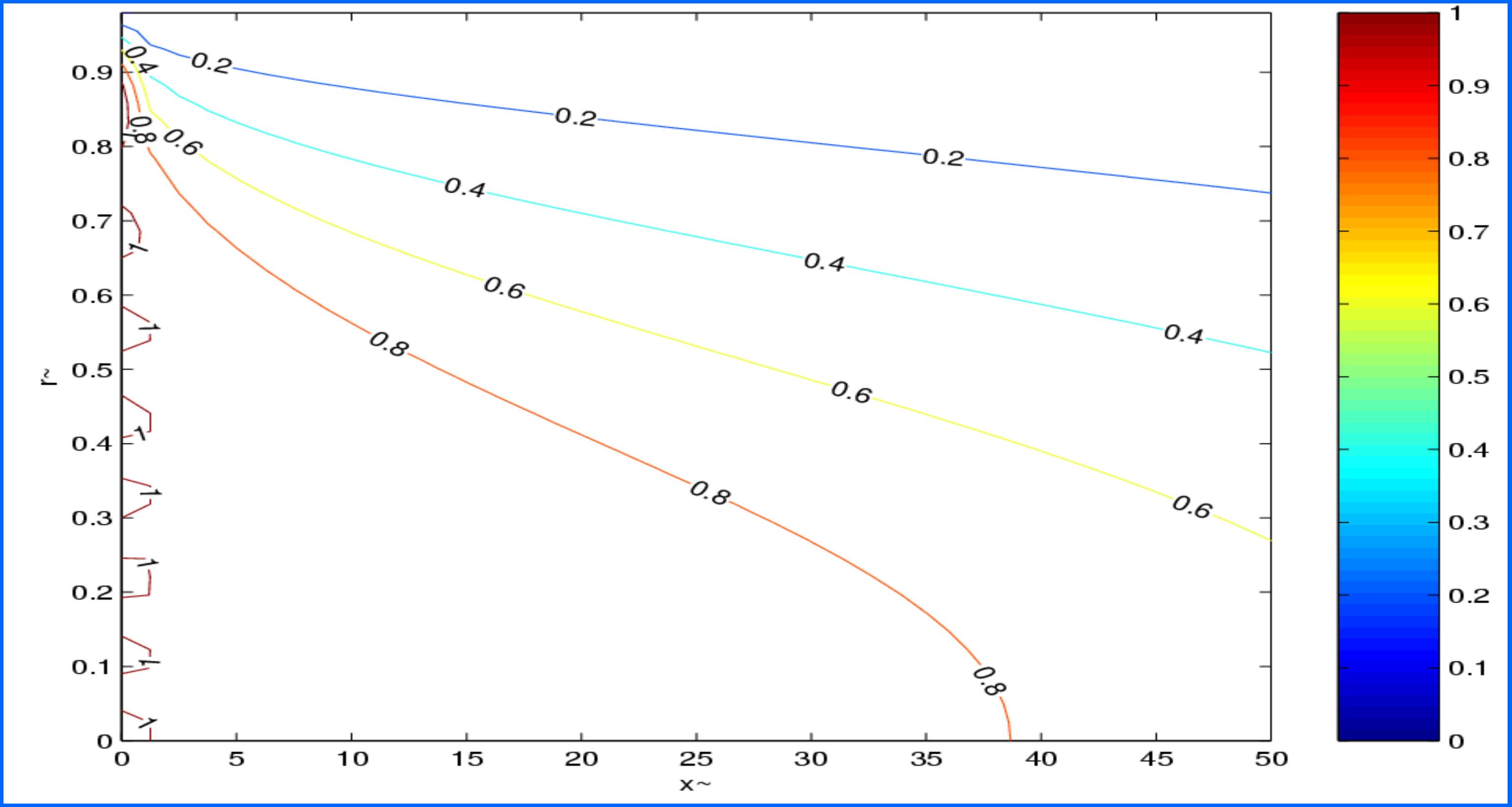
Local Vaporization Rate

$$\frac{\dot{m}R}{\rho D} = -\sum_{n=1}^{\infty} c_n \Theta_n'(\tilde{r}_i) e^{-k_n \tilde{x}} = -\frac{2}{\tilde{r}_i} \sum_{n=1}^{\infty} \left[c_n e^{-k_n \tilde{x}} \eta_i \, e^{-\beta_n \eta_i^2 / 4} \sum_{m=1}^{\infty} m \, a_{2m} \eta_i^{2m-1} \right]$$

Total Vaporization and Burning Rate

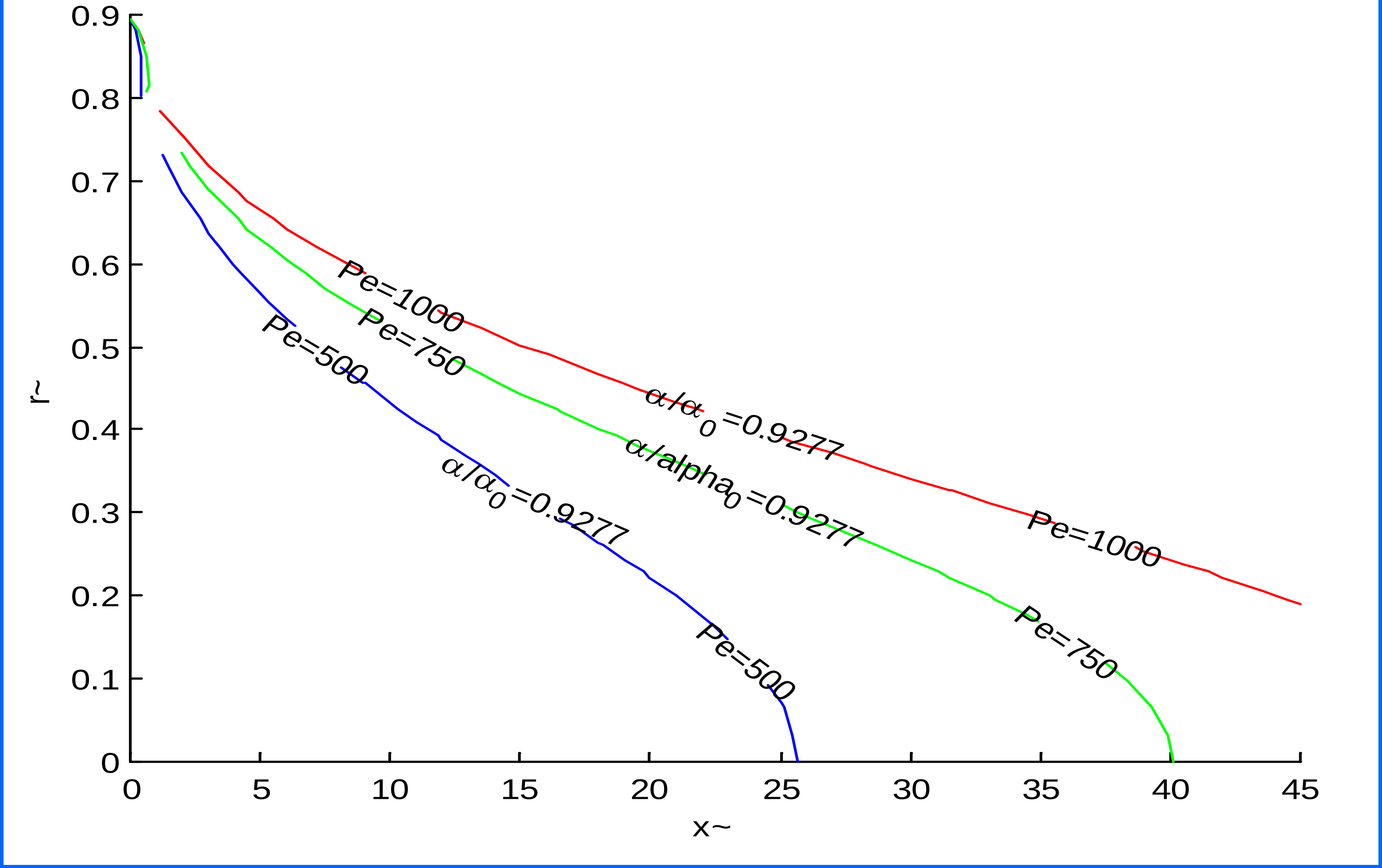
$$\frac{2\pi R_i}{\rho D} \int_o^{L/R} \dot{m} d\tilde{x} = 4\pi \sum_{n=1}^{\infty} \left[\frac{c_n}{k_n} \left(e^{-k_n L/R} - 1 \right) \eta_i \; e^{-\beta_n \eta_i^2 / 4} \sum_{n=1}^{\infty} m a_{2m} \eta_i^{2m-1} \right]$$

COMPUTATION USING SERIES SOLUTION



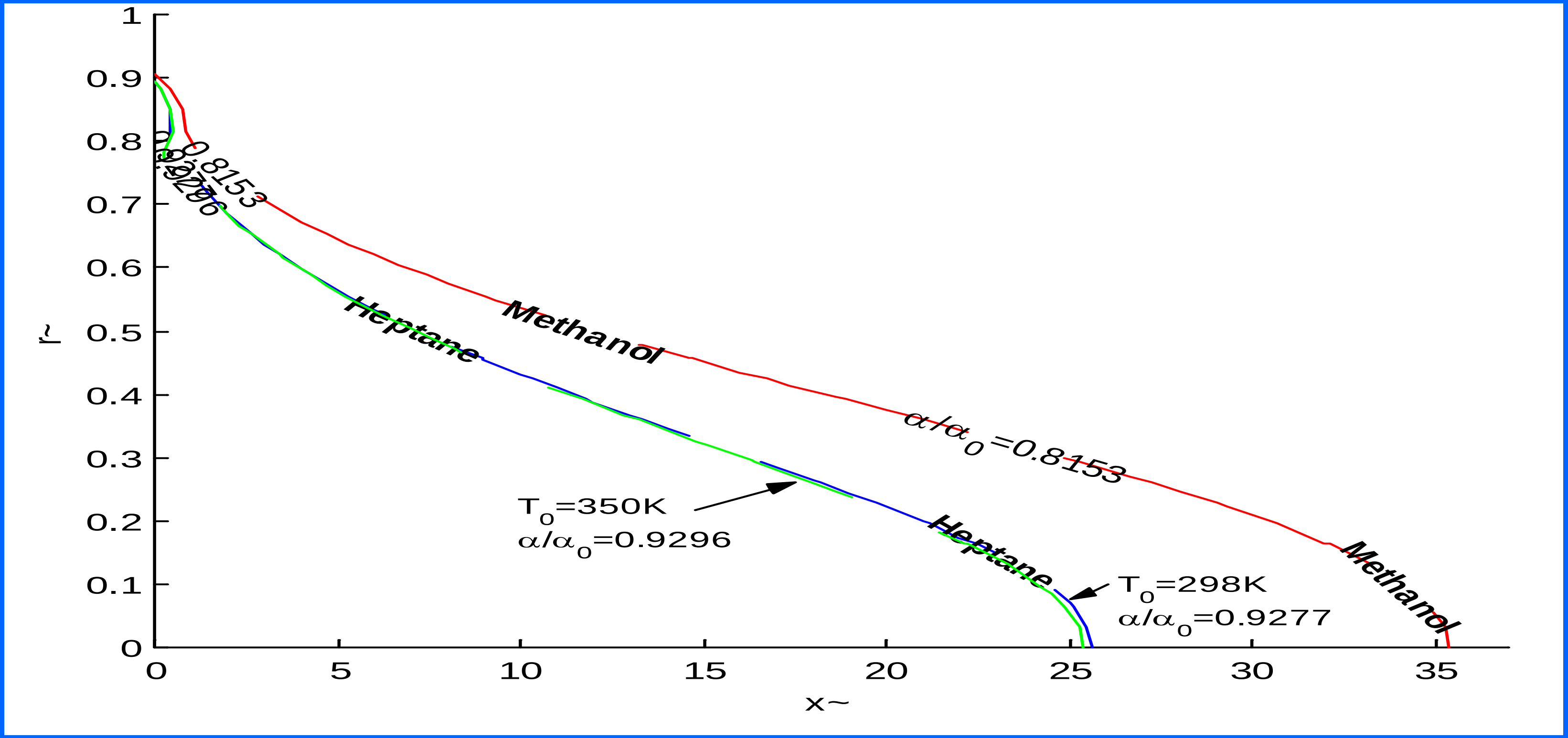
Scalar variable α / α_o contours for $Pe = 500$. This portion of the solution is independent of fuel choice. Increase in Pe extends the field downstream. For high Pe, the field becomes a function of r and x / Pe.

FLAME POSITION



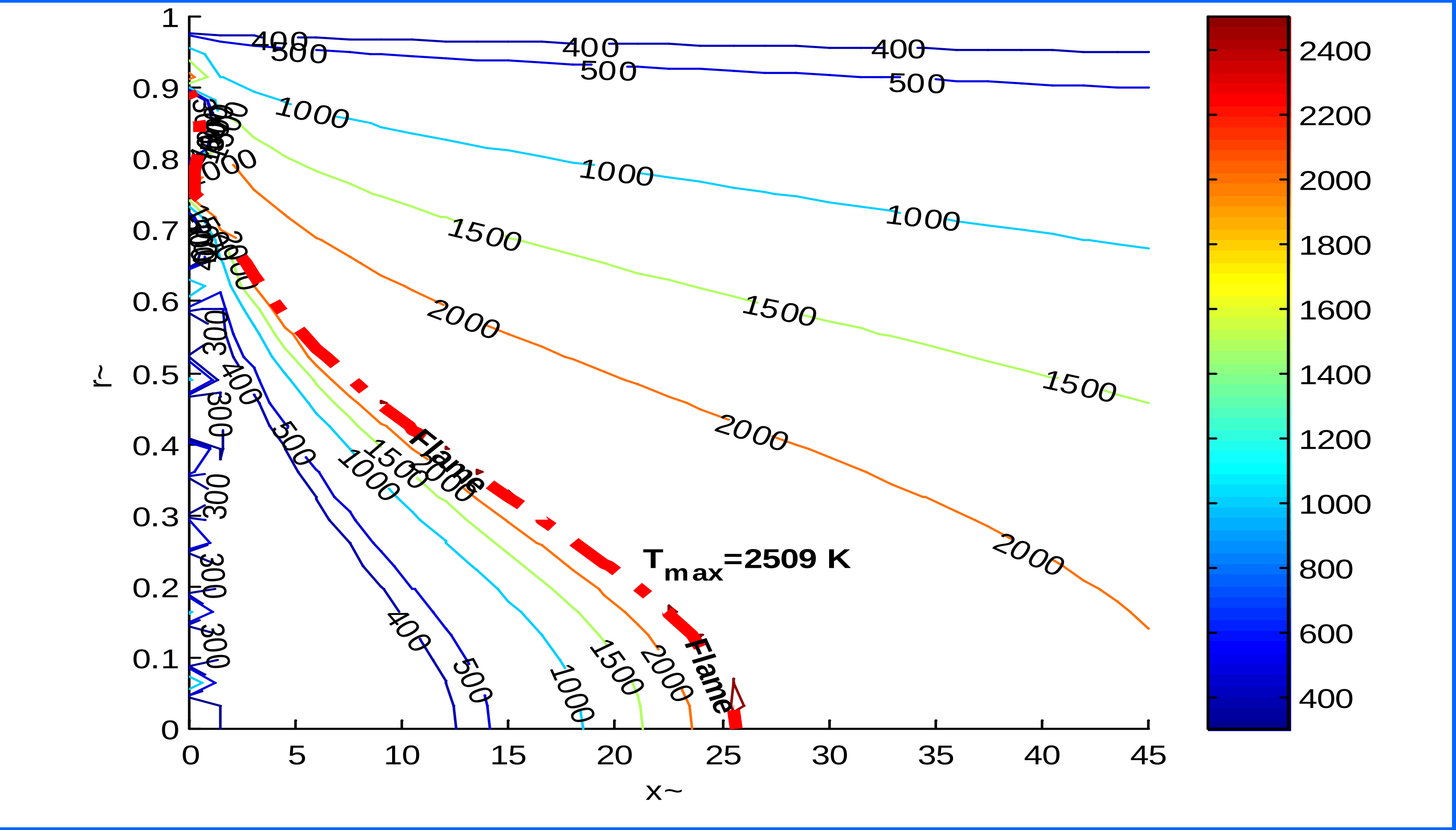
Diffusion-controlled thin flame has been assumed with heptane / air combustion for *Pe* = 500, 750, and 1000.

EFFECTS OF FUEL AND INITIAL FUEL TEMPERATURE CHOICES



Flame position changes little with initial fuel-temperature. Yet, the use of methanol extends the flame length. Why? CH_3OH vaporization rate is only slightly less than the C_7H_{16} rate so the flame length relates primarily to stoichiometric mass ratio; i.e., more fuel mass per air mass is needed.

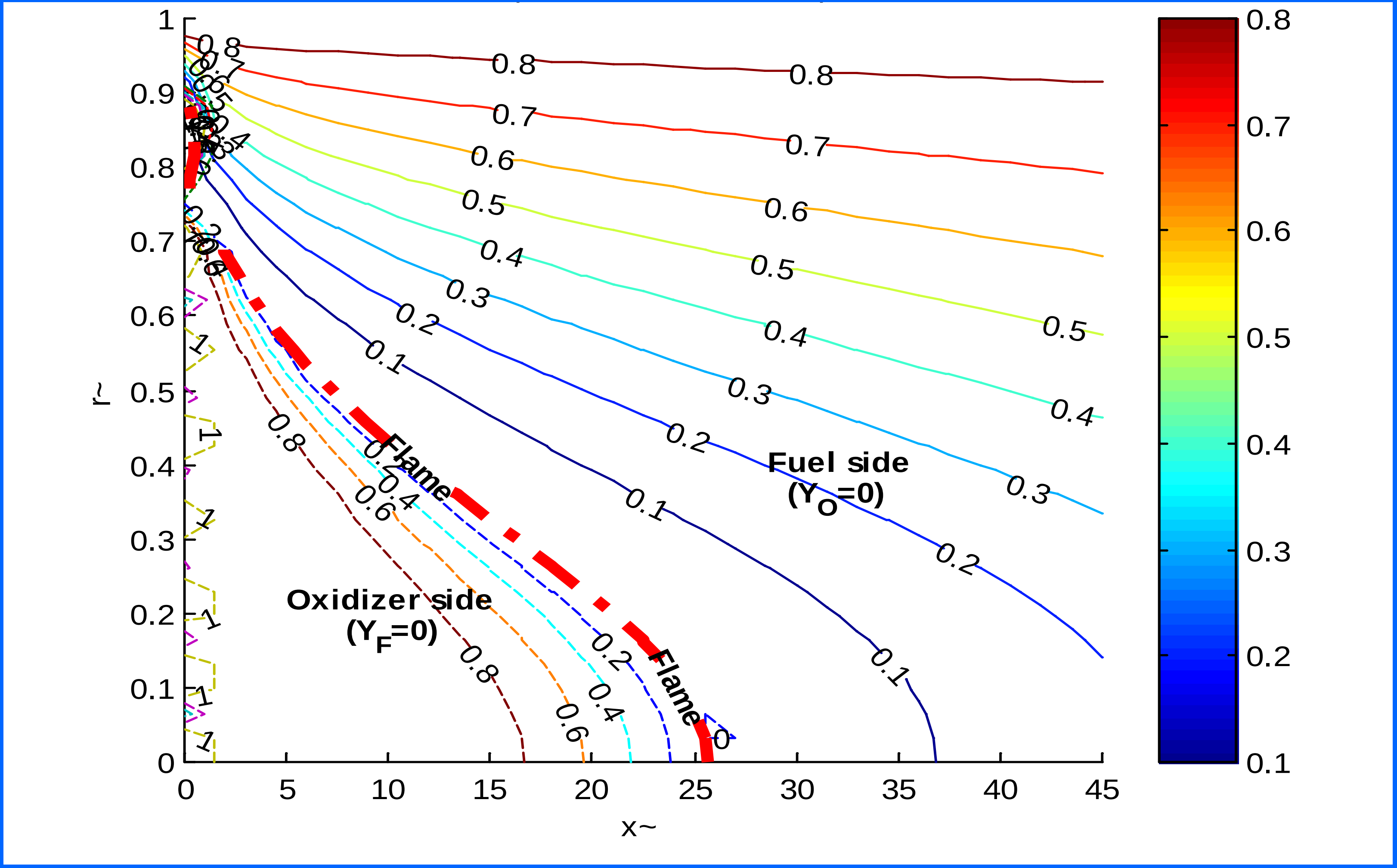
FLAME TEMPERATURE
Heptane at 298 K Bulk Temperature



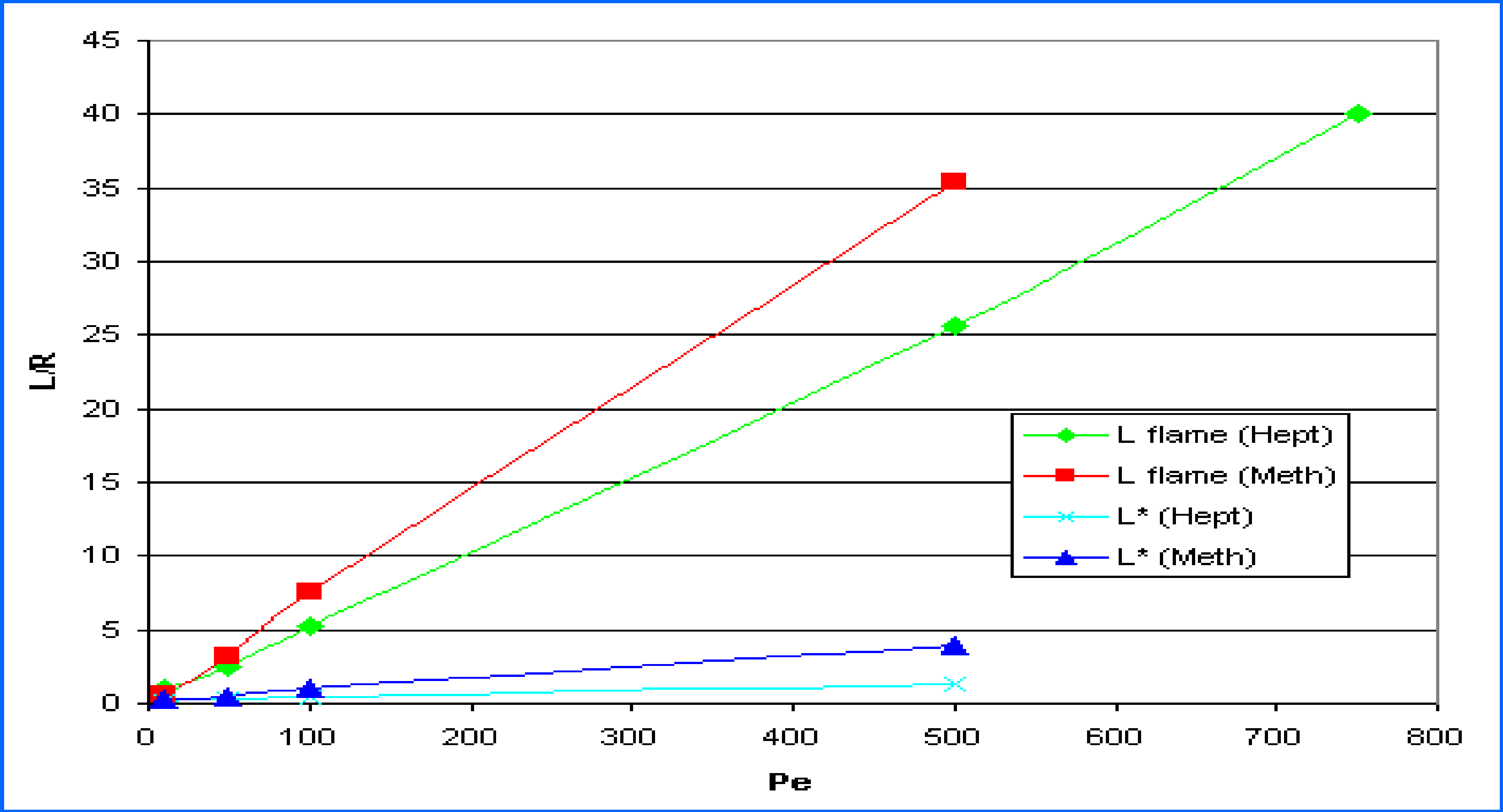
A two-phase diffusion flame occurs.

It is a cylindrical version of the Emmons problem.

MASS FRACTIONS
Heptane at 298 K Bulk Temperature

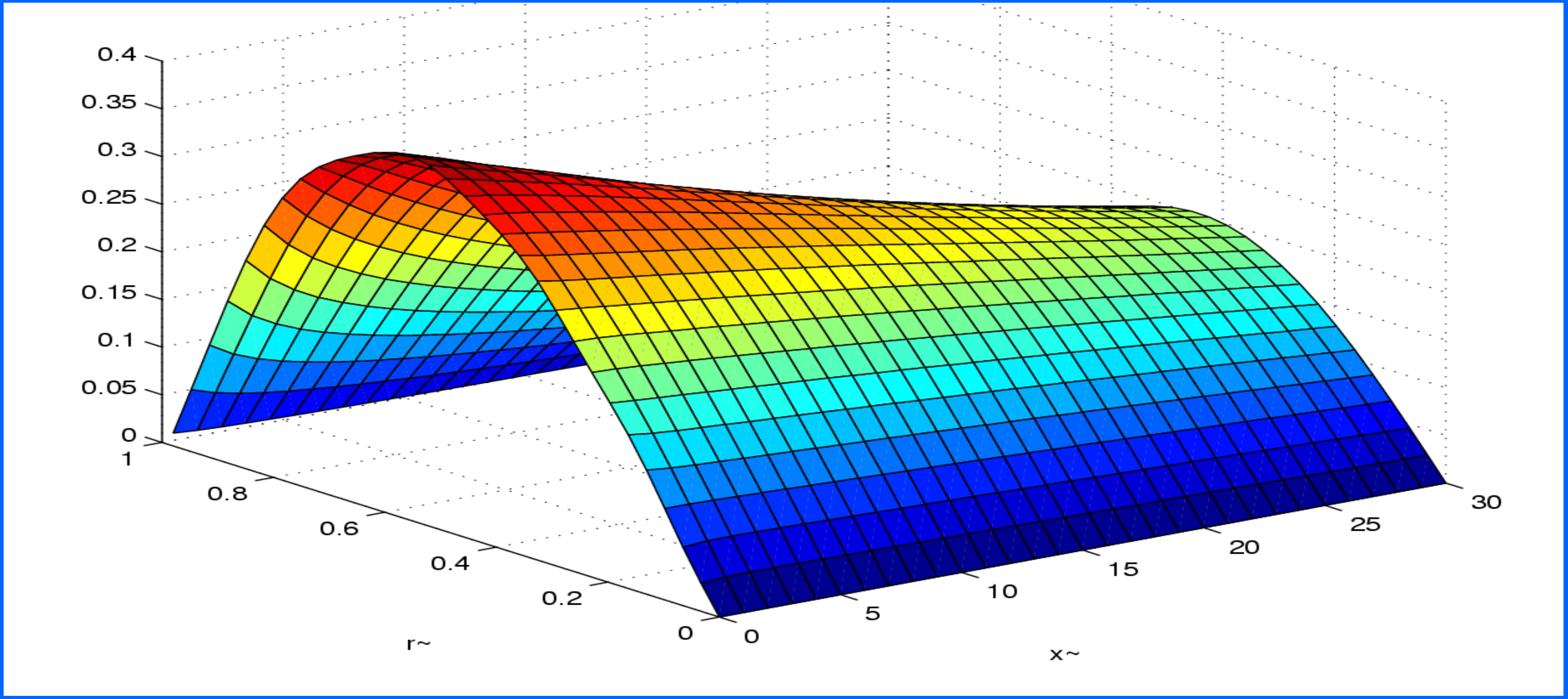


FLAME AND FILM LENGTHS



Challenge: flame lengths exceed stoichiometric film lengths. Avoid unprotected walls. Possible solutions: operate fuel rich; use additional inert liquid downstream; mix inert and fuel (e.g., water and alcohol); or enhance gas mixing rates using swirl and vortex generation.

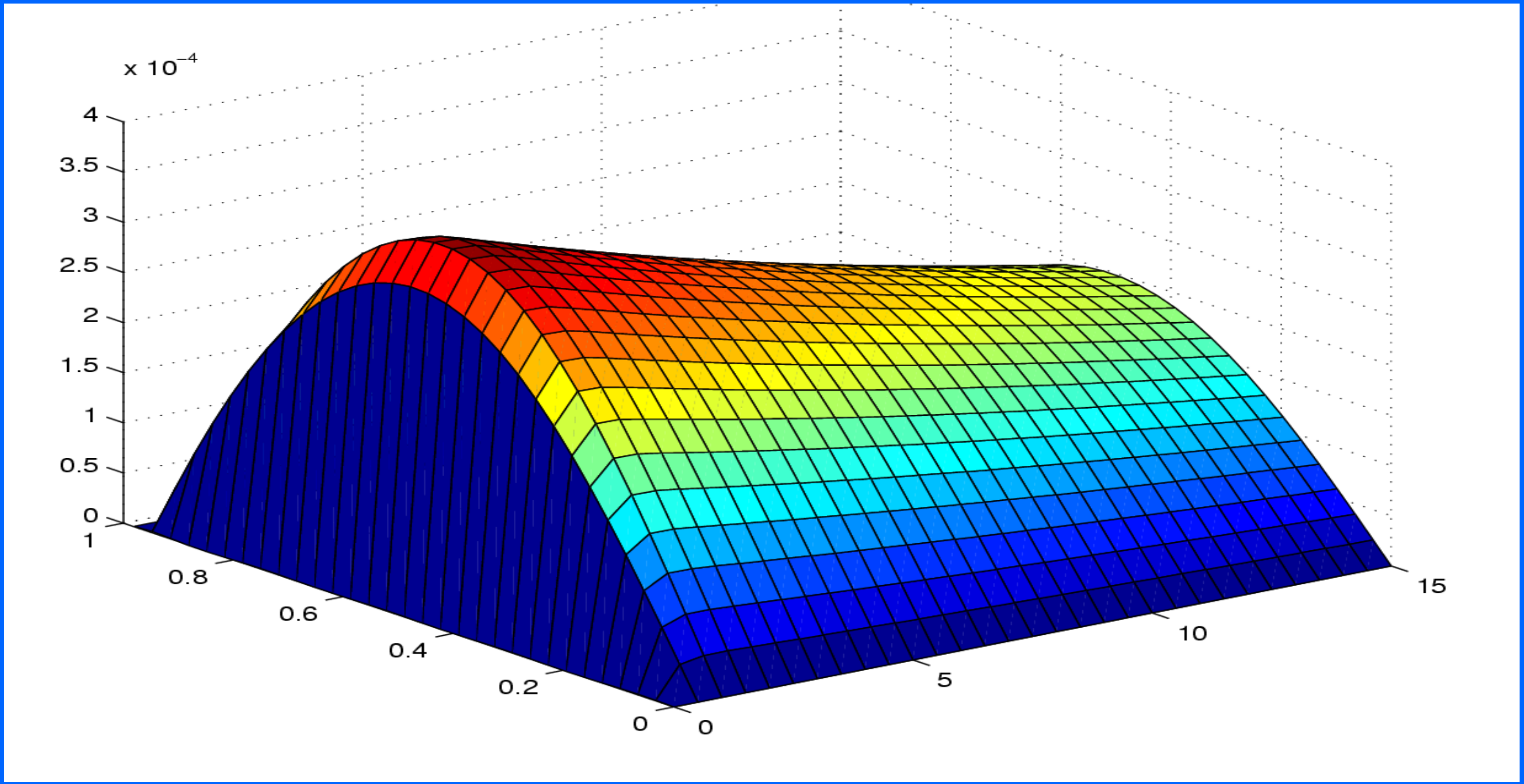
SWIRL-INDUCED TANGENTIAL VELOCITY



Re = 1000

Imposed swirl on inflow decays with downstream distance.

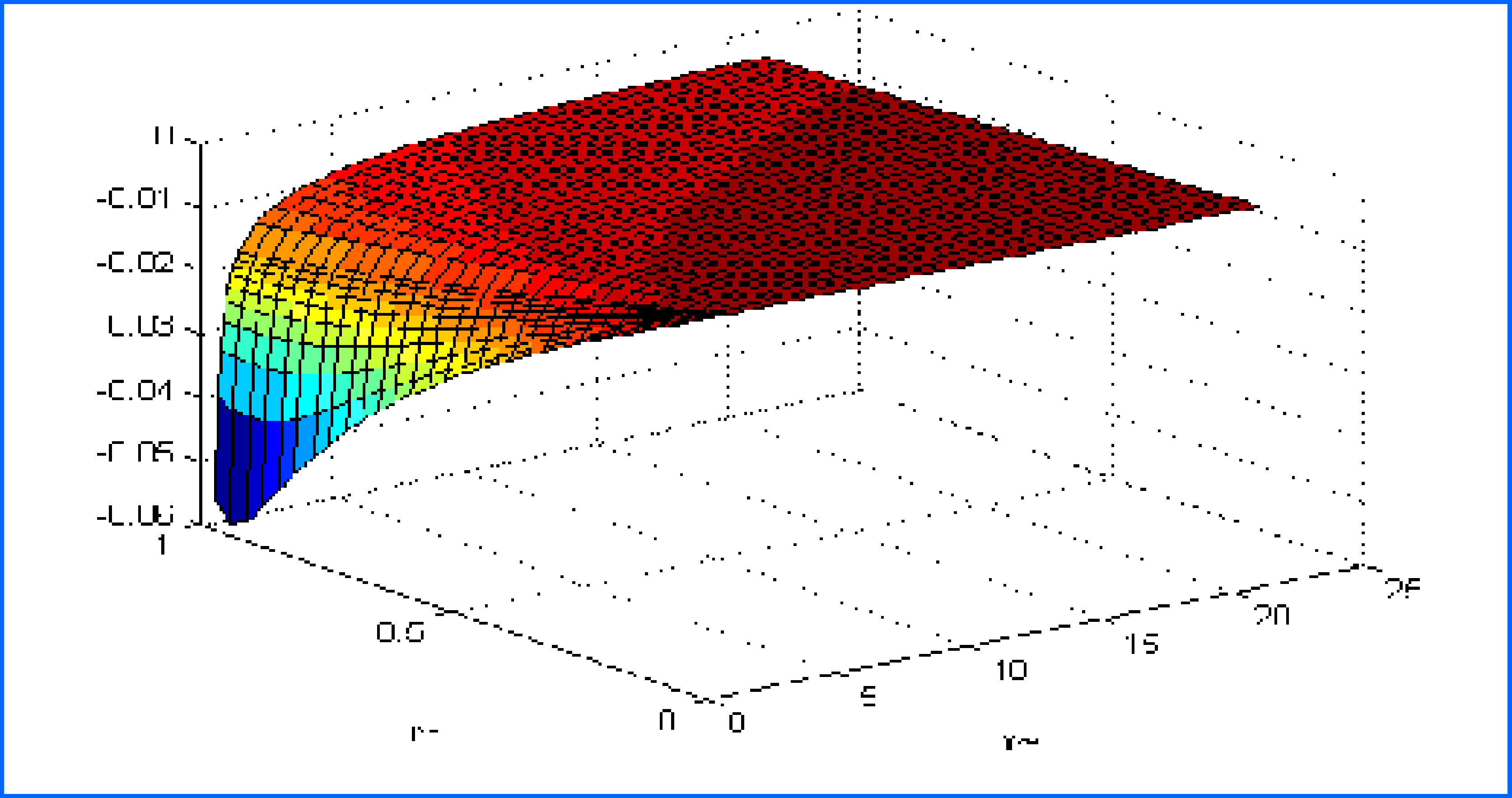
SWIRL-INDUCED RADIAL VELOCITY



Re = 1000

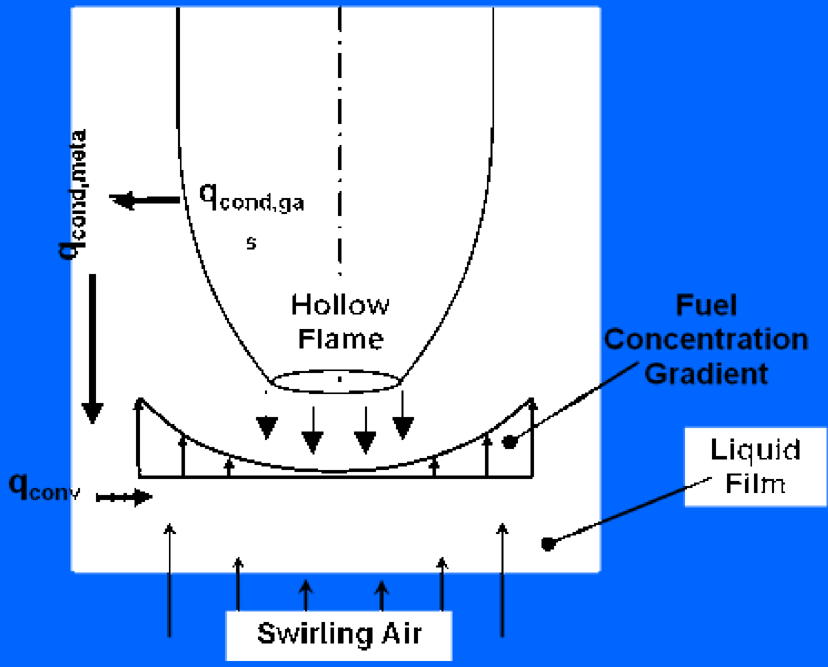
Centrifugal force causes outward radial velocity modifying transport.

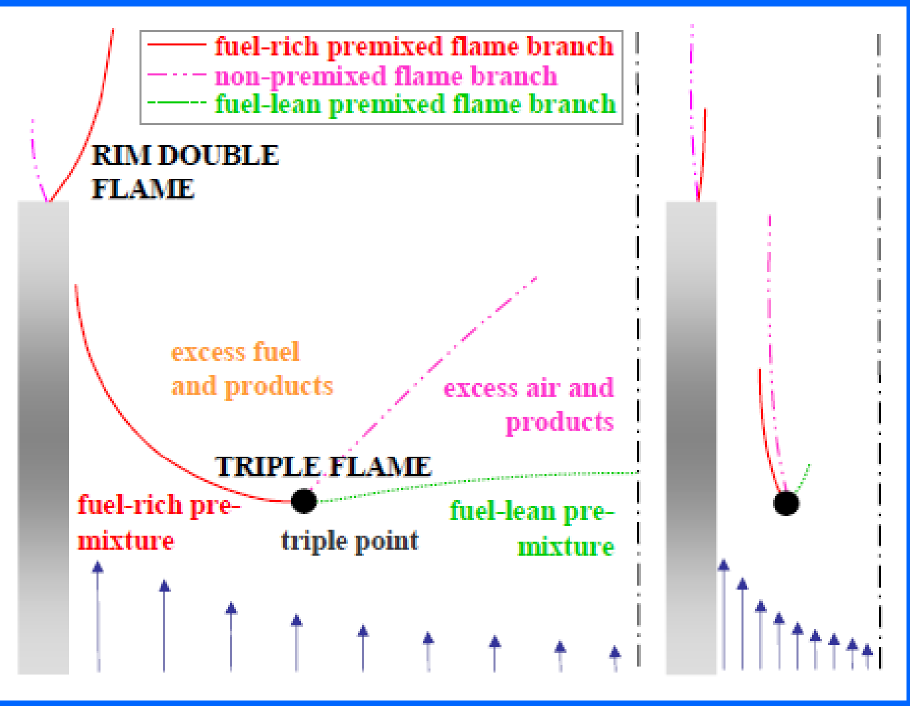
RADIAL STEFAN VELOCITY



Re **= 1000**

Vaporization causes an inward (negative) component of radial velocity that modifies transport.





Flame Stabilization

One possibility is that swirling air inflow causes a recirculation. This could apply with swirl vanes but did not appear with tangential air injection.

Stabilization at the rim with upstream flame propagation was not the mechanism because insulation with a nitrogen stream did not quench flame upstream.

The triple-flame (tri-brachial) structure apparently anchors the flame upstream.

Quartz vs. Metal

1.5 m/s

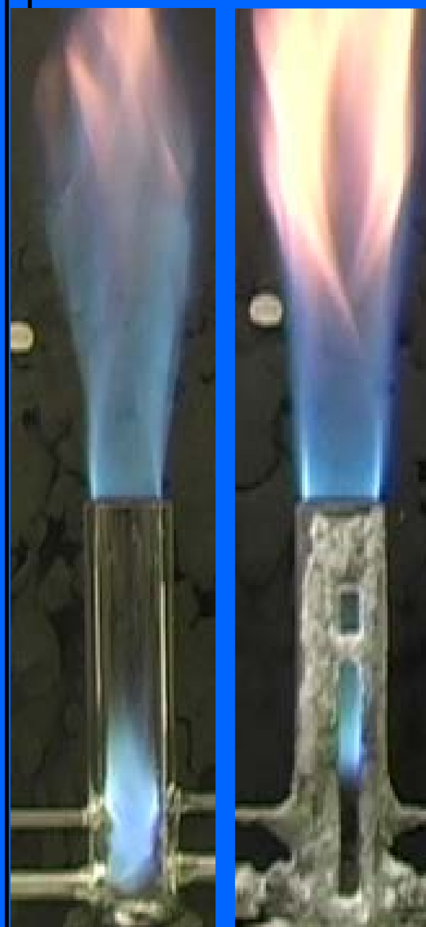
$\phi = 2.3$

unstable stable

1.7 m/s

$\phi = 2.0$

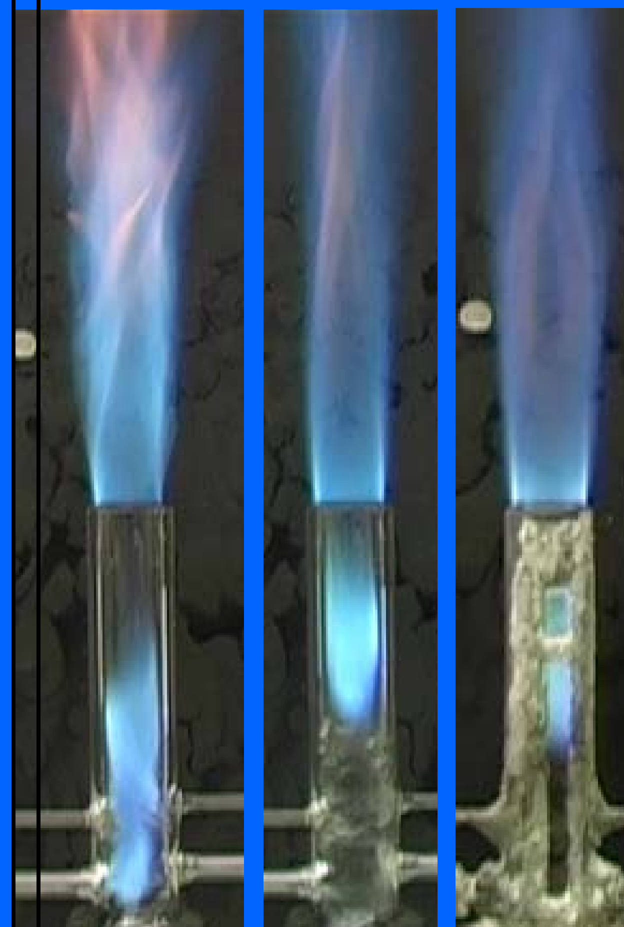
stable



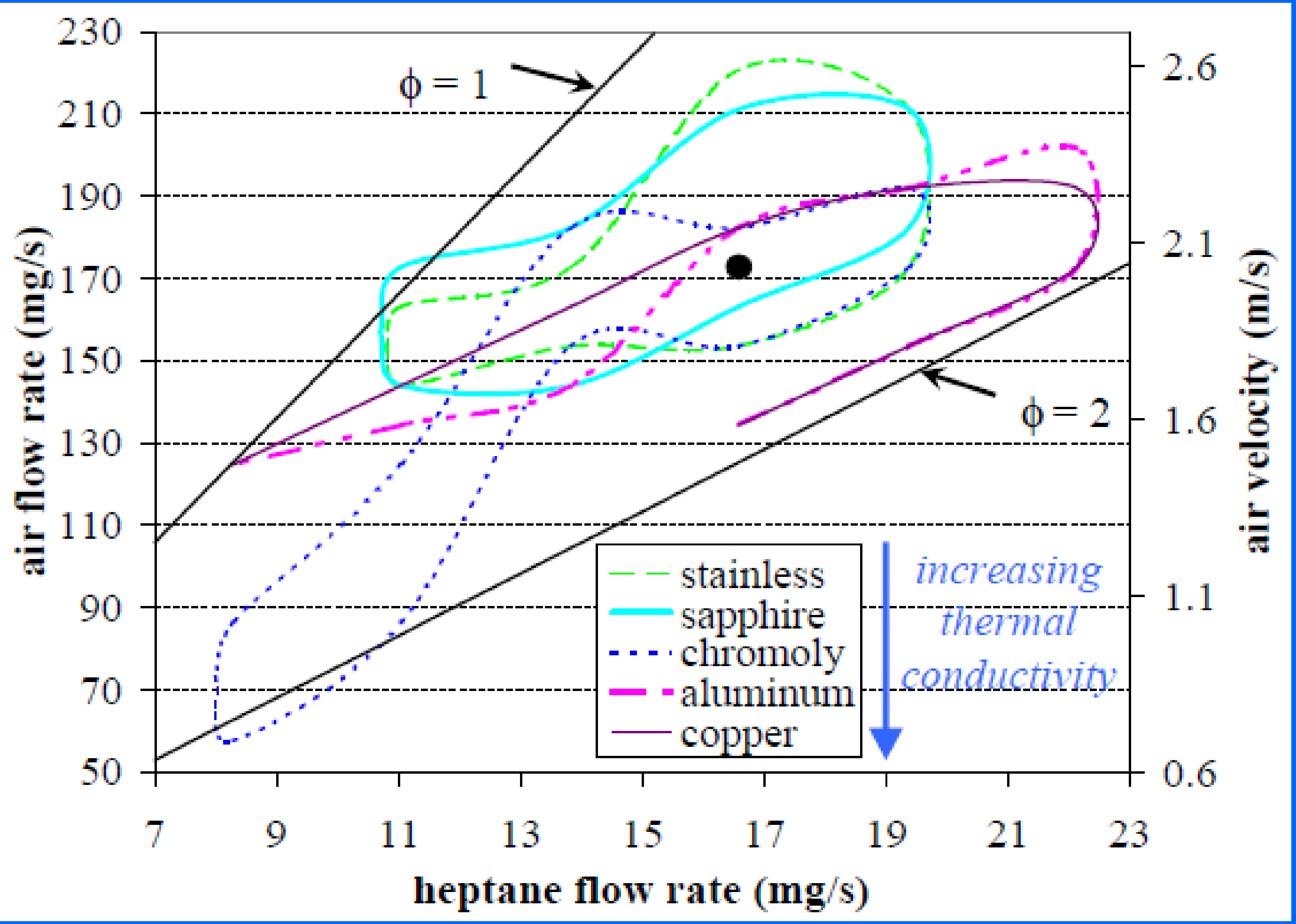
2.0 m/s

$\phi = 1.7$

unstable stable



Upstream heat transfer through cylinder walls helps to stabilize the flame. Increasing wall thermal conductivity increases stable operating domain.



Swirl Vane Stabilization

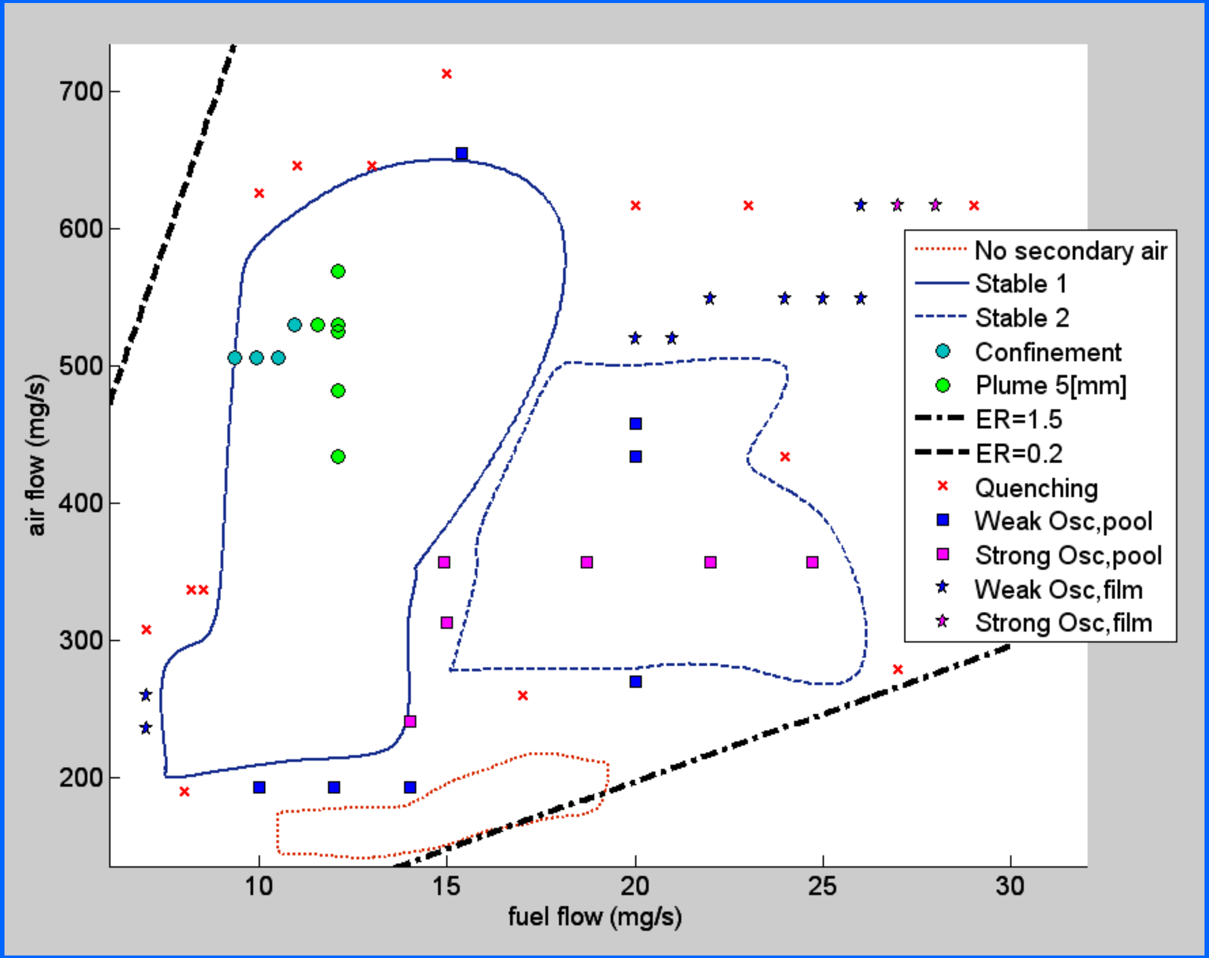
In recent studies, swirl vanes replaced tangential injection of Primary air. Tangential injection of fuel and secondary air is maintained. Only the bottom part of the three-section chamber is modified.

In preliminary tests, swirl vanes were not as effective as tangential air injection

Secondary Air Injection

Downstream secondary air injection allows robust performance. As more air is added, the flame volume is decreased and a confined flame is eventually obtained.

Secondary air plays a vital role in allowing flame confinement. A fuel-rich zone is required for stabilization. Problems with flame oscillation and pooling of fuel occur in some portion of domain; however, stable steady operation with total confinement (i.e., no exit plume) and no fuel pooling is achievable.



Outside of the pooling domain, the operation is not sensitive to the orientation with respect to gravity.

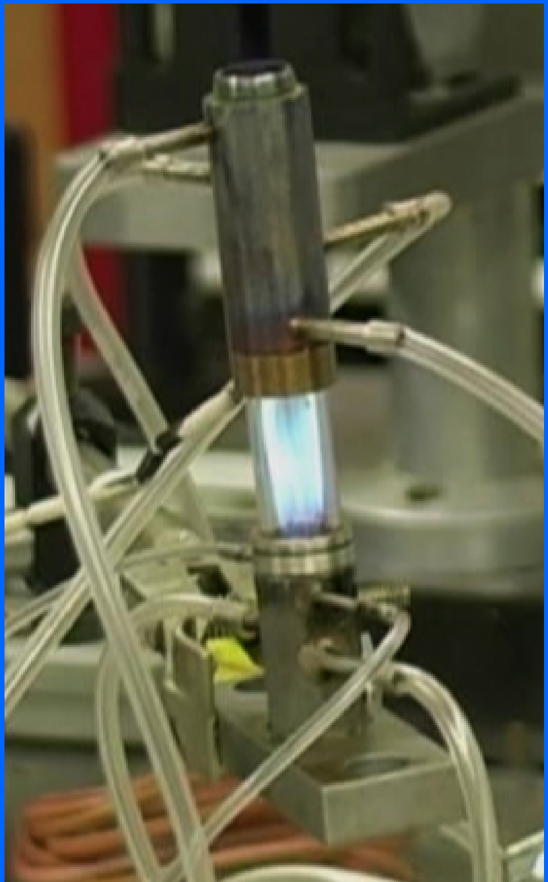
Chamber dimensions: length – 89.8 mm; internal diameter –9.7mm;
length from fuel injector to exit – 65 mm.

Injector diameters: two fuel – 1 mm; two primary air – 2.15 mm;
four secondary air – 2.7 mm.

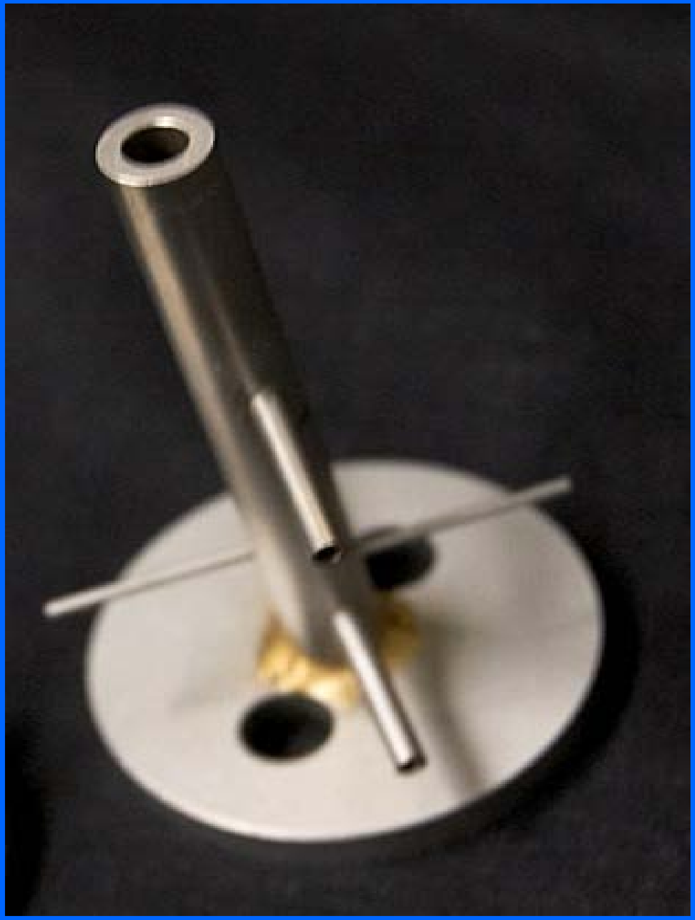
200 grams plus fuel; 380-660 watts (thermal); > 90% efficiency

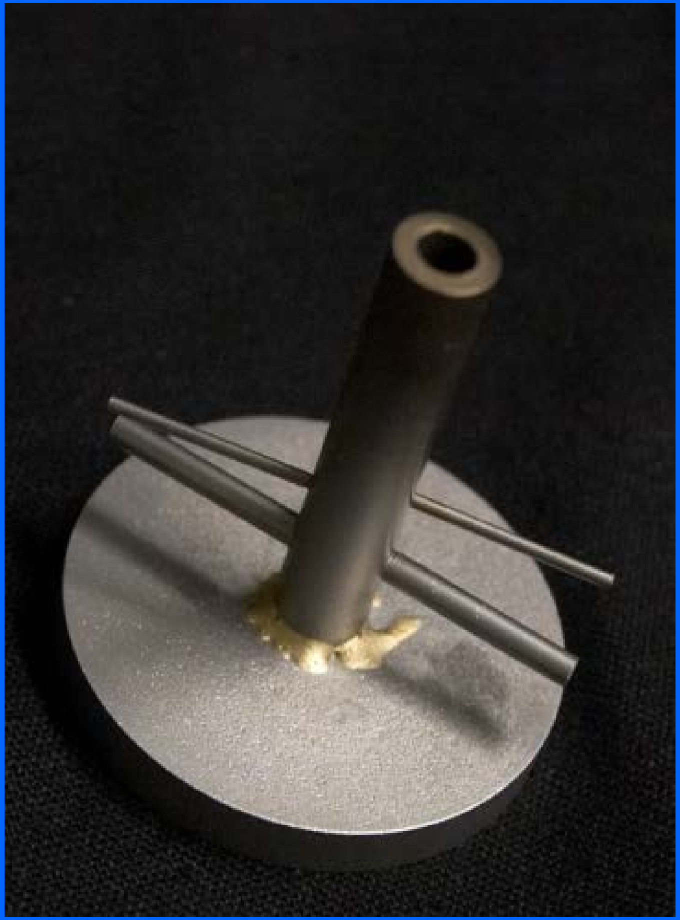
At highest power, about one hour of operation per 50 gm of fuel;

24-hour duration requires about 200 gm + 24 x 50 gm =1.4 kgm.

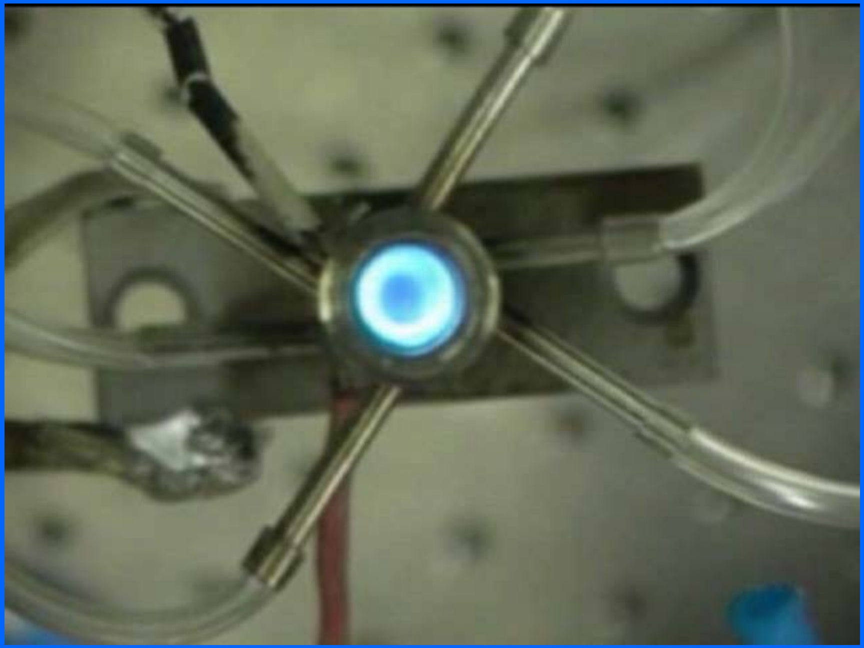


Hardware with 5.3-mm diameter was tested with two versions. No secondary air: 4.8 cm length, 1.06 cm^3 volume, two fuel injectors, two air injectors -- 170 W max with external plume.
Secondary air: 7.8 cm length, 1.73 cm^3 volume, two fuel injectors, four air injectors – 300 W max with external plume.





So far, the 0.53-cm-diameter hardware only operates in fuel-rich domain with an external plume. Flame stabilization was more difficult in the 78 mm version than in the shorter version. More examination is required to explain.



Nitrogen Rim Tests

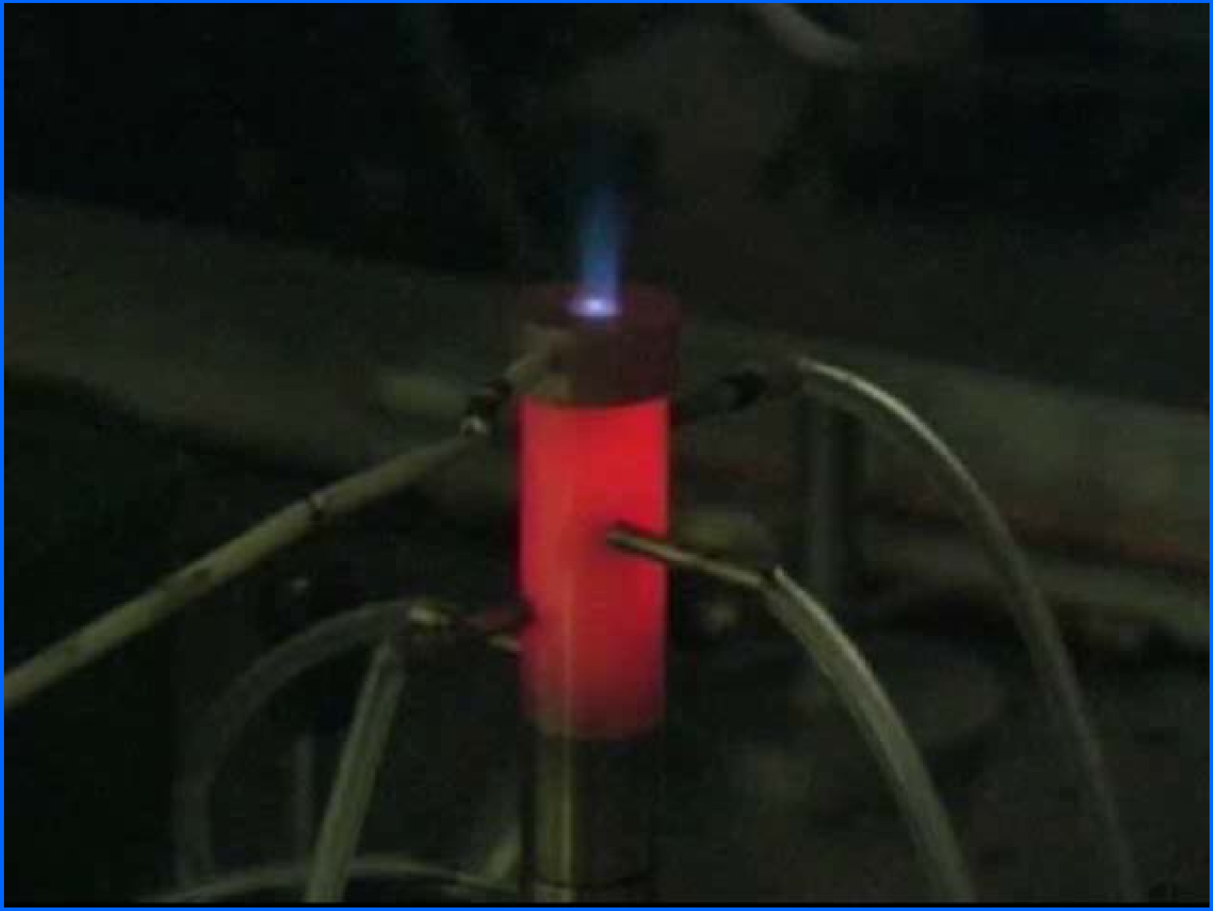
increasing nitrogen flow

Rim flame is not significant to the stability of the internal flame

Confinement of the Flame with Nozzle

Sudden closure of the secondary air flow caused the flame to exit and anchor outside of the chamber.

The flame can be confined again by gradually increasing the air flow.



Nozzle Effects

-- Nozzle raises the temperature and decreases the temperature gradient along the chamber wall ;
-- The heat exchange between the wall and the fuel film becomes more uniform. This process is like an oscillation damper technique;
-- A small change of the chamber pressure (0.25 atm) can help damp oscillations;
-- The pressure rise is limited by quenching effect due to fuel film dry out and back-pressure restricting flows in the fuel and air feedlines;
-- Thermocouple aquisition for a fixed ER value revealed a decrease of the standard deviation on the temperature signal of 25 up to 100 %. Frequency analysis of the sound signal showed the same result.

Concluding Remarks

- Liquid-fueled combustion can be maintained and confined in a volume of a few cubic centimeters using a fuel film.
- Gaseous-fueled flames cannot be confined in the same volume.
- Greater-than-90% thermal efficiencies are obtained indicating the concept provides good protection against heat loss and quenching.
- Swirl of both liquid fuel and air was essential.
- A tri-brachial flame resulted at the anchor point.
- Tangential injections appears to be superior to swirl vanes.
- 660 watts, nearly a horsepower, of thermal power was achieved making the concept an interesting candidate for a prime mover on small unmanned vehicles, hand tools, and electric generators.

More Concluding Remarks

- **The linearized analysis predicted some salient features but a nonlinear analysis is needed.**
- **High-pressure combustor experiments with a choked nozzle exit should be performed.**
- **Should pursue flame confinement in 5-mm diameter case.**
- **Alternative variations deserve further study; e.g., porous fuel feed, double-wall chamber.**
- **Direct thermoelectric generation is an interesting option.**

THANK YOU.