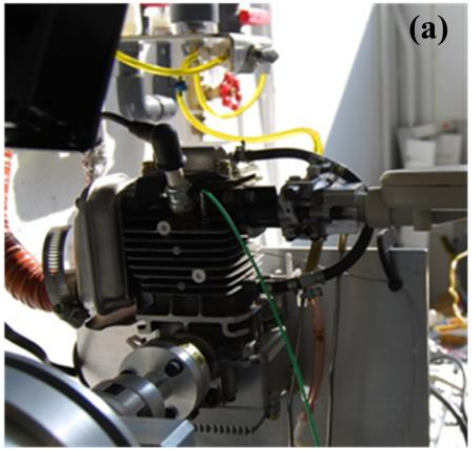
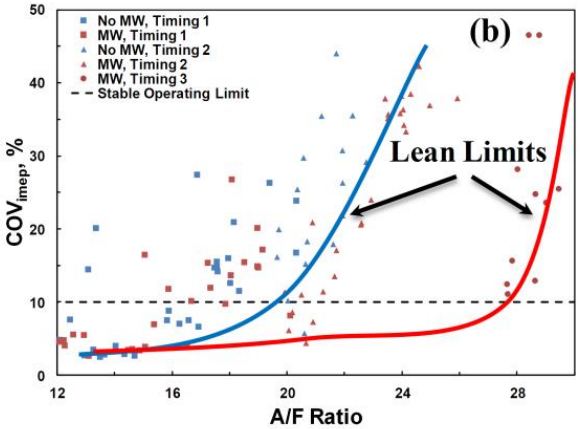
Microscale Power Generation: Challenges and Opportunities

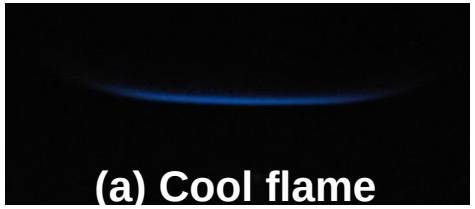
Yiguang Ju

Princeton University

ARPA-E kickoff meeting
Chicago, 2015.10.20







AFOSR: University Capstone Project

Contents

- **Development and Challenges of Mesoscale Power**
- **Flame Quenching Limit and Heat Recirculation**
- **Engine Lean Burn limit:**

  Ignition energy/ignition kernel size
- **Plasma Assisted Combustion:**

  A new opportunity for ignition/emission control of small scale engines?
- **Summary**

Small Engines (kW) in UAVs and Distributed power generation

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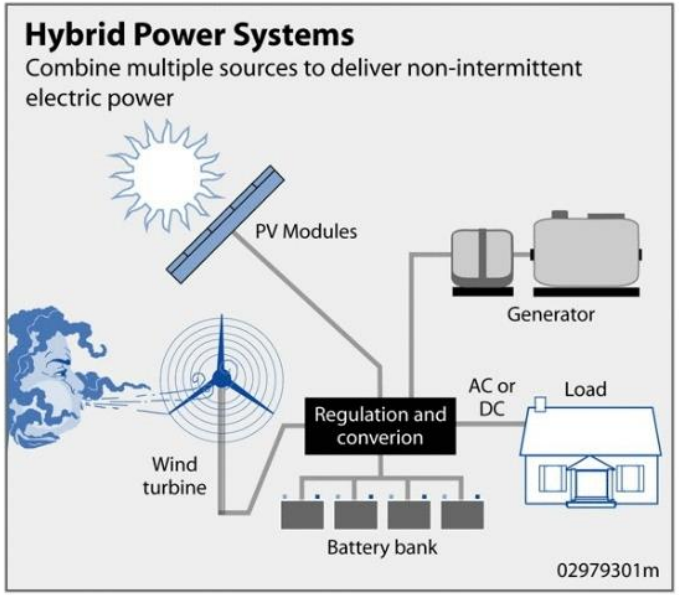
- Small UAVs for military and civilian operations.

- Hybrid power system for remote areas.



Challenges:

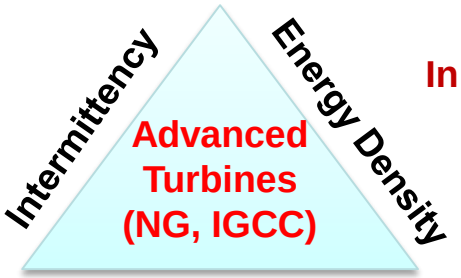
Efficiency, efficiency, efficiency…
Emissions..

https://en.wikipedia.org/wiki/Stand-alone_power_system

Sustainable energy triangles: ideally

Sustainable electricity

Wind, solar…



In Reality

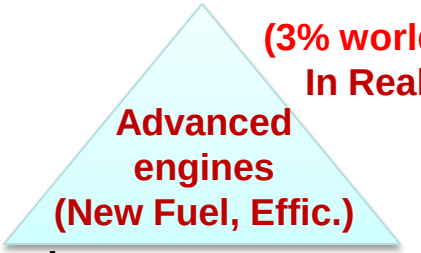
Smart grids

Energy storage

Sustainable transportation

Biofuels

(3% world, 10% US)
In Reality



Batteries
Fuel cells

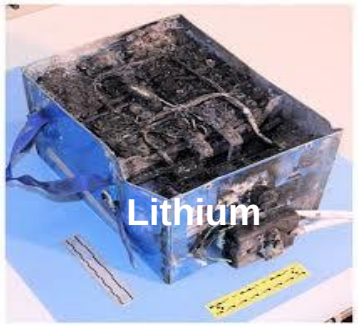
Synfuels

Slow progress

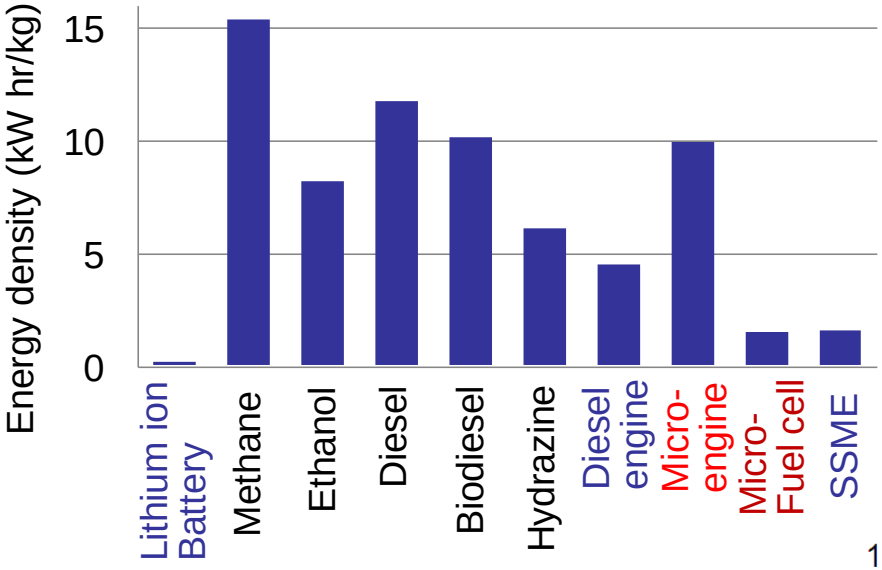
Aviation?

Gasoline: 40 MJ/kg,
8 gal/min : ~16 MW

Battery: < 1 MJ/kg
Tesla charger 120 KW

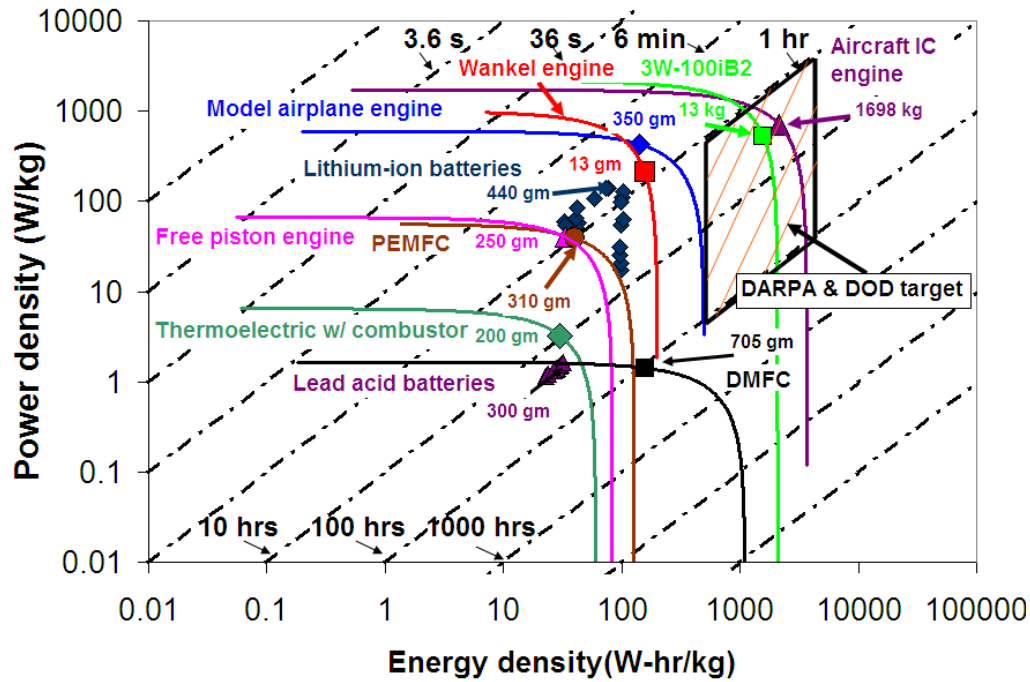


Comparison of specific energy/power densities



Ju Y. and Maruta K., Progress in Energy and Combustion Science, *37*(6), 669-715.

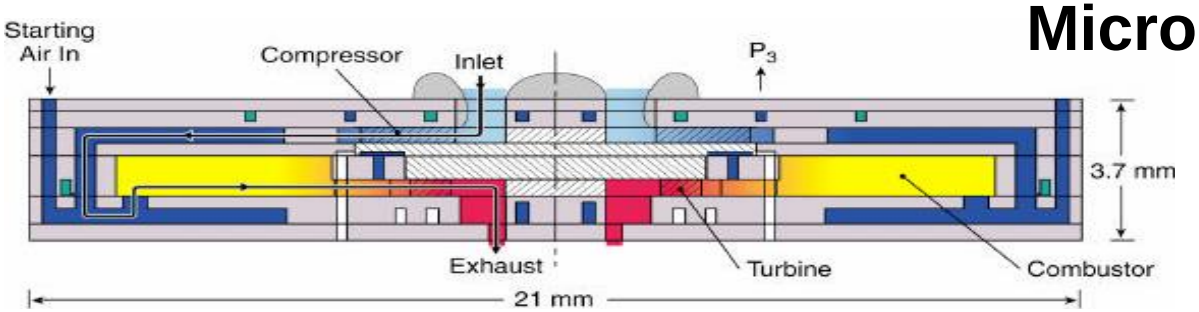
The Ragone plot



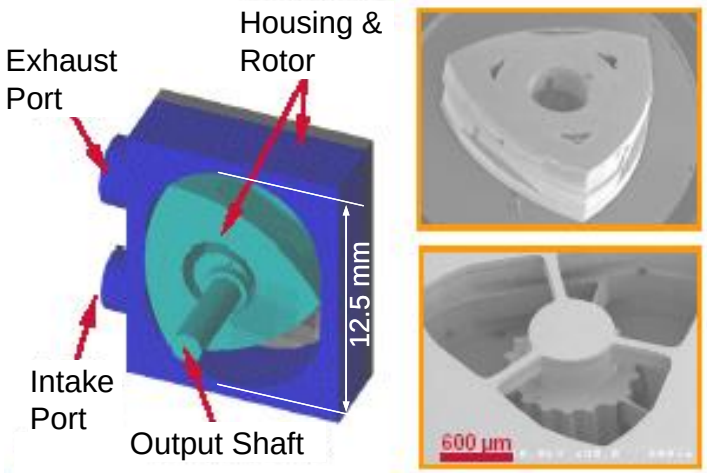
Combustion engines have high power density and energy density!

2. Development and Challenges of Microscale Power Generators

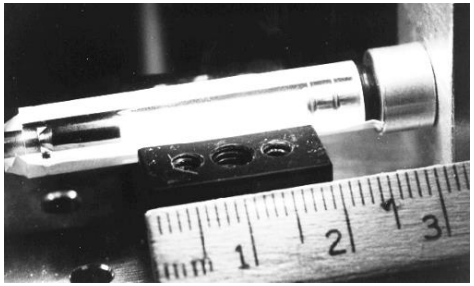
Minimization with moving parts

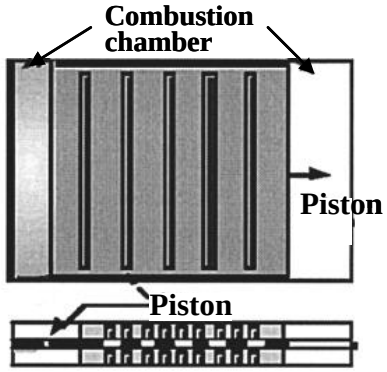


Micro turbine (MIT)



UCB rotary engine





free-piston "knock" engine

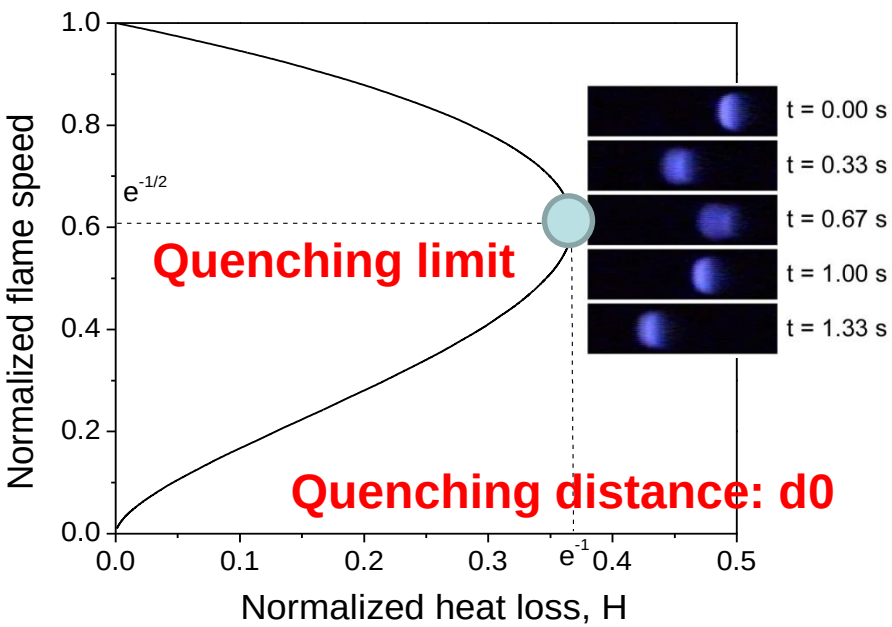
- **Sealing and leakage are big problems!**
- **Large surface area and heat loss**

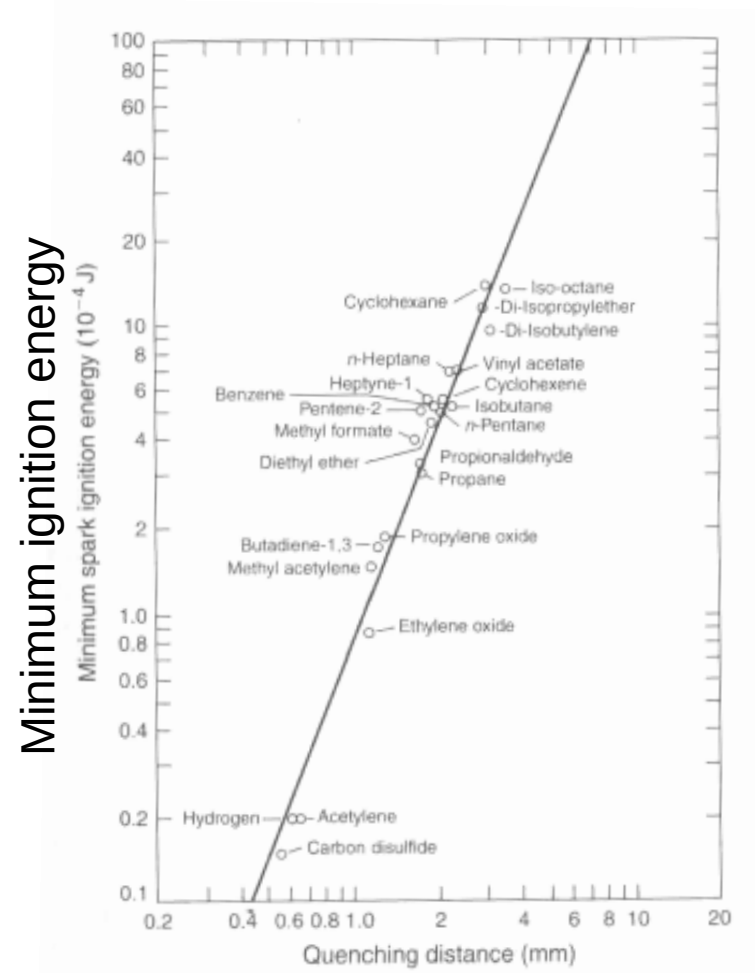
Combustion limits of small scale combustion

Scaling of heat loss: a d^2 law

$$H \equiv \frac{\text{heat loss to the wall}}{\text{total chemical heat release}} \approx \frac{4\delta_f^2}{d^2} Nu$$

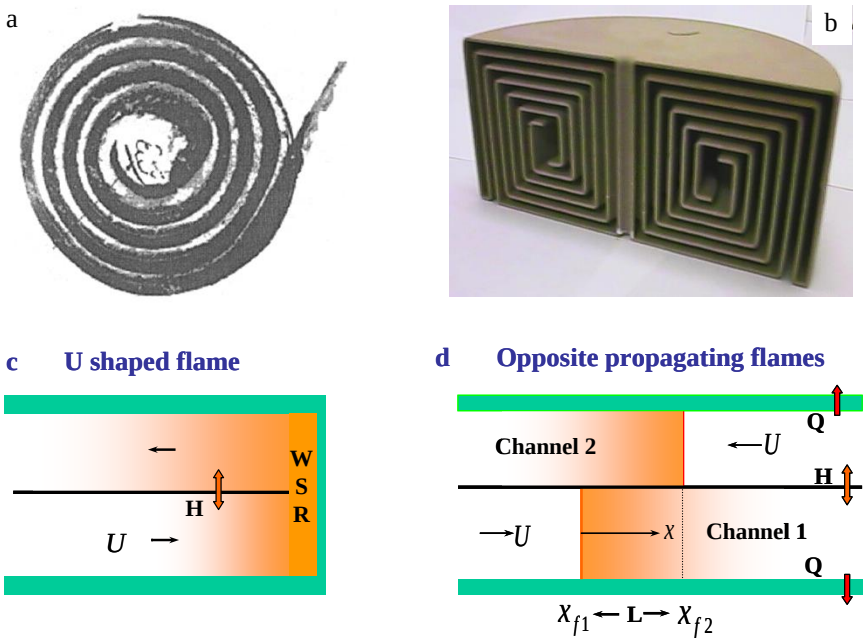
Flame speed vs. heat loss

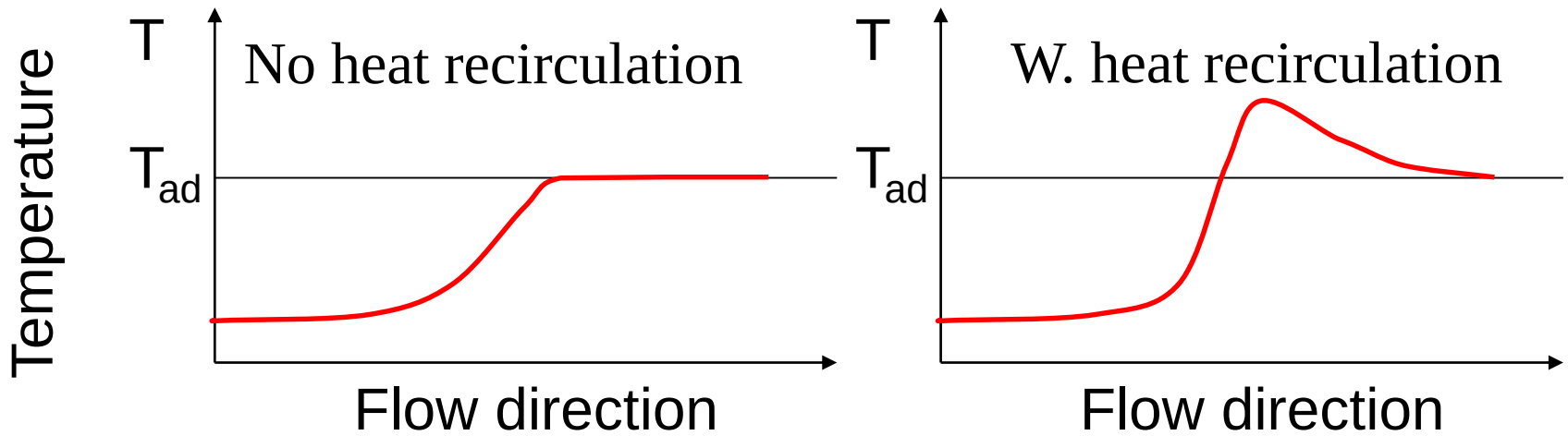




Quenching distance

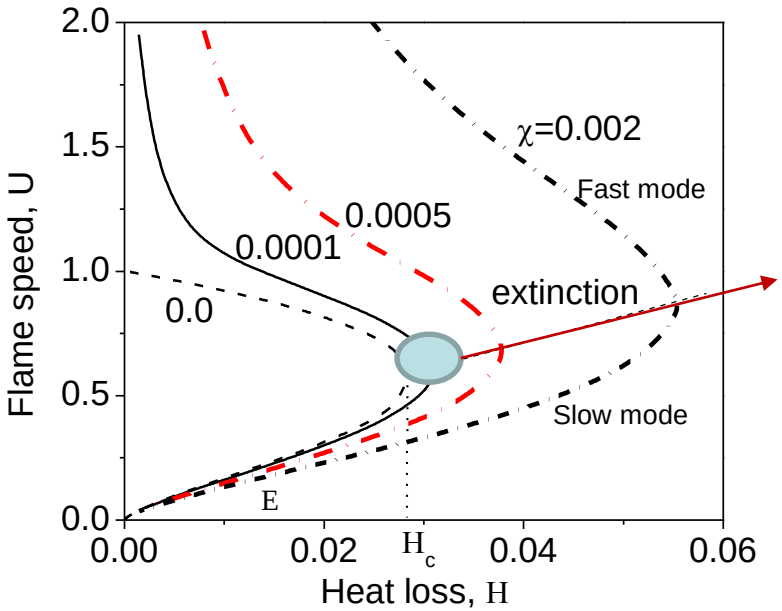
Heat recirculation to reuse heat loss

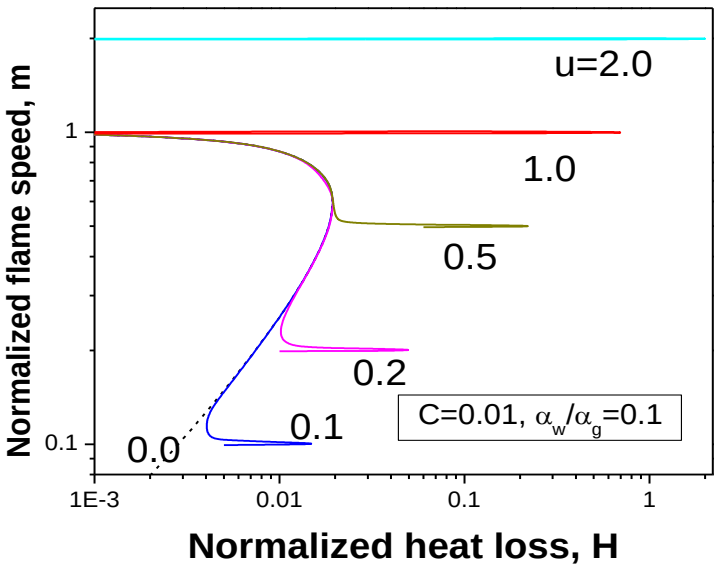




Heat recirculation allows lean burn and breaks quenching limit…

$$H \equiv \frac{\text{heat loss to the wall}}{\text{total chemical heat release}}$$

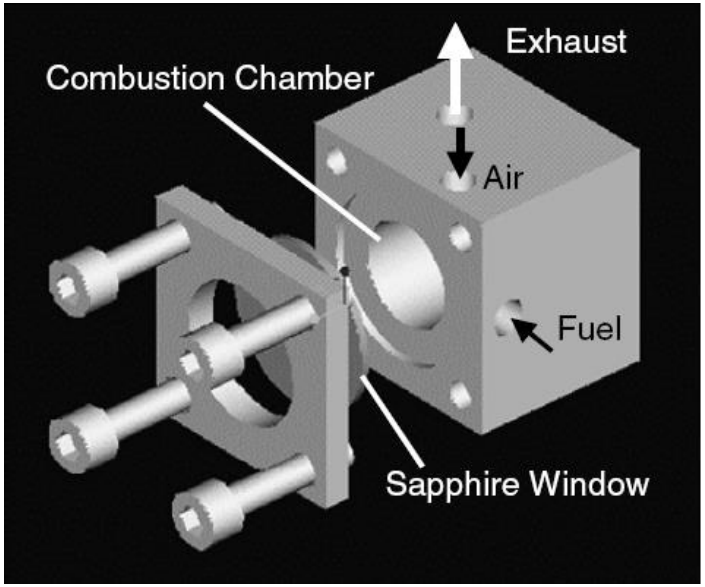


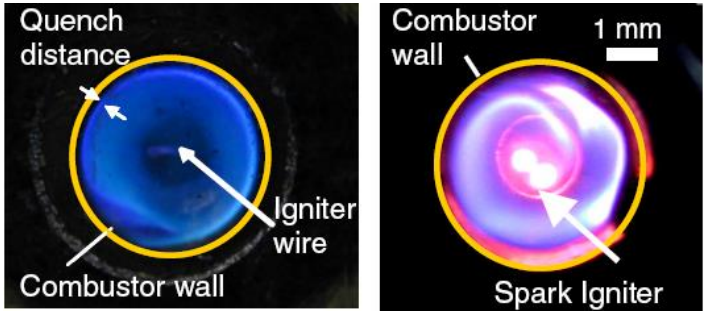


- Combustion can happen beyond critical heat loss
- Flame speed can be higher than adiabatic flame speed

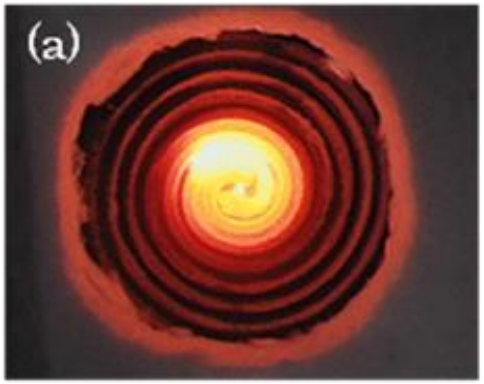
- Combustion limits depends the flow speed

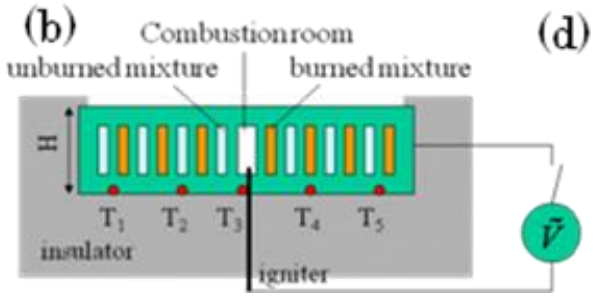
Heat recirculation and burning w.o. moving parts





Penn-state vortex engine: 49.1 mm^3

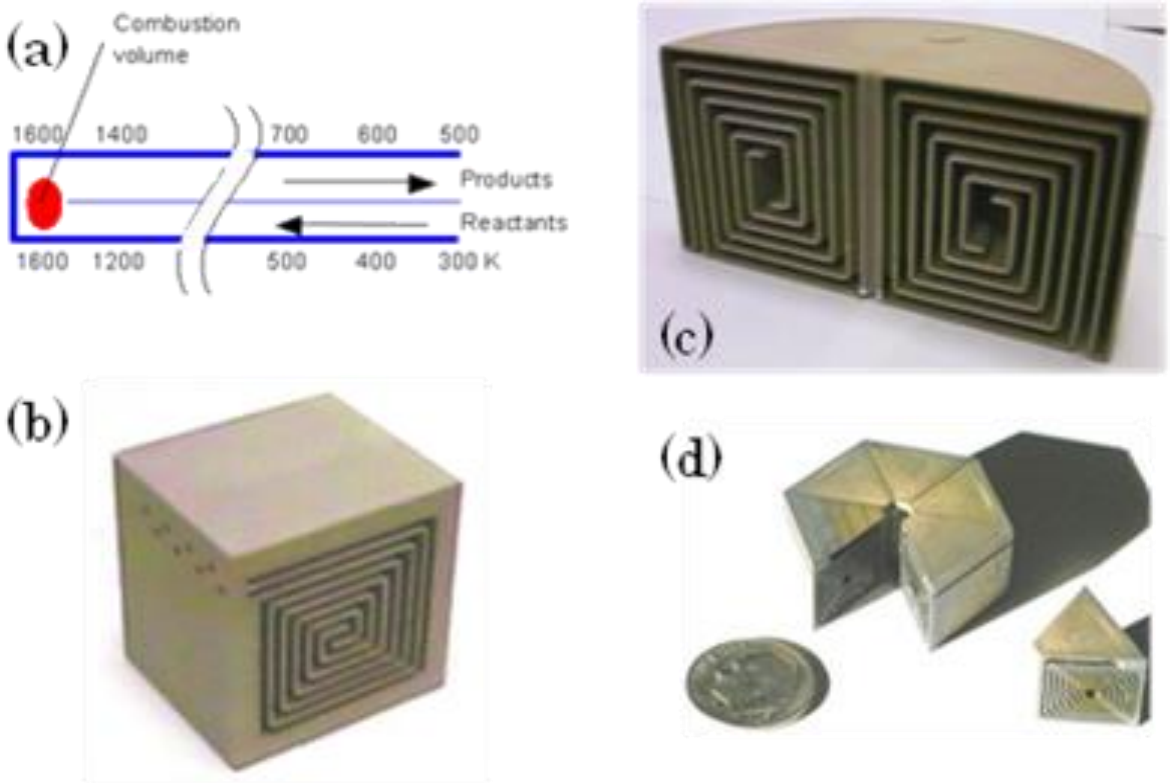




Disk-shaped Swiss-roll combustors
Tohoku University

Efficient burning, but only as a heating source

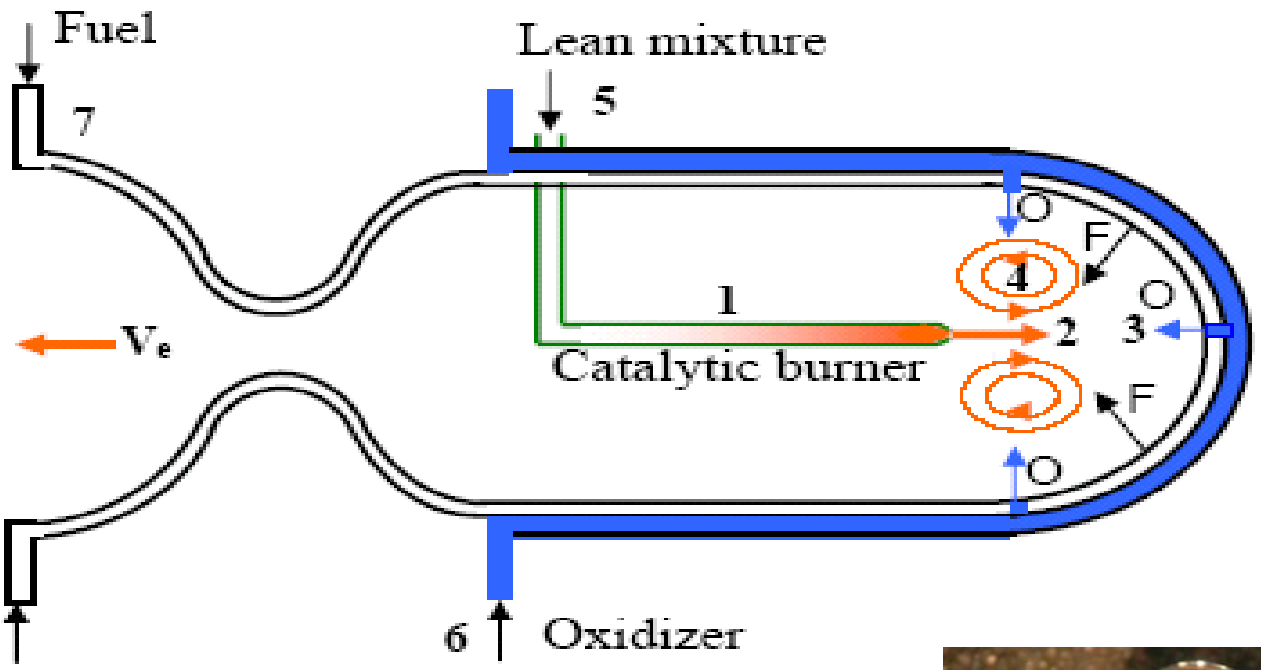
Swissroll combustor（PU, USC，TU）

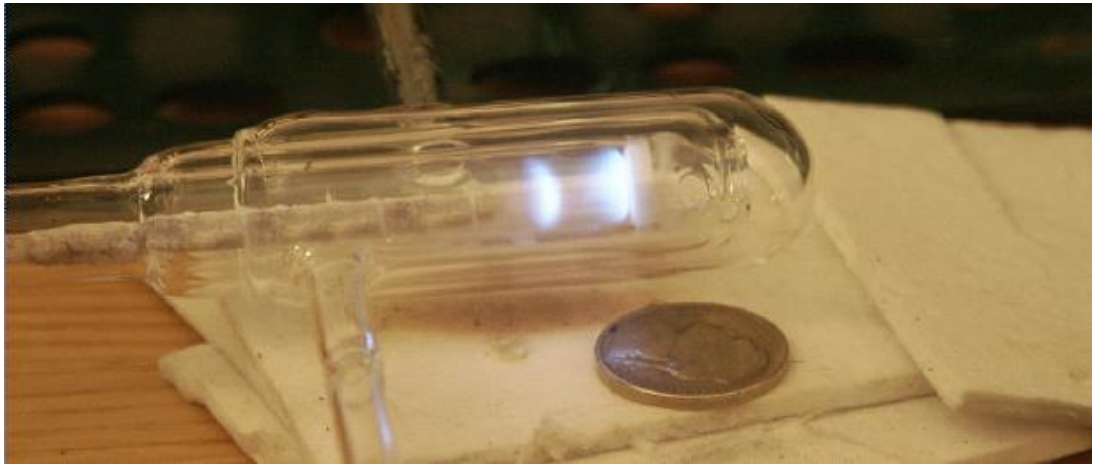


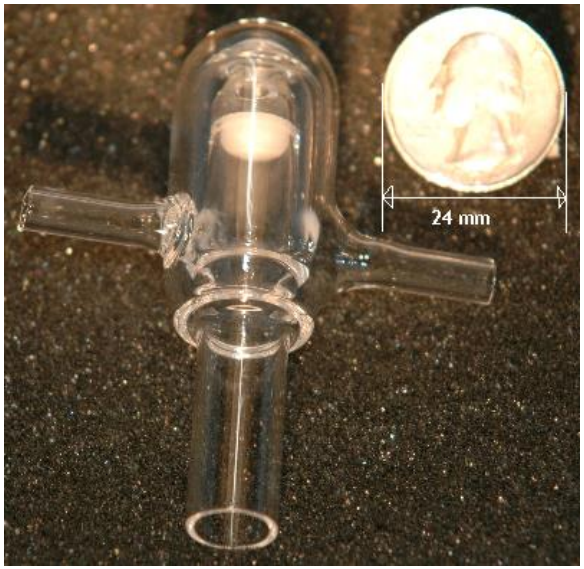
Scheme of heat recirculating burners and burner prototypes fabricated at USC combustion physics laboratory. (a) concept of heat recirculation in U-shaped channel, (b) 2-D Swiss-roll burner, (c) Macro- and (d) meso-scale, toroidal 3-D burners. Both macro- and meso-scale versions attained self-stabilized combustion.

Thermoelectric? but temperature gradient is two small, efficiency is low

Mesoscale catalytic two-stage burner: Princeton







Small internal combustion engines: 1-10 HP

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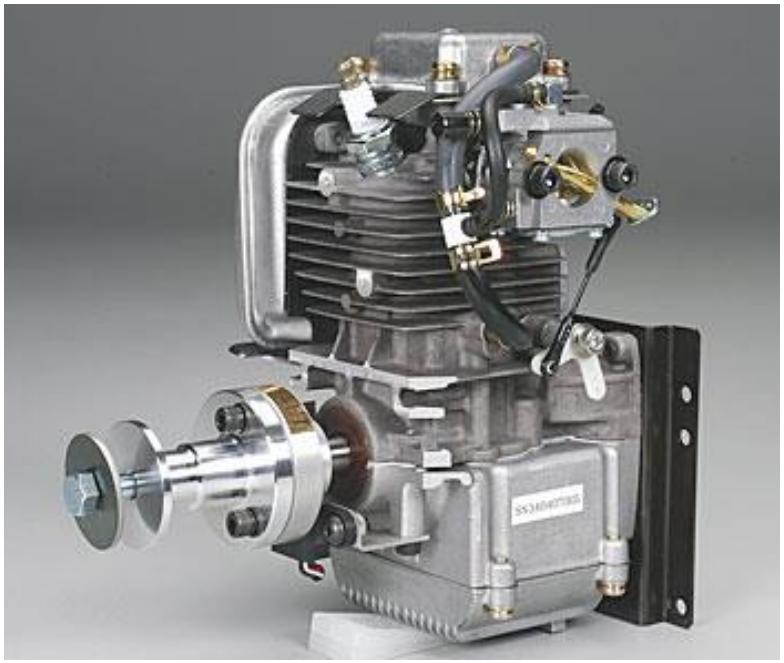
- Weight: 5.89 lbs (2.674 kg)
- Displacement: 2.1 cu in (34cc)
- Bore/Stroke: 1.54x 1.10 in (39x28 mm)
- Practical RPM: 1000-7500
- Horsepower: 2 hp (1491 W) @ 7500 RPM
- Peak Torque: 1.446 lb ft (0.20kgm) @ 5,000 RPM

Fuji Imvac BF-34EI



Poor engine stability in lean burn

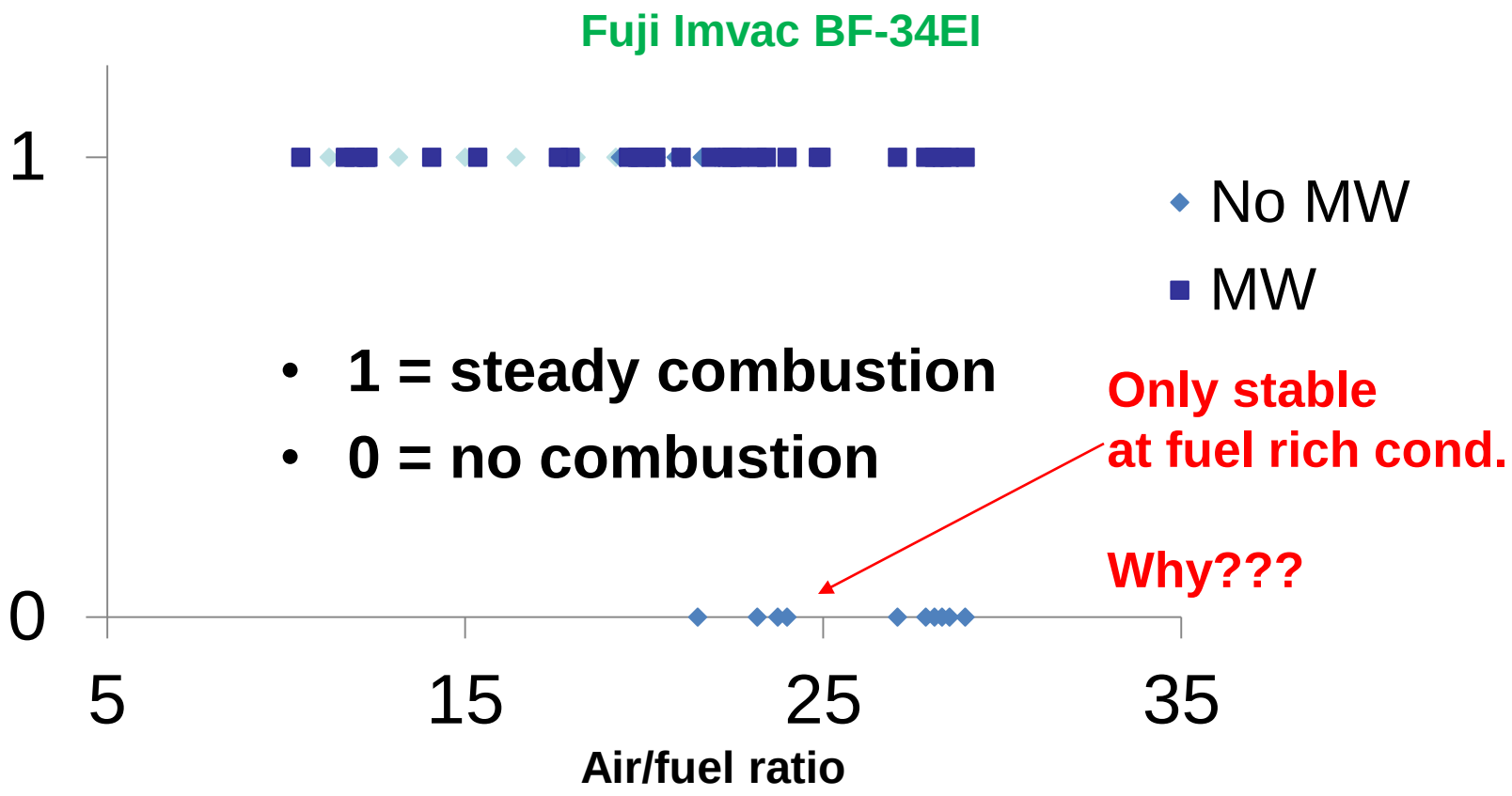
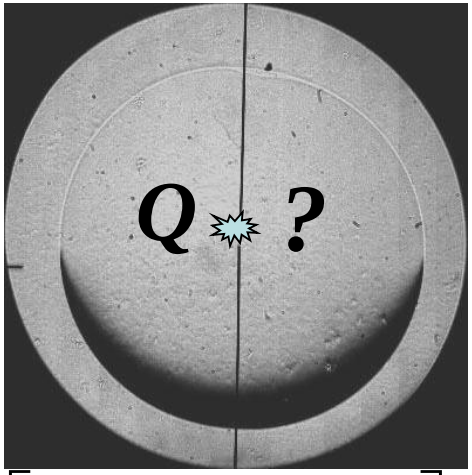


Fig.1 Dependence of engine steady state running on air/fuel ratio

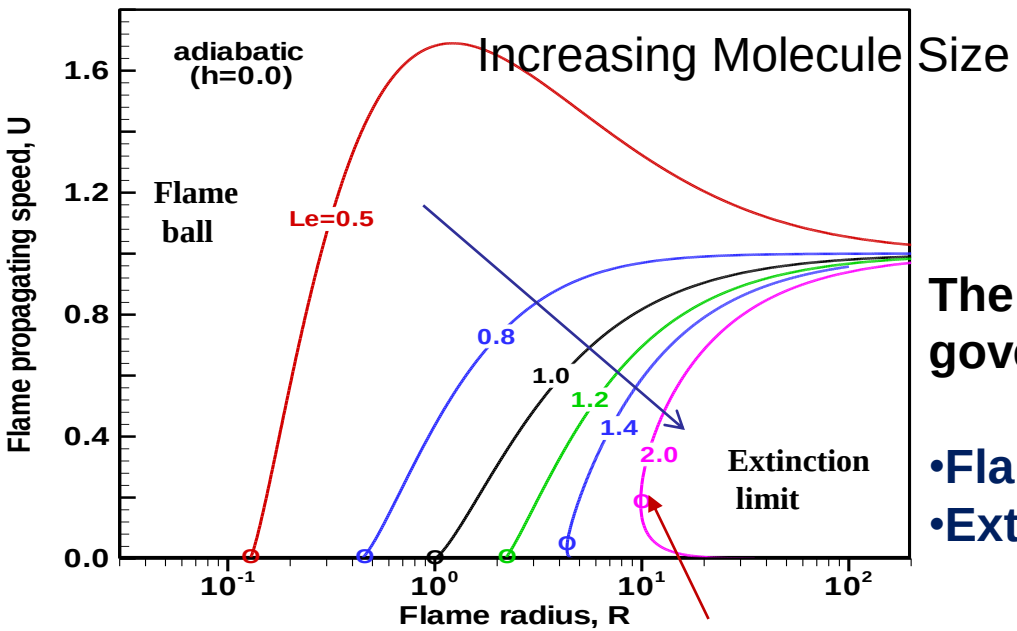
Minimum Ignition Energy?



Assumptions and simplification:

- **1D quasi-steady state, Constant properties**
- **One-step chemistry**
- **Center energy deposition**
- **Adiabatic**

$$T_f \cdot \frac{R^{-2}e^{-\mathrm{U}R}}{\int_R^\infty \tau^{-2}e^{-\mathrm{U}\tau}d\tau} - \mathrm{Q}\cdot R^{-2}e^{-\mathrm{U}R} = \frac{1}{\mathrm{Le}}\frac{R^{-2}e^{-\mathrm{ULe}R}}{\int_R^\infty \tau^{-2}e^{-\mathrm{ULe}\tau}d\tau} = \exp\left[\frac{Z}{2}\frac{T_f-1}{\sigma+(1-\sigma)T_f}\right]$$



$$Le = \frac{\text{Thermal diffusivity}}{\text{Mass diffusivity of fuel}}$$

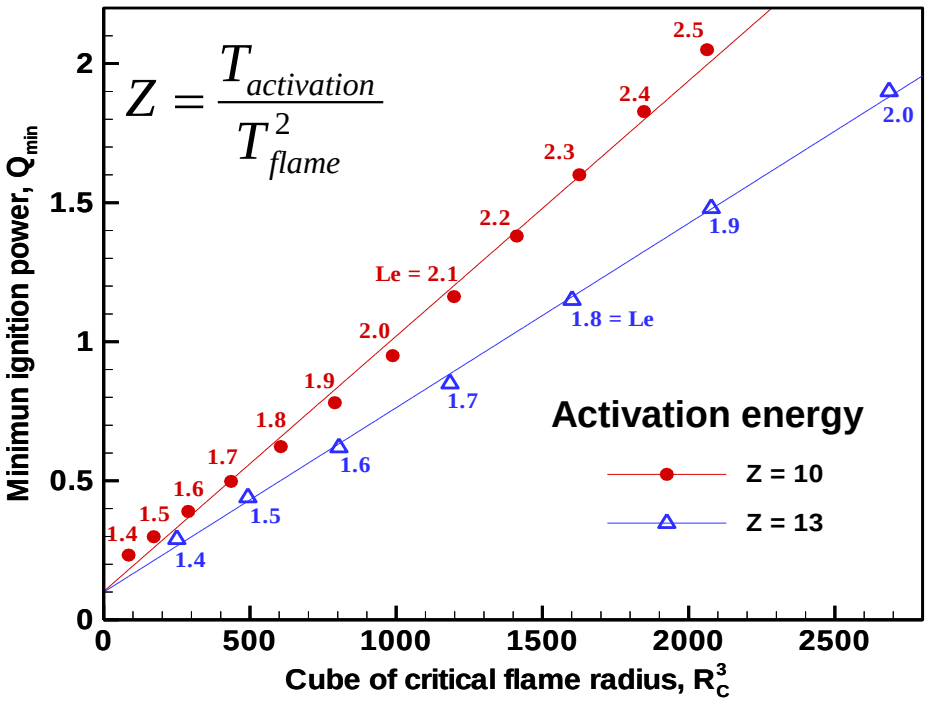
The critical ignition size and energy is governed by two different length scales:

- **Flame ball size (small Le)**
- **Extinction diameter (large Le)**

Source: Chen & Ju, Comb. Theo. Modeling (2007)

R_c: critical radius

Minimum Ignition Energy depending on fuel molecule size



Activation temperature: The temperature needed to initiate a particular chemical reaction

$$Le = \frac{\text{Thermal diffusivity}}{\text{Mass diffusivity}}$$

Molecule size of fuel ⇧ = Mass Diffusivity ⇩ = Le ⇧

- Smaller molecules lead to lesser ignition energy
  - Plasma can dissociate fuel into smaller molecules
- Lesser activation energy leads to lesser ignition energy.
  - Plasma can create species which will have small activation energy when reacting with the fuel, i.e. radicals and electronically excited molecules.

How do we improve engine ignition reliability?

Make the spark > R_c !

Source: Chen, Burke, Ju, *Proc. Comb. Inst. Vol.33* (2010)

Non-equilibrium plasma: large ignition kernel

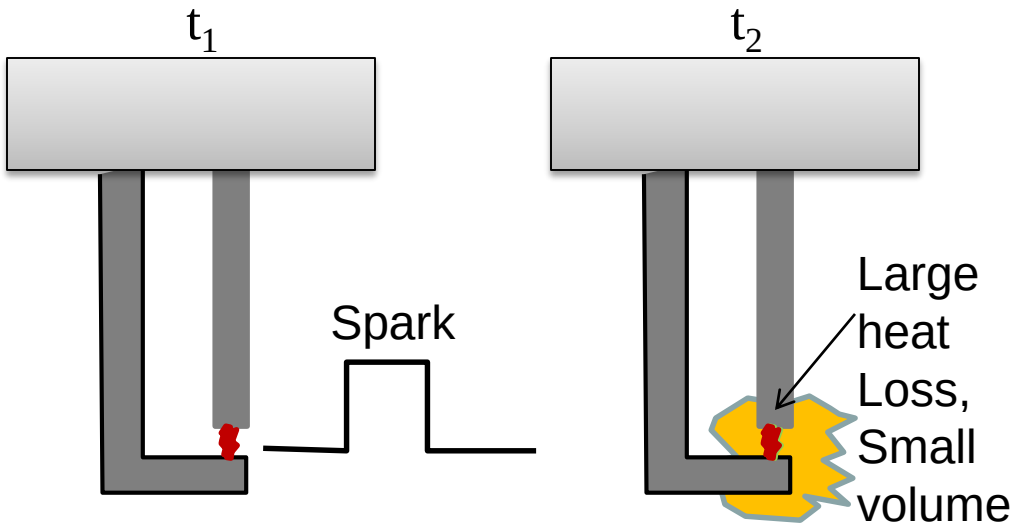


Fig.1 Current spark ignition plug: large heat loss, small volume

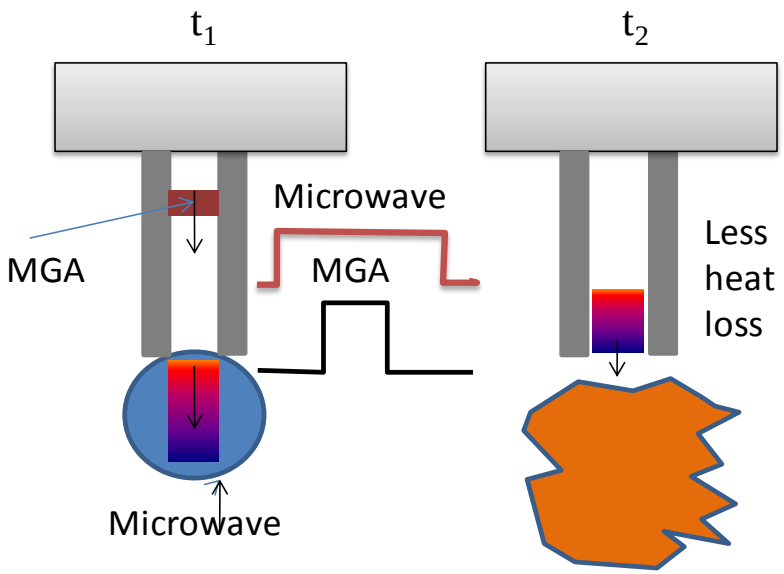


Fig.2a New microwave gliding ignition Increased volume, less heat loss

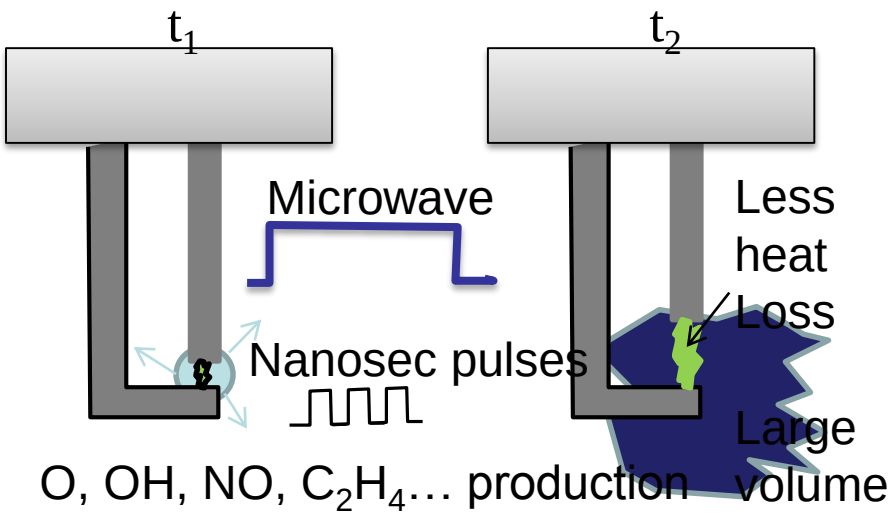
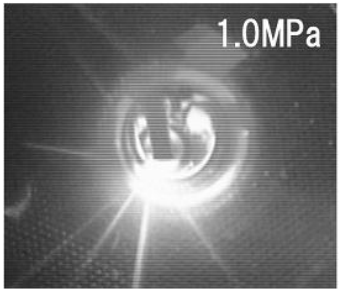


Fig.2b New microwave repetitive nanosec ignition with radical production, increa volume, less heat loss

Enlarge ignition kernel size by plasma



Comparison of ignition using microwave, gliding arc and conventional discharge at 10 atm (Knite Inc. and Imagineering Inc.)

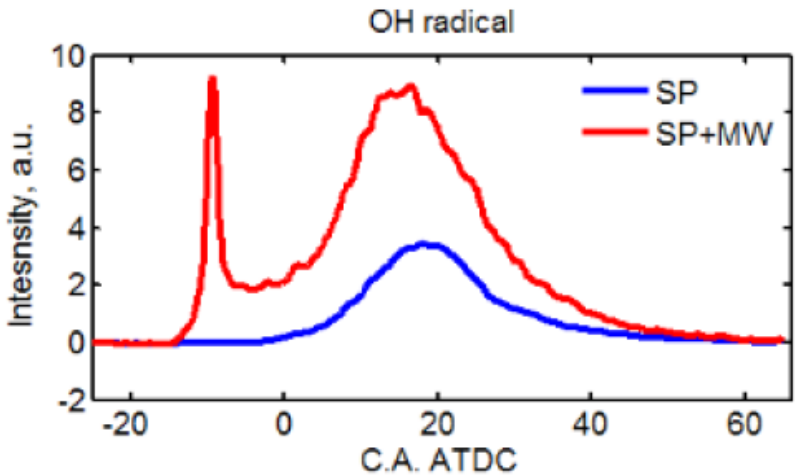
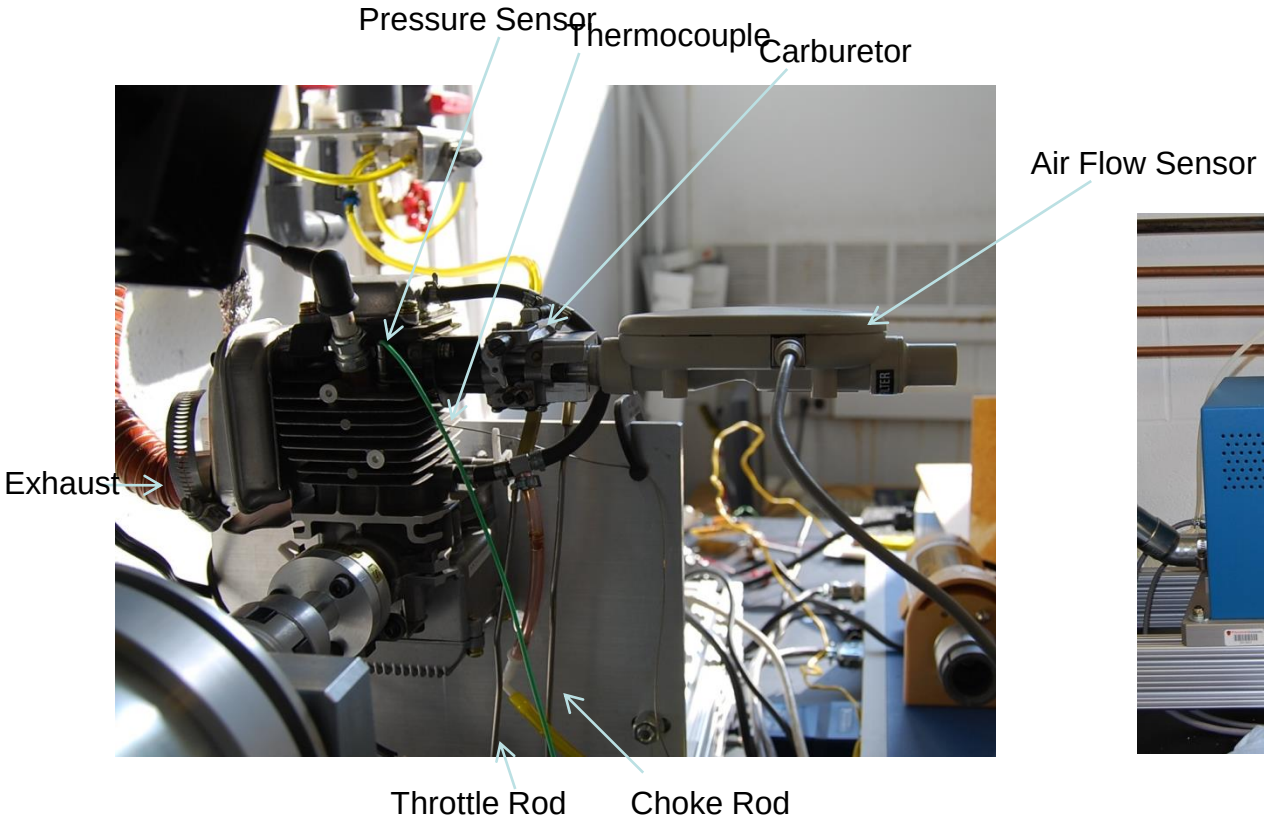
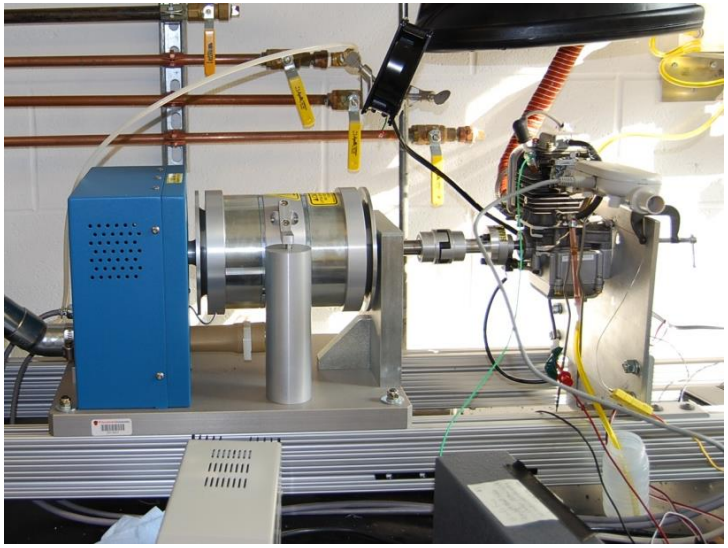


Fig.7 Comparison of measured OH intensity as a function of time in a gasoline engine by using a conventional spark plug and a conventional spark with microwave

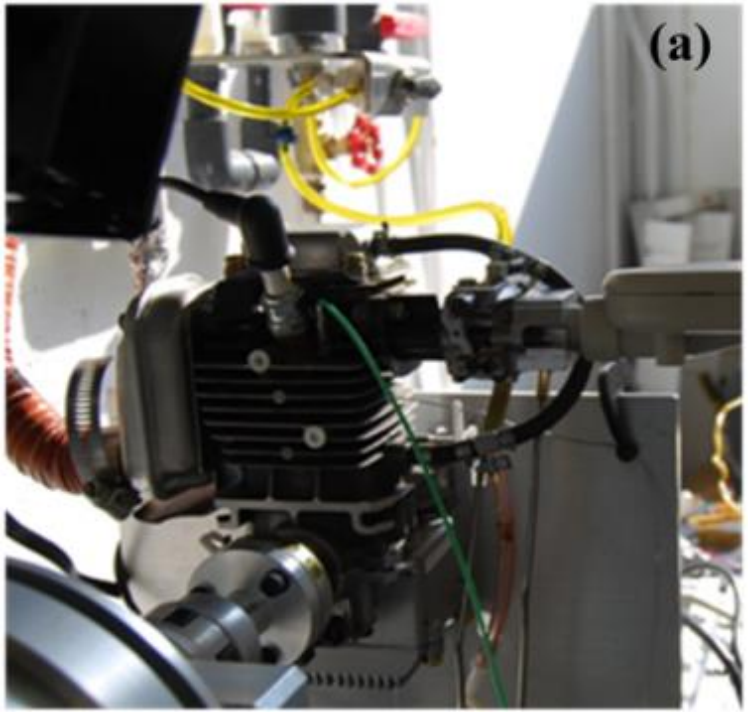
Test Facilities

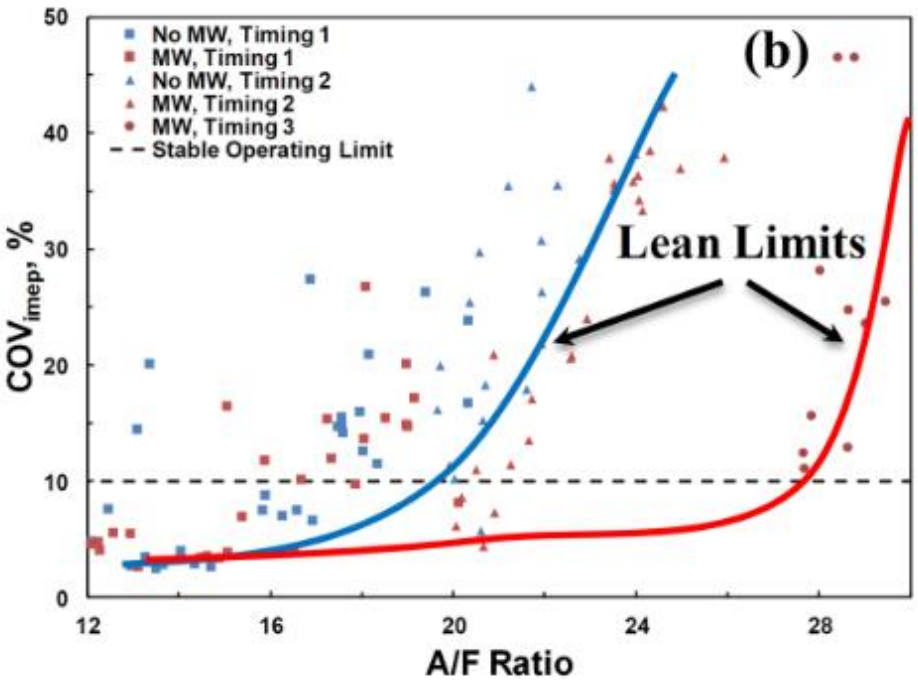




Small engine test facility at Princeton University

Success of plasma assisted combustion in engine





30% extension of lean burn!

It is not the fuel is too lean, it is the ignition spark size too small!

COV: Coefficient of Variation

Lefkowitz et al. 2012, Ikeda et al. 2009

Microwave enhancement

Lean limit of a Fuji (34 cc) engine was extended dramatically (30%) by a microwave igniter, at 2000 RPM

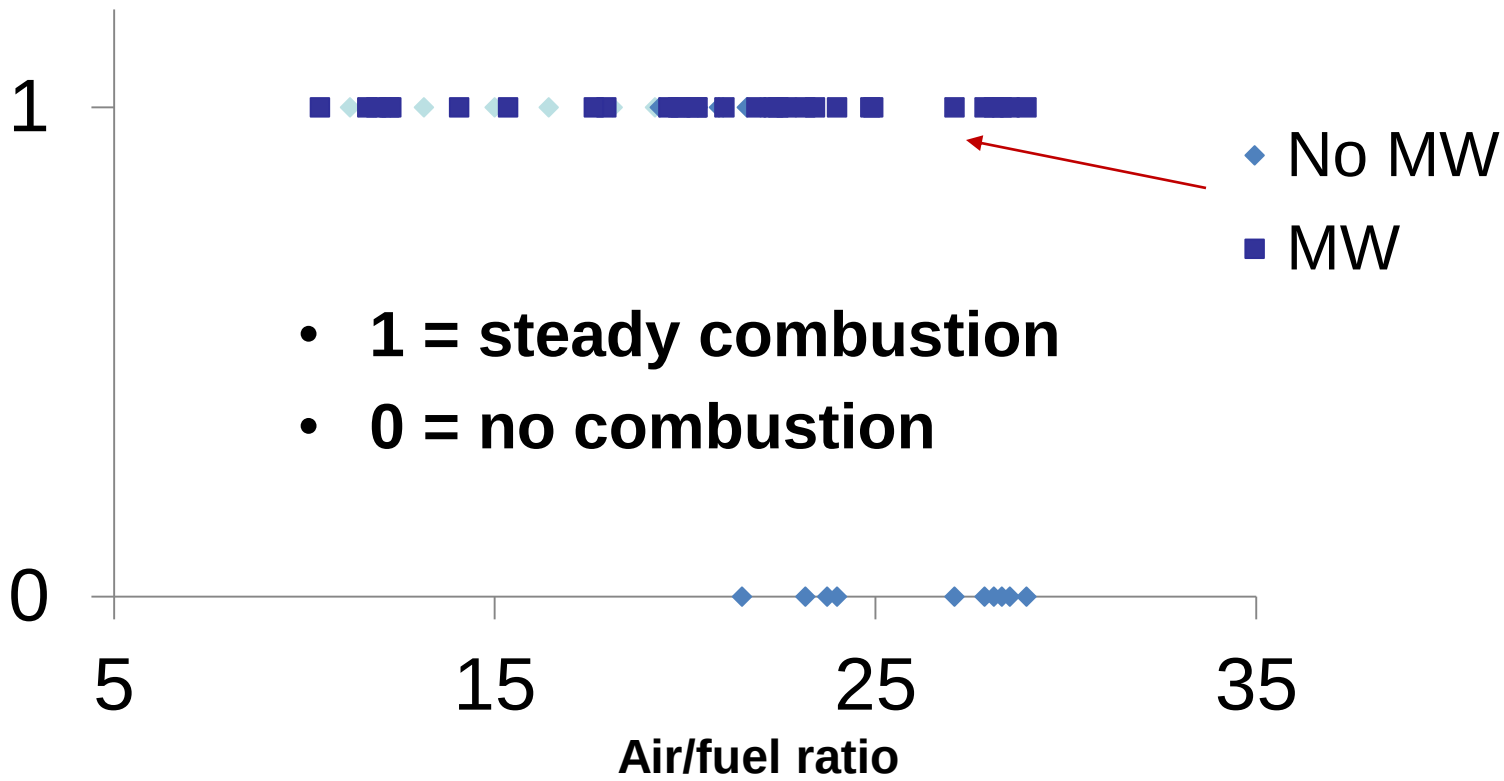
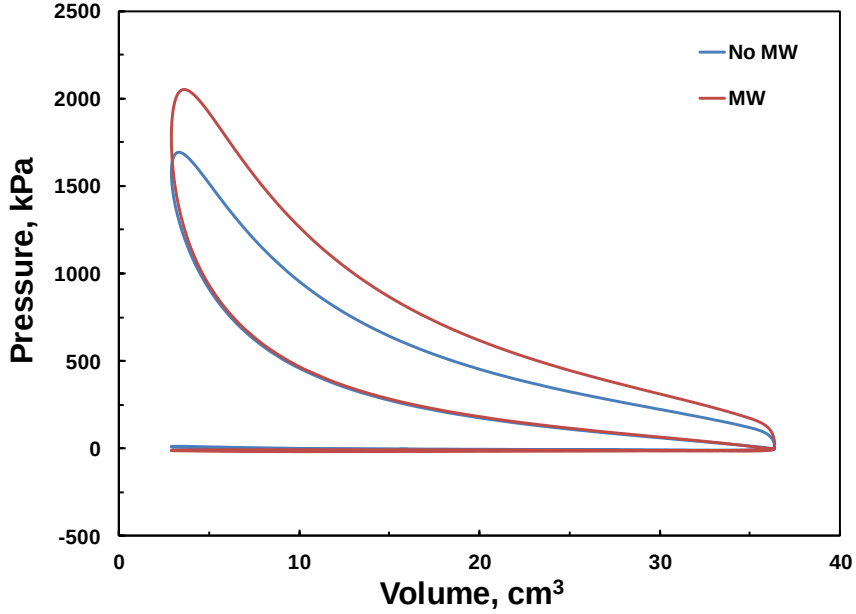
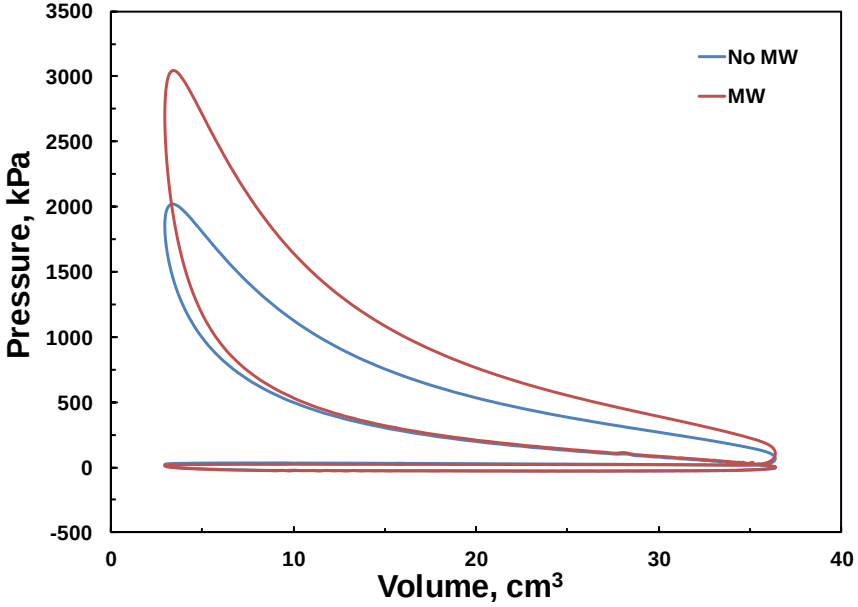


Fig.1 Dependence of engine steady state running on air/fuel ratio for ig with and without microwave discharge.

P-V Plots





- Left, 2000 RPM, A/F = 23.5
- Right, 5000 RPM, A/F = 22.2

Flammability Limit
Existing Plug-based Ignition Systems

- Regular spark plugs

  Equi. Ratio < 1.4

- Regular spark plugs with thin (Iridium/Platinum) electrodes

  Equi. Ratio < 1.6

- RF, "plasma", etc. plugs

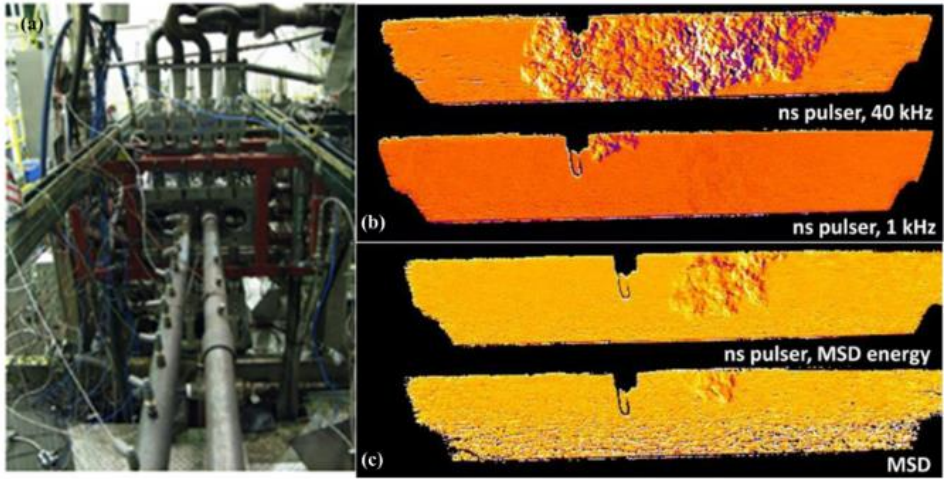
  Equi. Ratio < 1.8

- **Distributed NS Sparks**

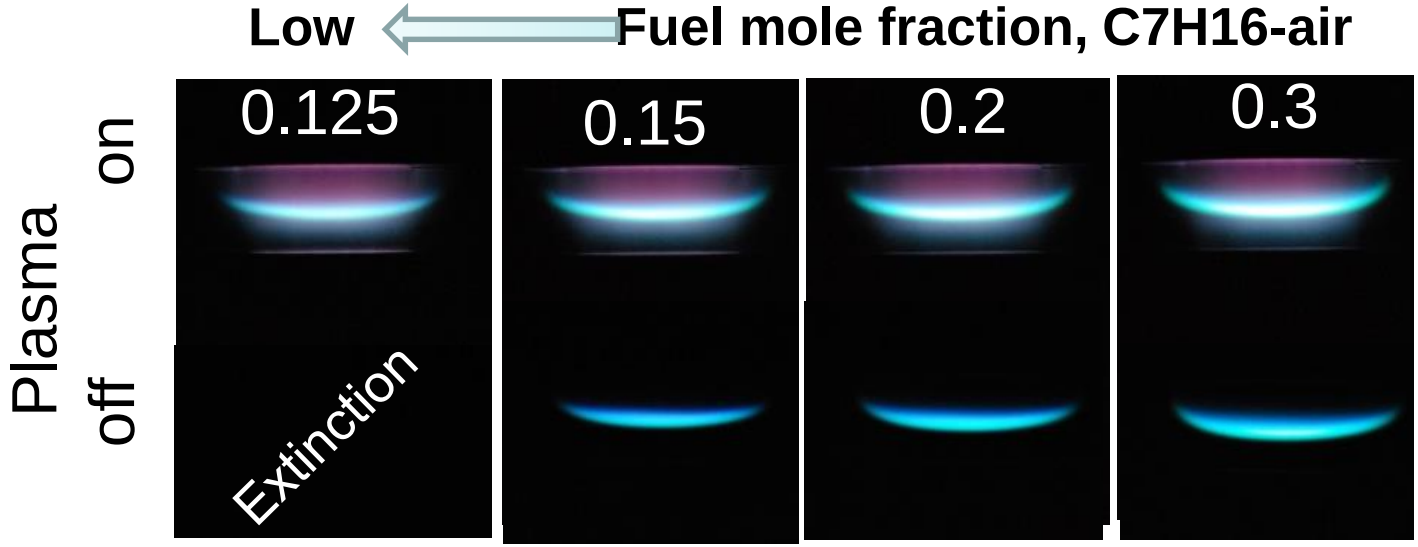
  Equi. Ratio **> 3**

Andrey Y. **Starikovskiy**

More examples of success of plasma assisted combustion



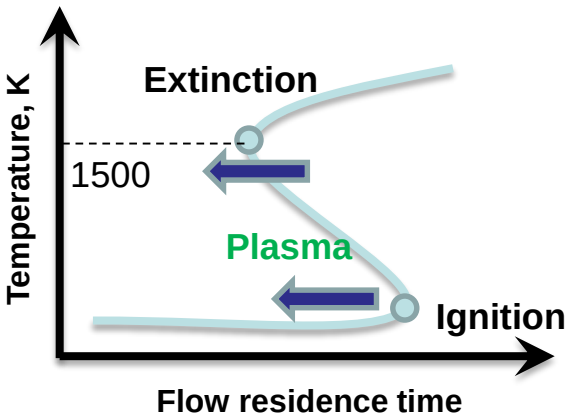
Pulse detonation engine, nanosecond
Lefkowitz and Ombrello et al. 2013



Opportunity: Plasma change combustion limits?

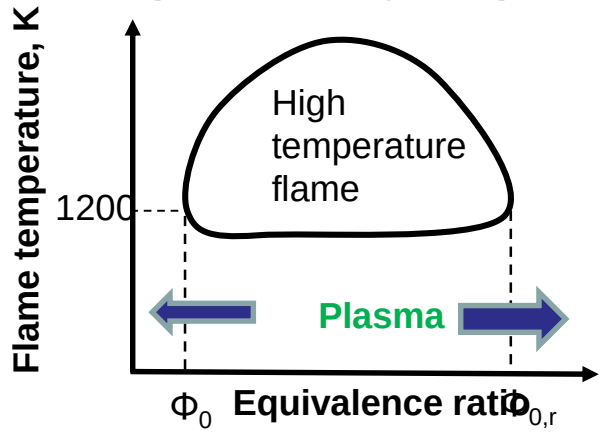
How plasma can assist combustion?

Ignition/extinction S-curve



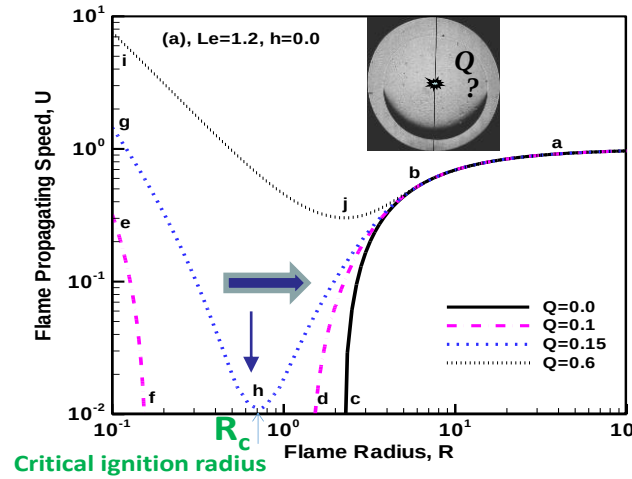
- Shorten ignition time
- Extend extinction limit

Flame speed and propagation (Flammability limit)



- Increase flame speed
- Extend flammability limit

Ignition to flame transition (critical radius, R_c)



- Make ignition kernel > Rc
- Accelerate ignition to flame trans

Plasma assisted fuel oxidation: chemical pathways

Ju and Sun, Plasma assisted combustion, PECS. 2015.

$e + O_2 = O + O(^1D) + e$

$H + O_2(^1\Delta_g) = O + OH$

$O(^1D) + RH = OH + R$

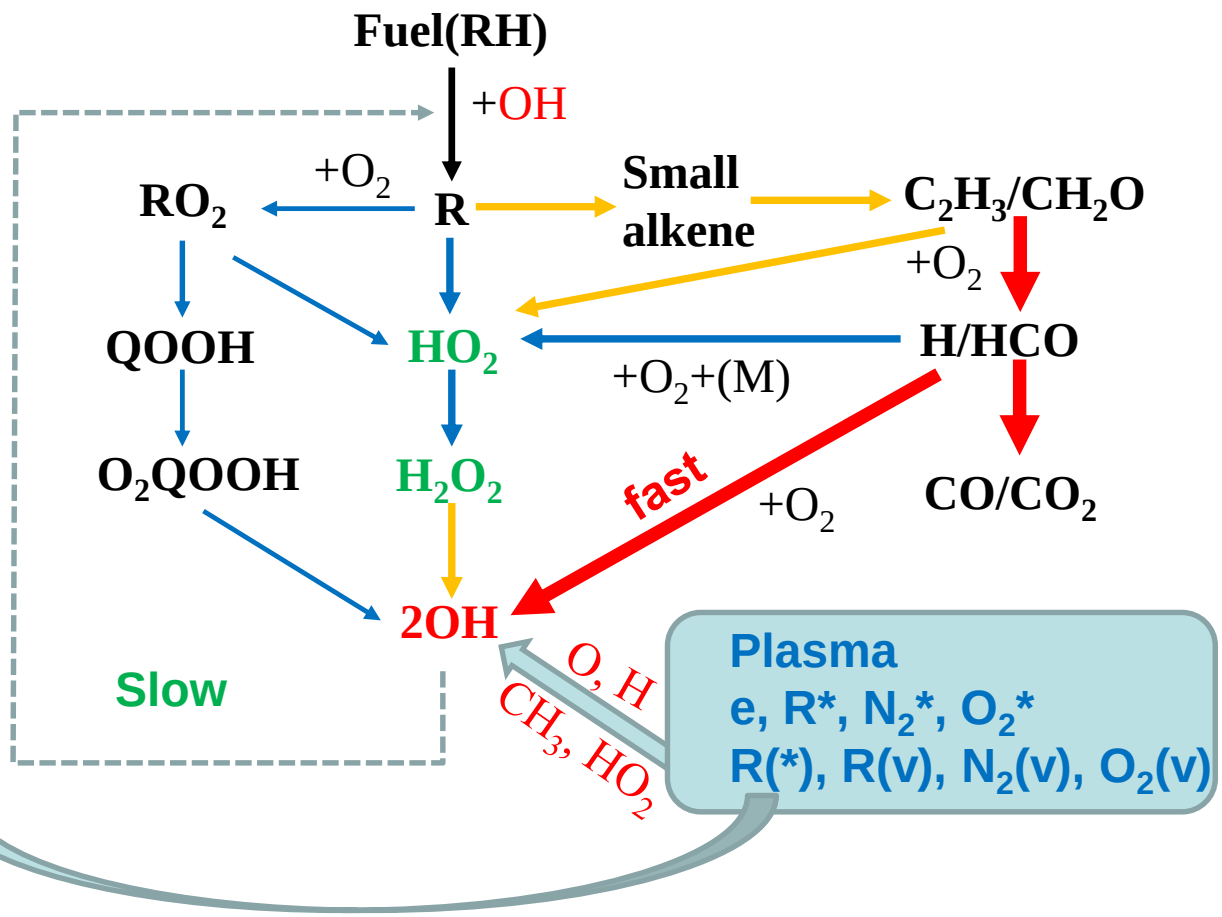
$N_2(A,B,C) + O_2 = O + O + N_2$

$N_2(v) + HO_2 = OH + O + N_2$

$R(v,*) + O_2 = RO + OH$

$= ???$

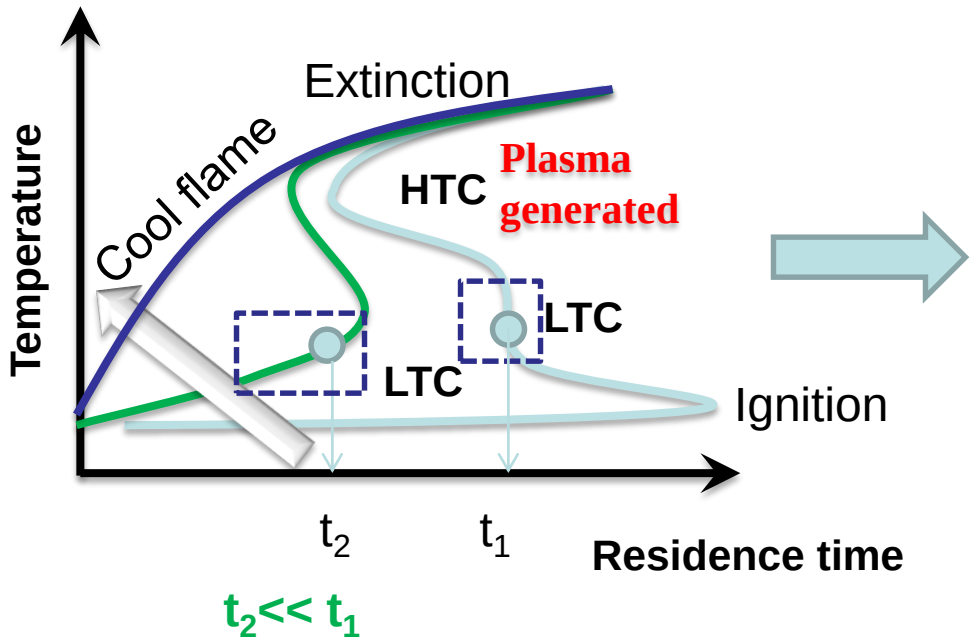
$O_3 + M = O + O_2 + M$



A schematic of the key reaction pathways for high pressure fuel oxidation of at different temperatures (**blue arrow**: Below 700K; yellow arrow: 700-1050 K; red arrow: above 1050K).

What if a fuel has low temperature chemistry

Plasma assisted cool diffusion flames



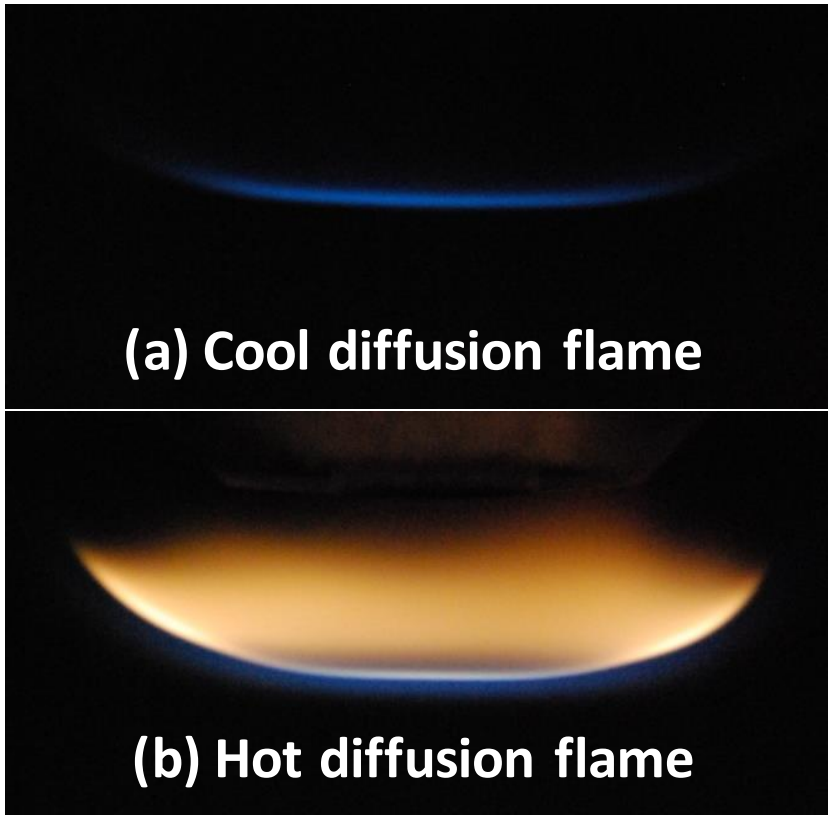
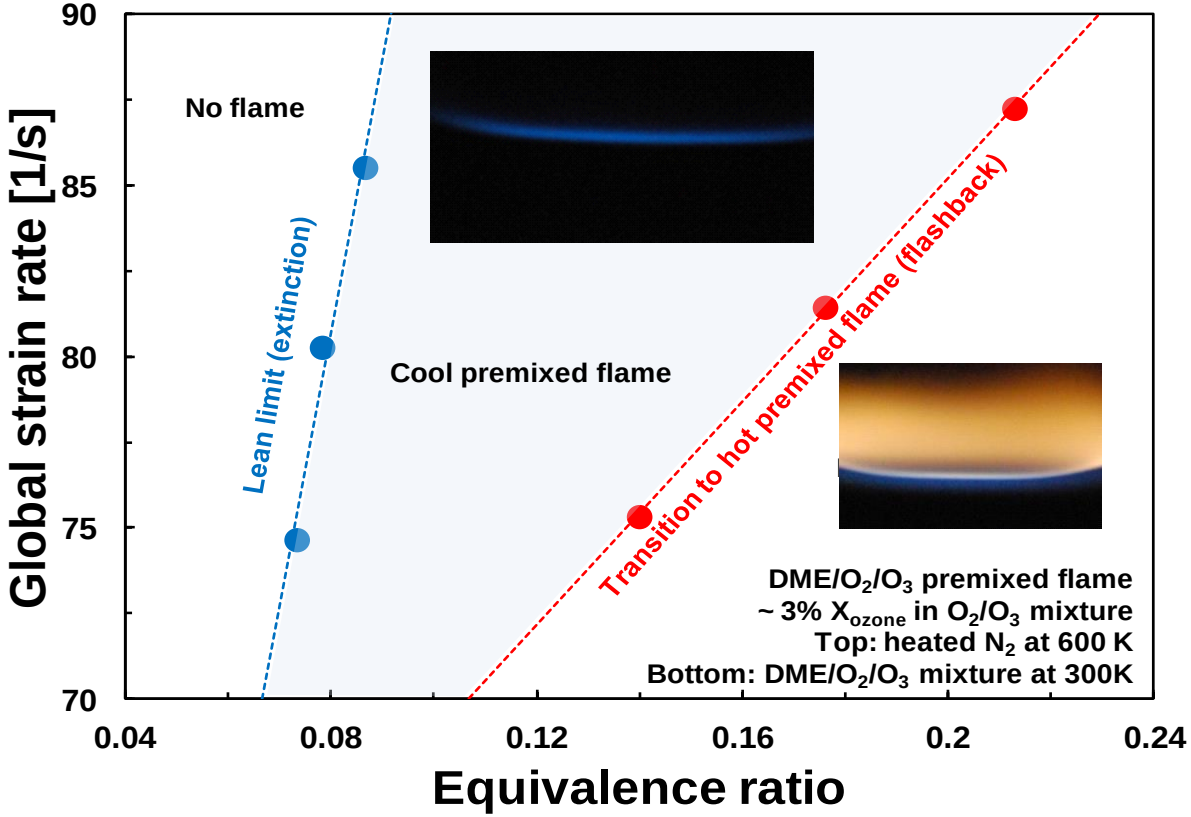


Fig.18b Direct photos of n-heptane/oxygen cool diffusion flame (a) and hot diffusion flame (b) flames, observed at the identical flow condition, fuel mole fraction of 0.07 and strain rate of 100 s^{-1} (Won et al. 2014).

Cool flames has no soot and NOx emission

Plasma assisted premixed cool flames



Regime diagram of cool and hot premixed flames for DME/O_2/O_3 mixture in global strain rate and equivalence ratio

Cool flame burns leaner with no soot emissions

Conclusions

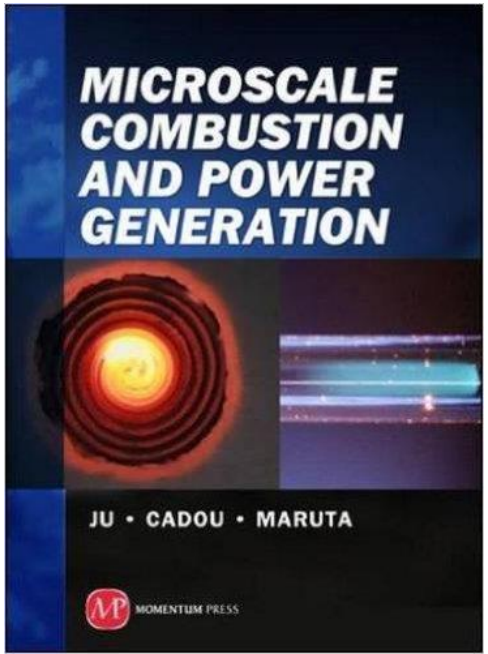
- **Heat loss, sealing, moving parts are problems for small scale power generation.**
- **Heat recirculation and thermal management can enable higher flame speed and sublimit combustion.**
- **Ignition in a small scale engine can be problematic at fuel lean condition due to the critical ignition radius.**
- **Plasma can enlarge the ignition kernel size, and produce chemistry effect to enhance ignition and combustion.**
- **Plasma produced cool flames provide a new way to control combustion and emissions in small scale engines.**

Thanks!

Question?

3 references

1. Ju, Y., & Maruta, K. (2011). Microscale combustion: Technology development and fundamental research. *Progress in Energy and Combustion Science*, *37*(6), 669-715.

2. Ju, Y., & Sun, W. (2015). Plasma assisted combustion: Dynamics and chemistry. *Progress in Energy and Combustion Science*, *48*, 21-83.

3. Ju,Y., Cadou, C., Maruta, K., Microscale Combustion and Power Generation, Momentum Press (January 22, 2015), ISBN-13: 978-1606503065