Burning and Sooting Behavior of Ethanol Droplet Combustion under Microgravity Conditions

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Work in Progress Poster 1F3-02

This work is excerpted from a paper in Combustion Science and Technology
In Press, May 2004

30th International Symposium on Combustion
University of Illinois, Chicago
Chicago, IL
July 25-30, 2004

Work supported under NASA Agreement NCC3-1049

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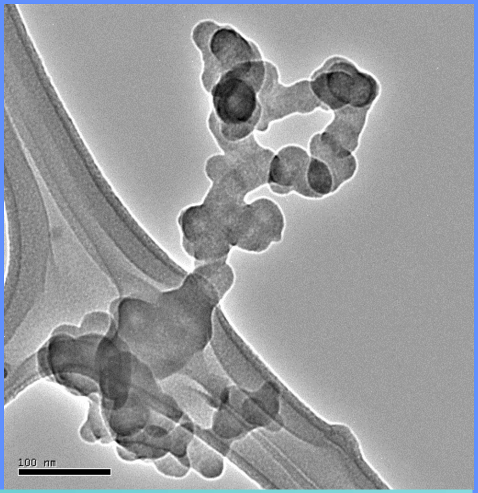
Abstract

In an effort to gain a better understanding of the burning and sooting behavior of ethanol, isolated droplet combustion experiments were performed in the 2.2 sec droptower at NASA Glenn Research Center. The measurement of the burning rate, soot standoff ratio and soot volume fraction are described in which initial droplet diameter, oxygen concentration, ambient pressure and inert were varied. The experiments reveal that while ethanol droplets burn in 1 atmosphere air without soot formation, luminous radiation from soot particles is observed at higher pressures, with increased sooting at higher oxygen volume fraction. Increases in the oxygen concentration at elevated pressures results in a non-monotonic behavior in the measured soot volume fraction. These experiments provide the first quantitative measurements of the soot volume fraction for ethanol droplet burning under microgravity conditions.

Motivation of Study

Better understanding of influence of sooting on burning process is required

- Radiative heat losses
- Changes in thermophysical properties
- Fuel mass flux barrier
- Reduction of effective heat of combustion



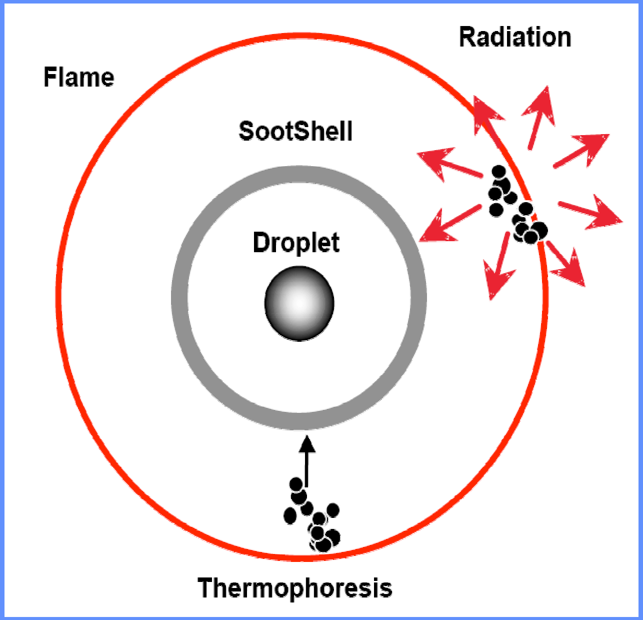
Ethanol is a very important fuel:

- A renewable energy source
- Alternative fuel
- An effective fuel additive

As a result ethanol accounts for 1% of the highway motor fuel market in the US

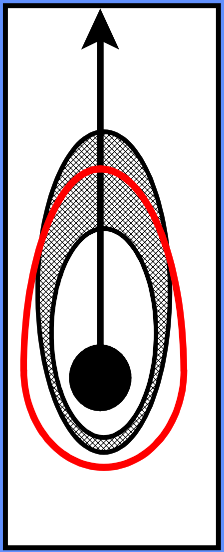
Objectives of Study

- Determine the influence initial droplet diameter, pressure, oxygen concentration and inert on soot concentration
- Determine the influence of soot concentration and radiation on droplet burning rate
- Obtain a complete set of experimental measurements to benchmark evolving droplet combustion and soot models

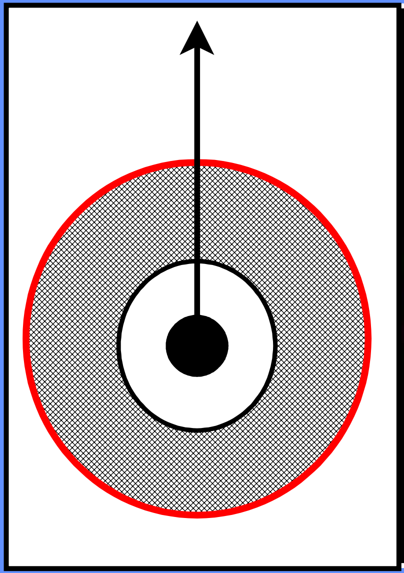


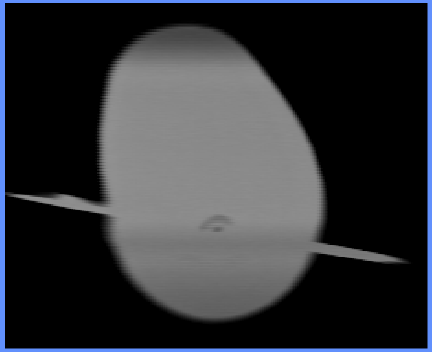
Need for Microgravity

Goal : Reduce Grashof number

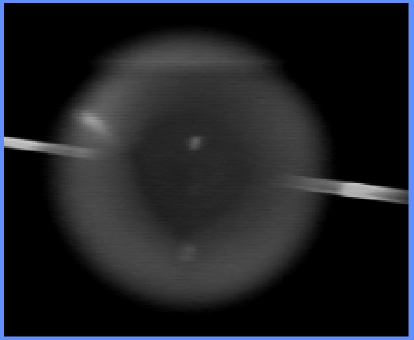


$$Gr = \frac{\frac{\Delta\rho}{\rho} g d_f^3}{D_g^2}$$

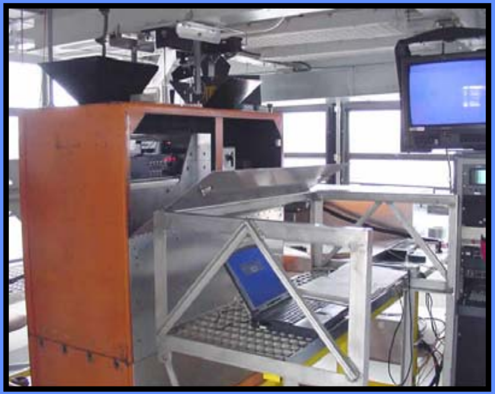




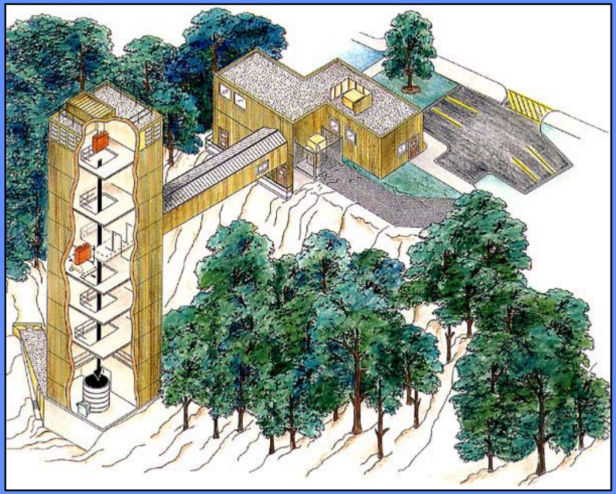
Microgravity Facility	Gravity Level
Drop tower	10^{-4} g - 10^{-6} g
Parabolic flight aircraft	10^{-1} g - 10^{-3} g
Sounding rockets	10^{-4} g
Orbiting spacecraft	10^{-6} g

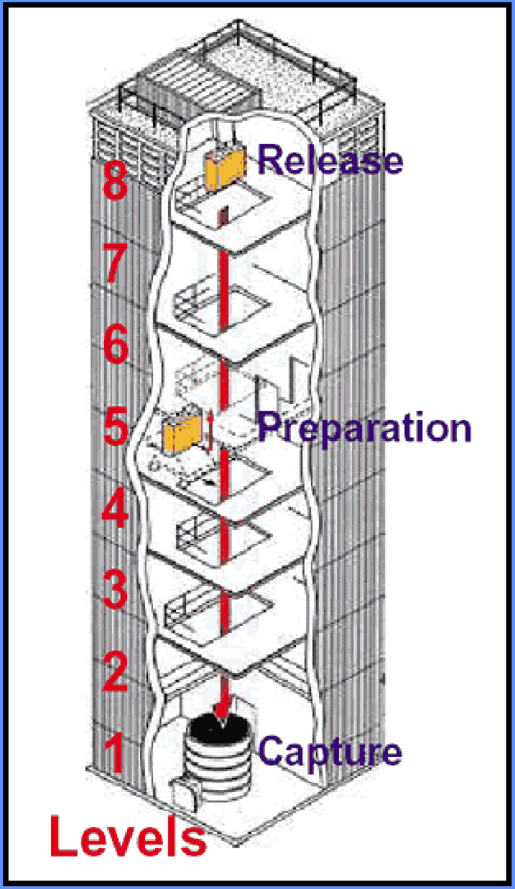


NASA 2.2 Second Droptower

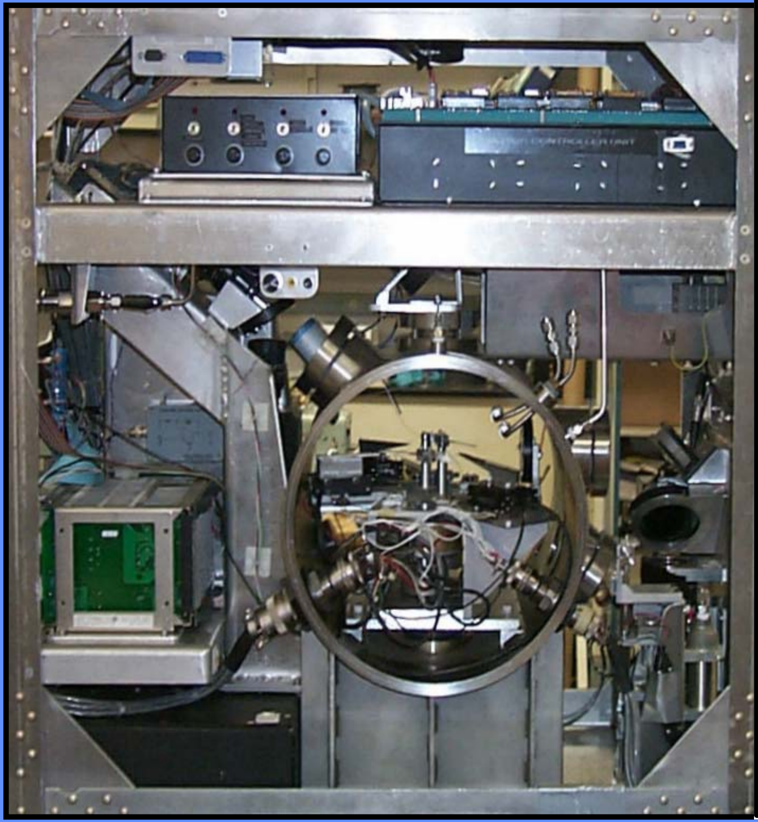


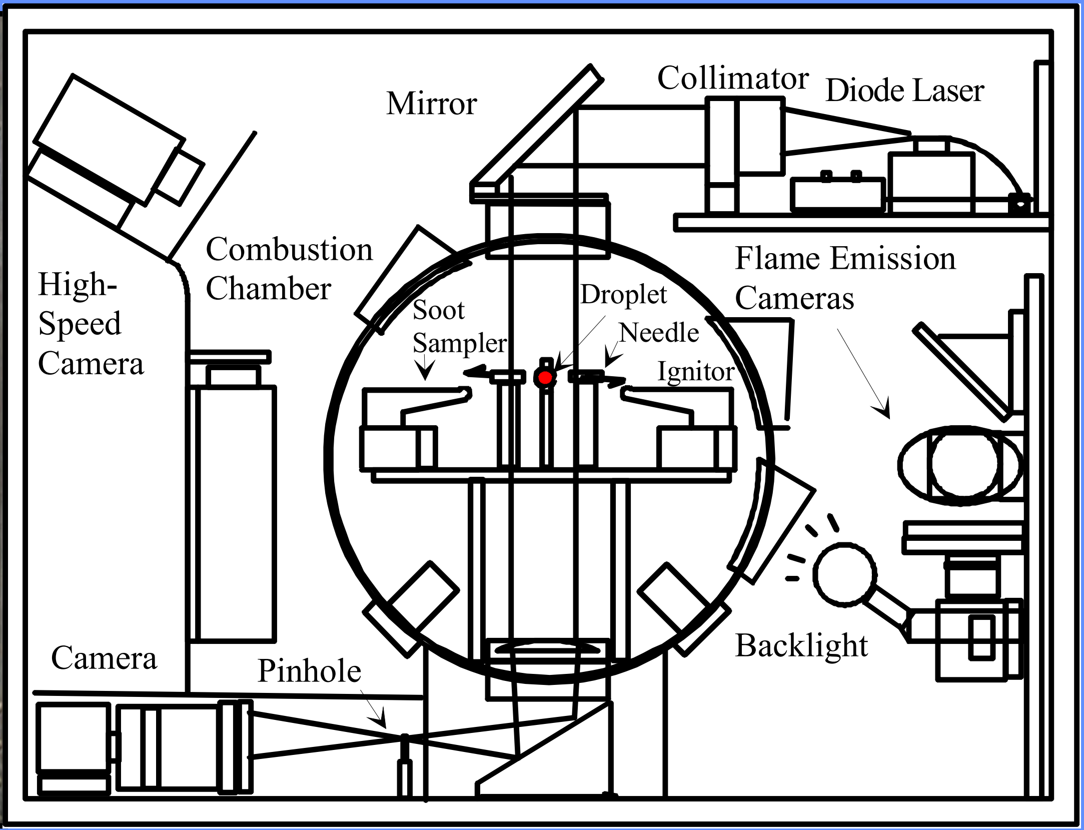
- 84 m. long
- 2.2 seconds of micro- gravity time
- Gravity level of 10^{-5}g





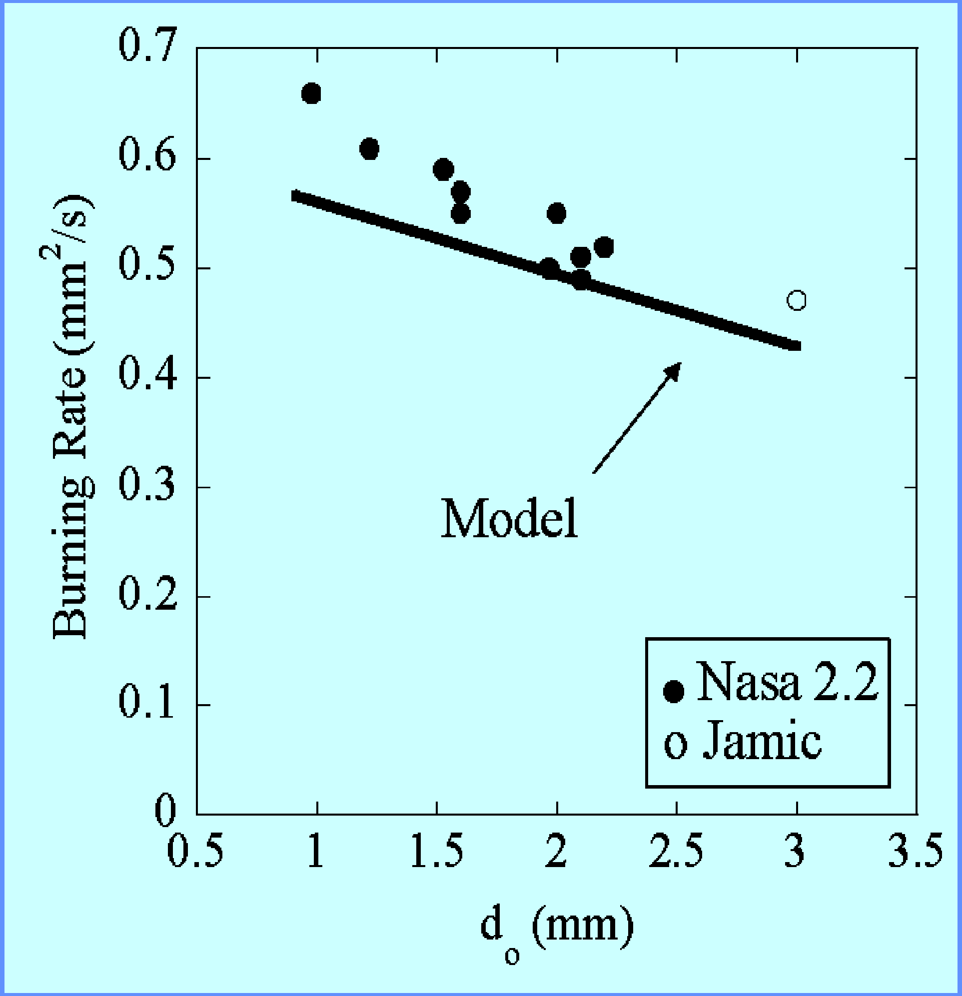
Drexel/NASA Droplet Combustion Rig





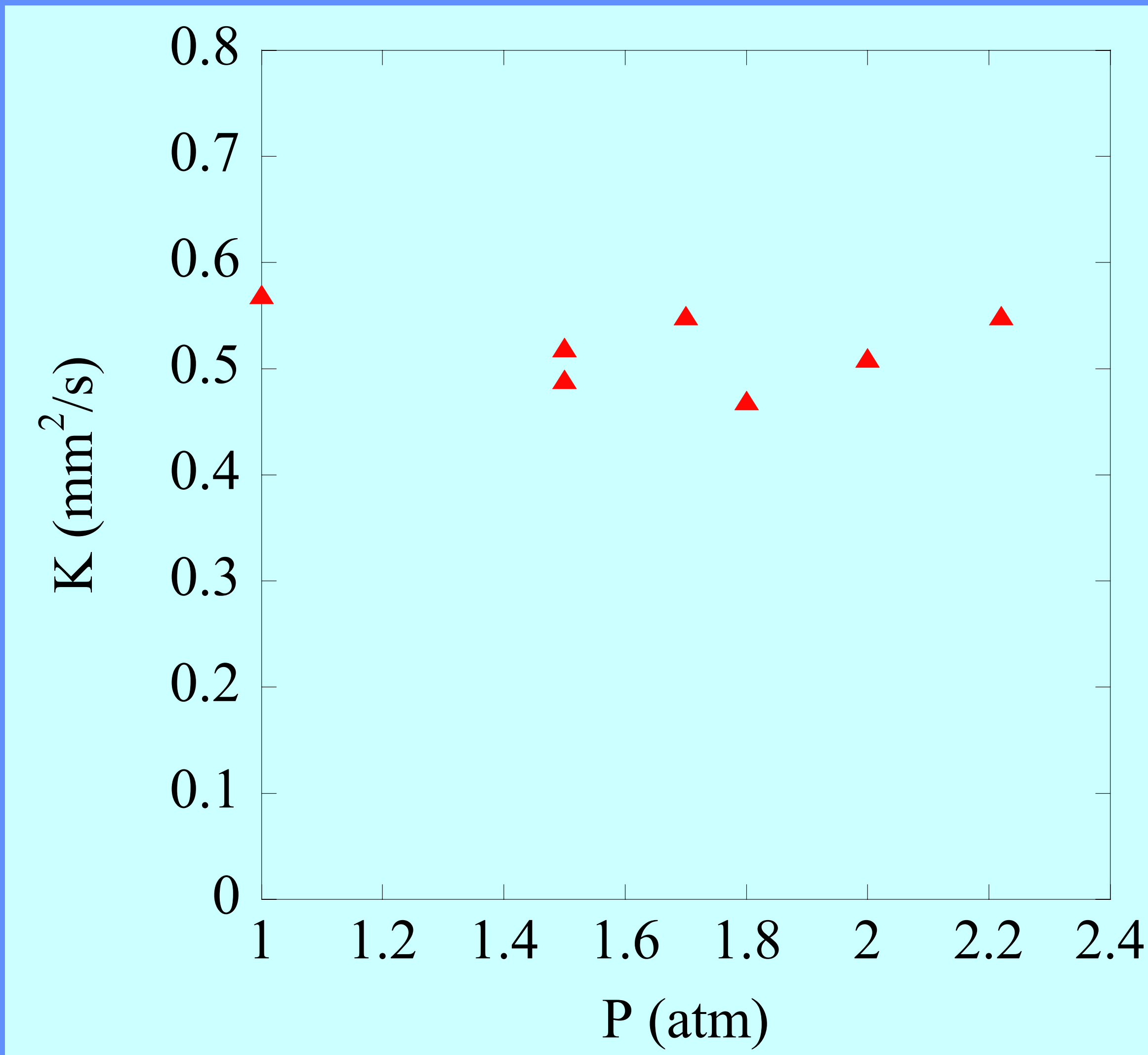
- Fiber supported droplet combustion rig
- Can be used in all ground based μg facilities

Effect of Initial Diameter on Burning



- Soot free burning
- Non-luminous radiative heat losses become more dominant
- Data validates numerical model

Effect of Pressure on Burning Rate



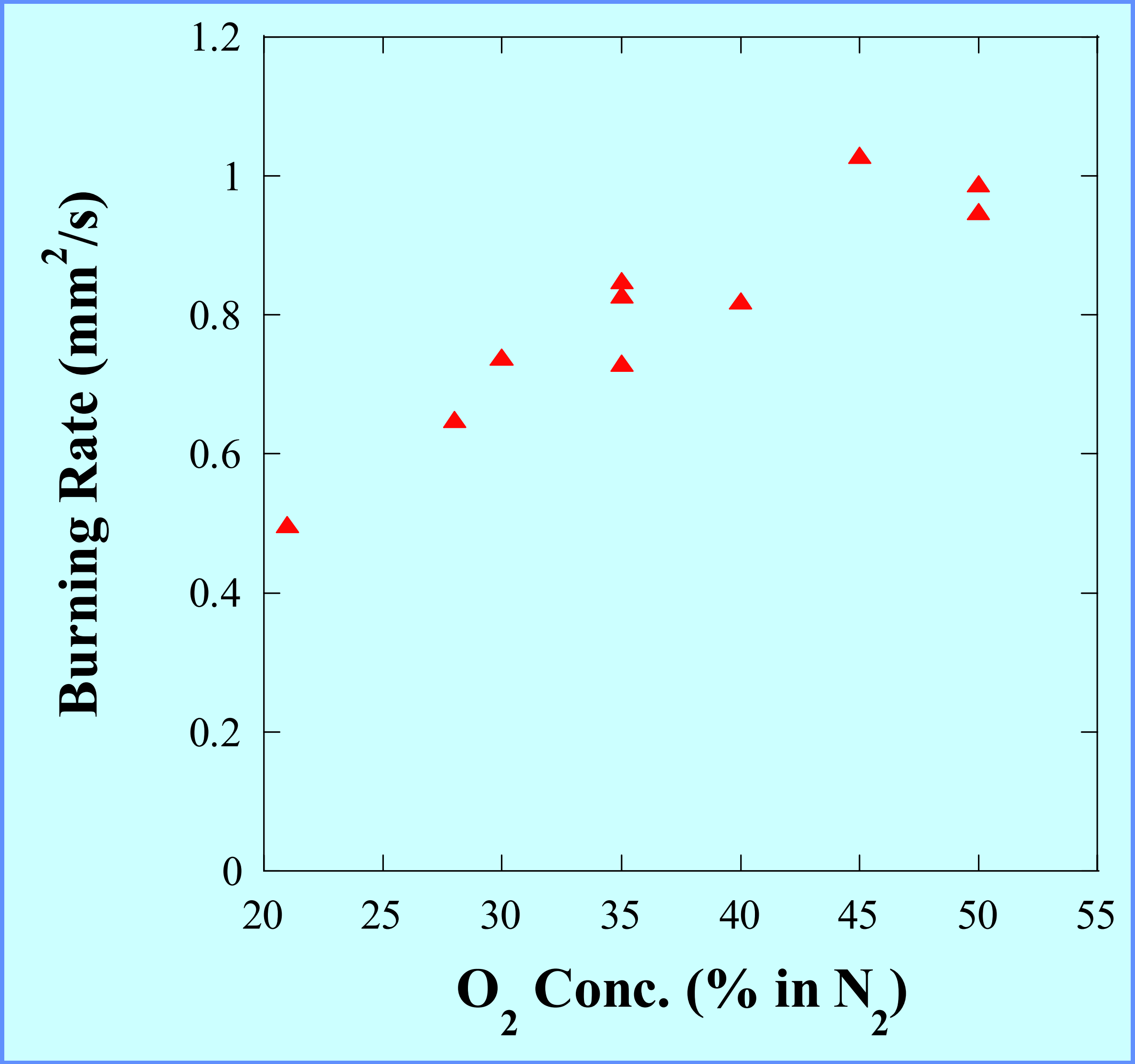
1 atm

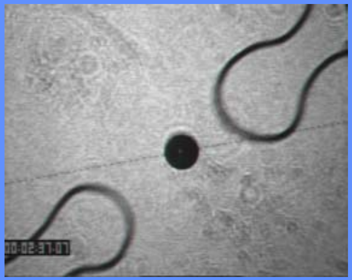
1.5 atm

2.2 atm

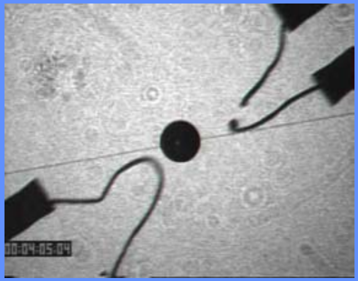
Droplet burning rate is independent of ambient pressure in the range of 1 atm to 2.2 atm

Effect of O_2 Conc. on Burning Rate

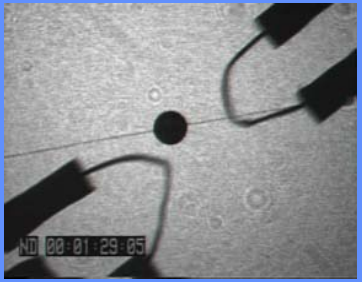




21 % O_2



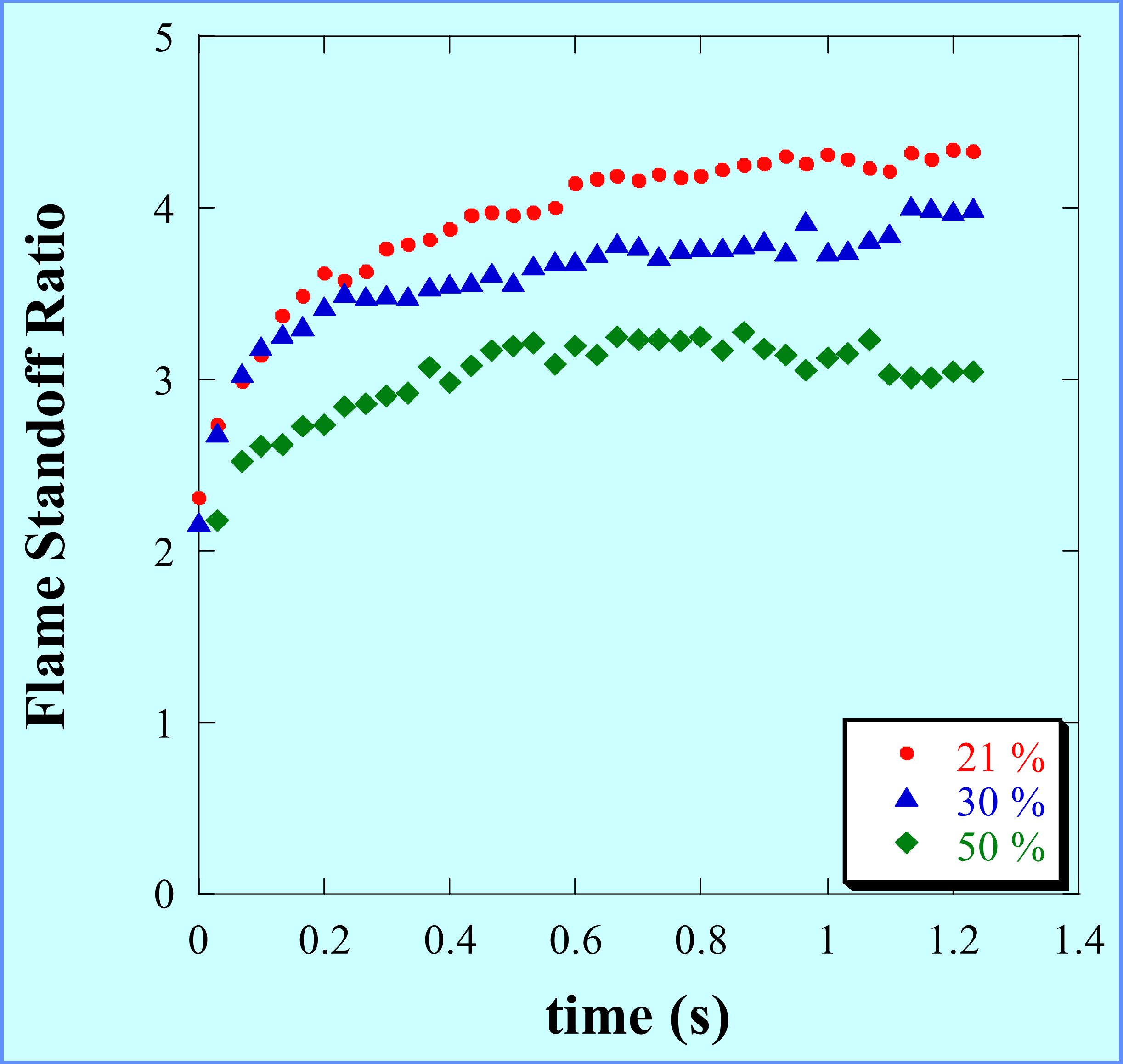
35 % O_2



50 % O_2

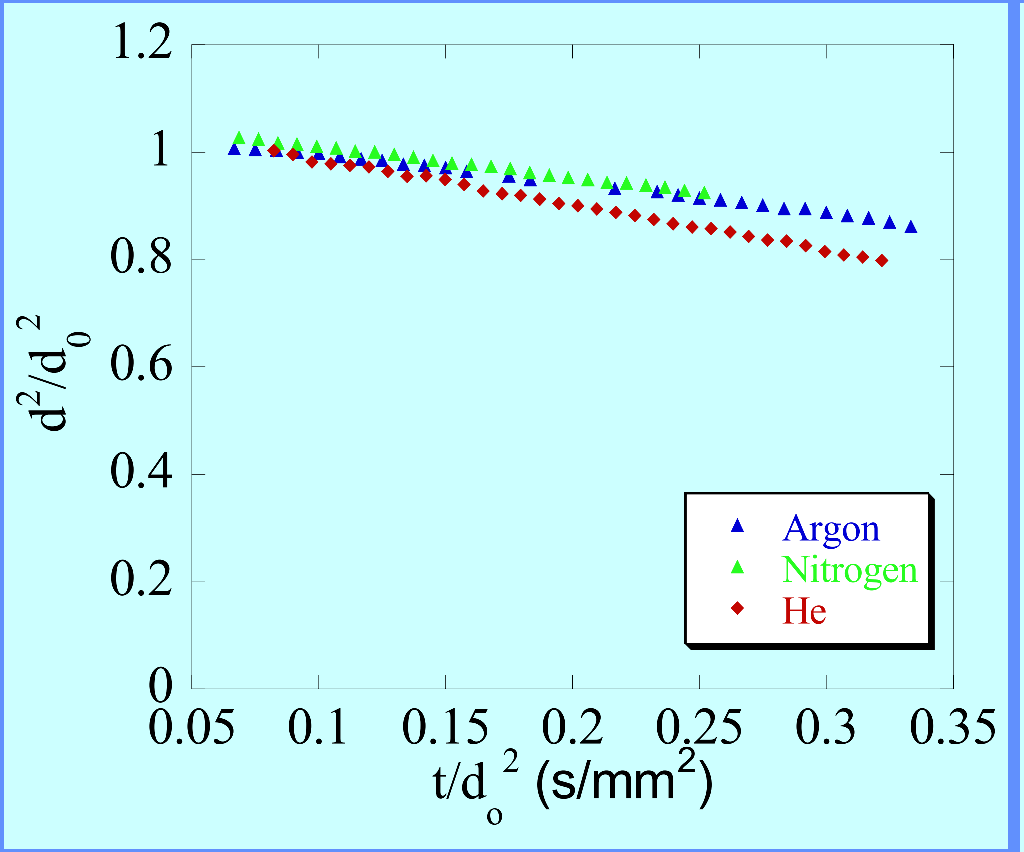
Burning rate is enhanced with increasing O_2 concentration.

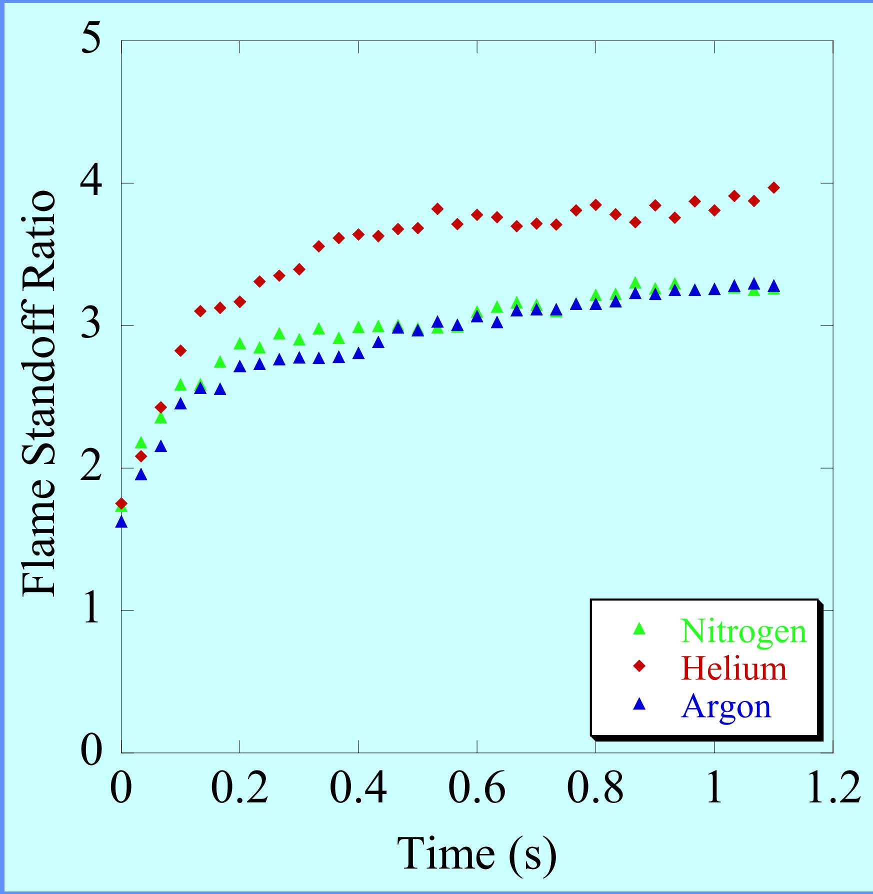
Effect of O_2 Conc. on Burning Rate



- Flame resides closer to droplet
- Higher temperature gradient exists in the region between the flame and the droplet
- Burning rate is enhanced

Effect of Inert on Burning Rate





- Ethanol burns 1.7 times faster in He/O_2
- Sooting is also believed to be responsible for lower burning rates in Ar/O_2 ambient

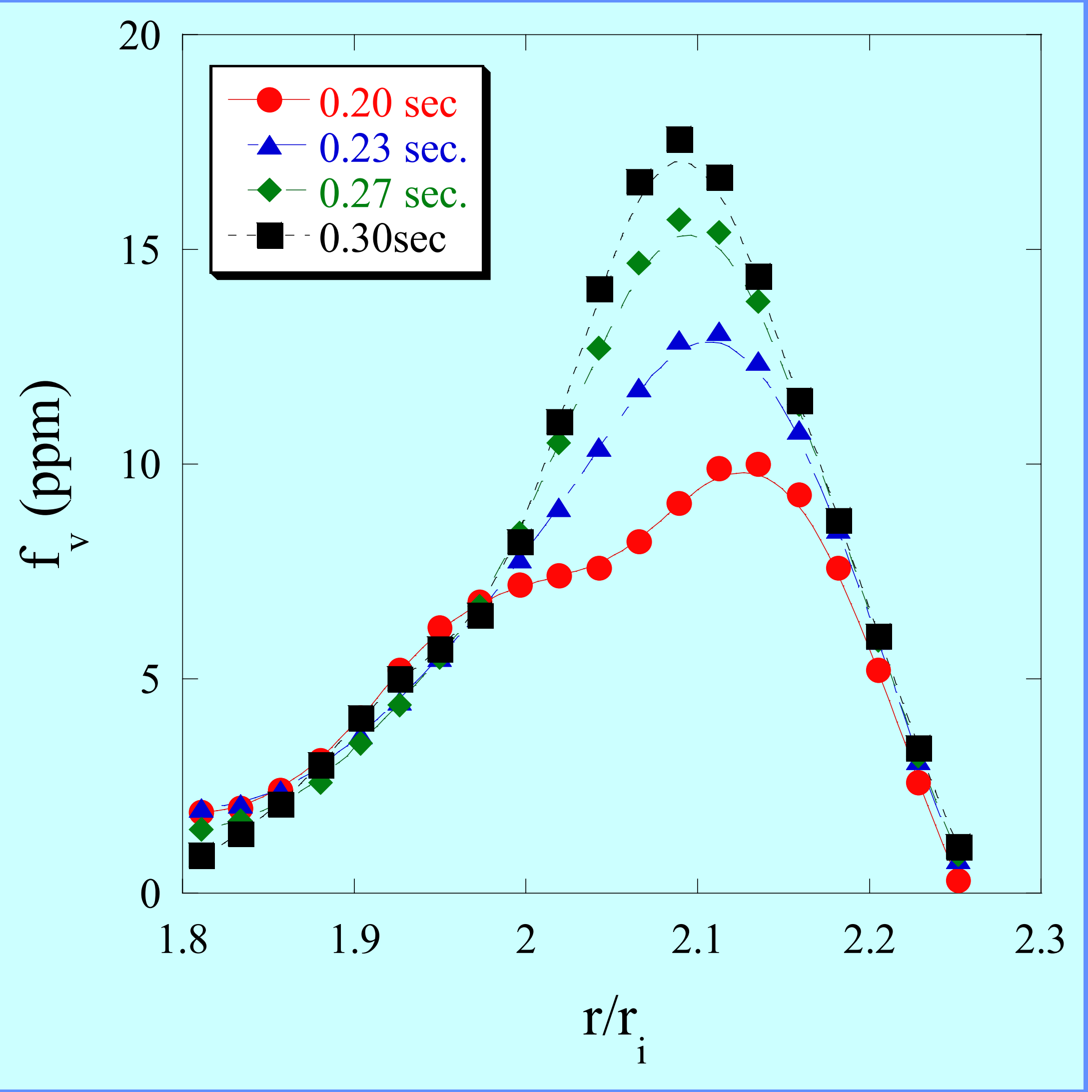
Effect of Pressure on Sooting Behavior

1.0 atm	1.4 atm	1.8 atm	2.2 atm	2.4 atm

Laser backlit images of 2.2 mm ethanol droplets burning at 30% O_2 in N_2 and varying pressures

- Sooting is sensitive to ambient pressure and oxygen concentration

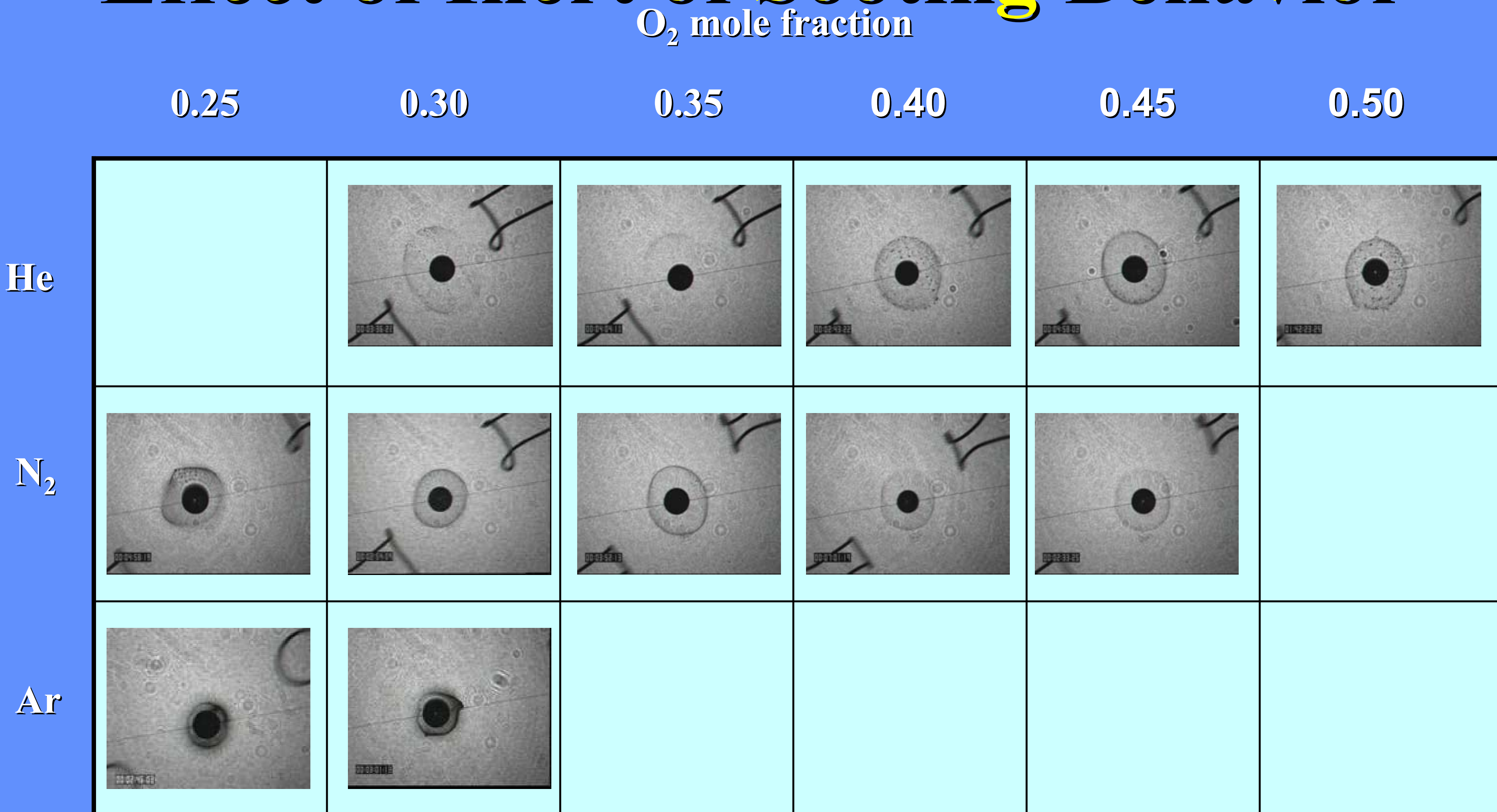
Soot Volume Fraction Distribution



Soot volume fraction distribution in 30% O_2 in N_2 and 2.4 atm

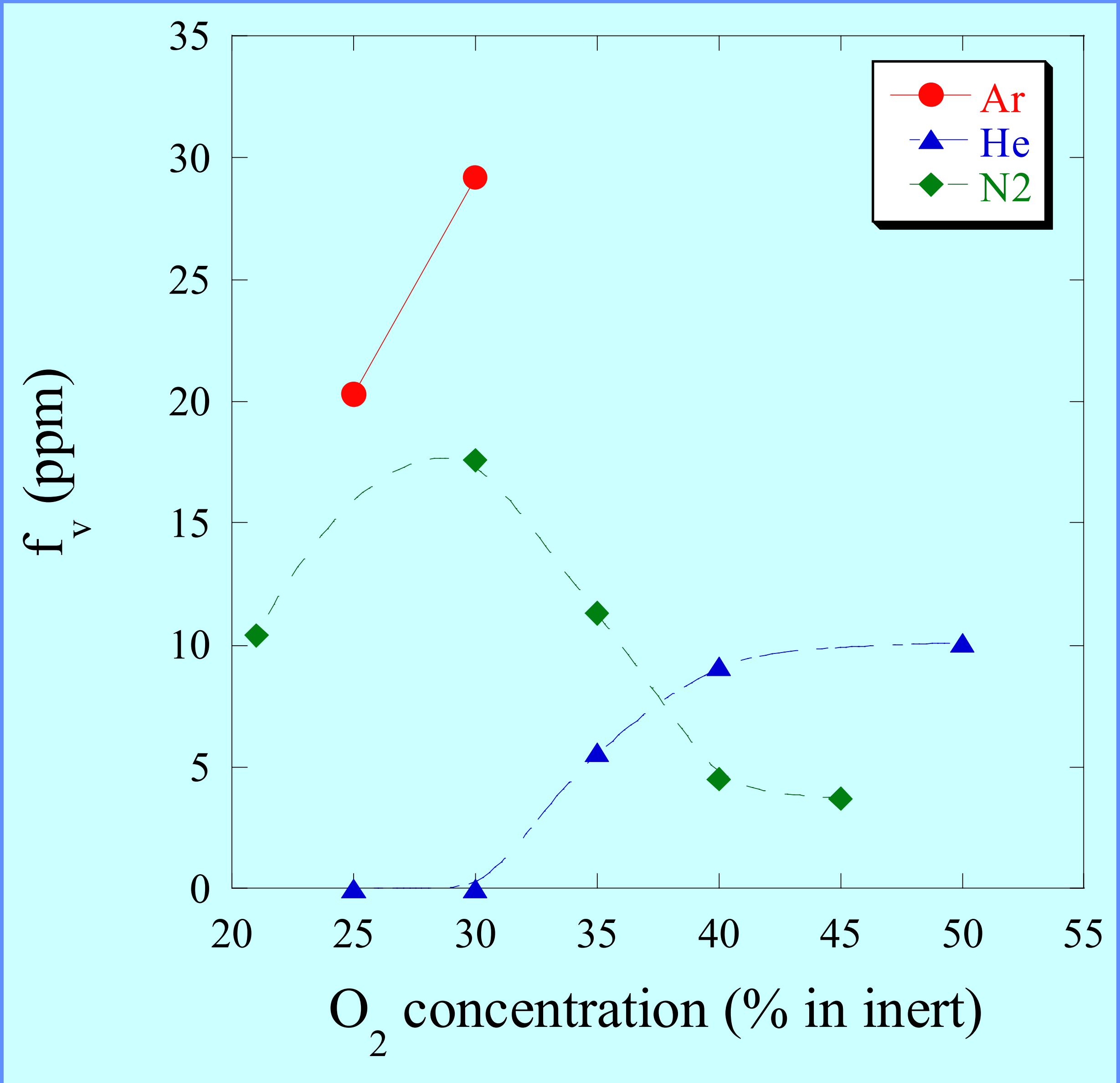
- The sootshell location resides closer to the droplet surface with the progression of time
- The maximum soot volume fraction also increases as a function of time

Effect of Inert of Sooting Behavior



- Sooting shows a non-monotonic behavior with O_2 concentration
- Ethanol produces the most amount of soot in Ar/O_2 ambient
- Sootshell resides closest to the droplet in Ar/O_2 ambient

Maximum Soot Volume Fraction



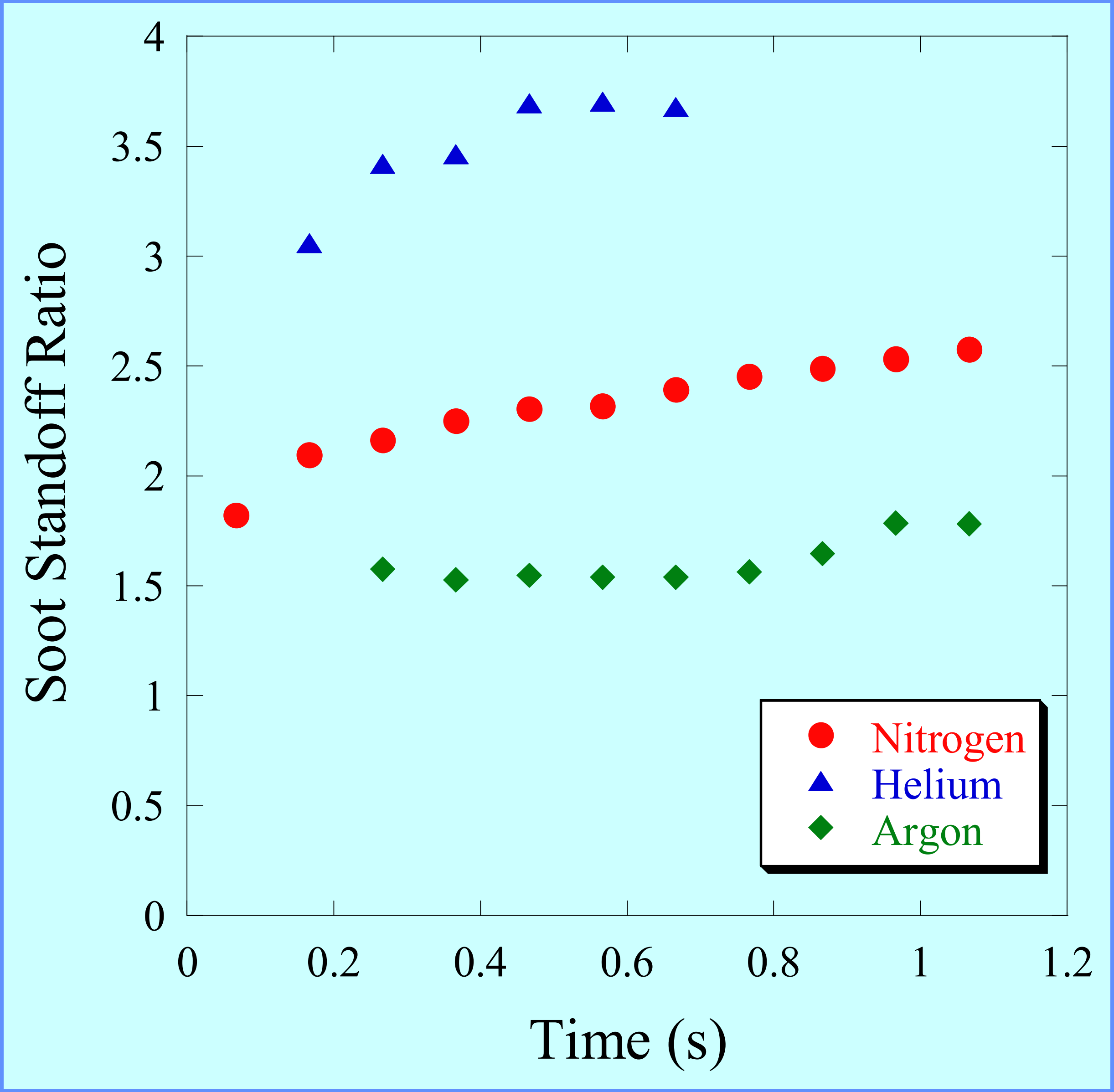
- **Non-monotonic sooting behavior with increasing O_2 concentration**
- **Residence time, temperature and oxidation are the major factors causing this behavior**

Characteristics of Sooting Behavior

	d (mm)	K (mm^2/s)	FSR	t_{res} (s)	T_{flame} (K)	f_{vmax} (ppm)
30% O_2 in Ar	1.94	0.55	3.9	0.27	2344	29.2
30% O_2 in N_2	2.02	0.56	3.9	0.25	2105	17.6
30% O_2 in He	1.99	0.96	4.7	0.12	1809	~0

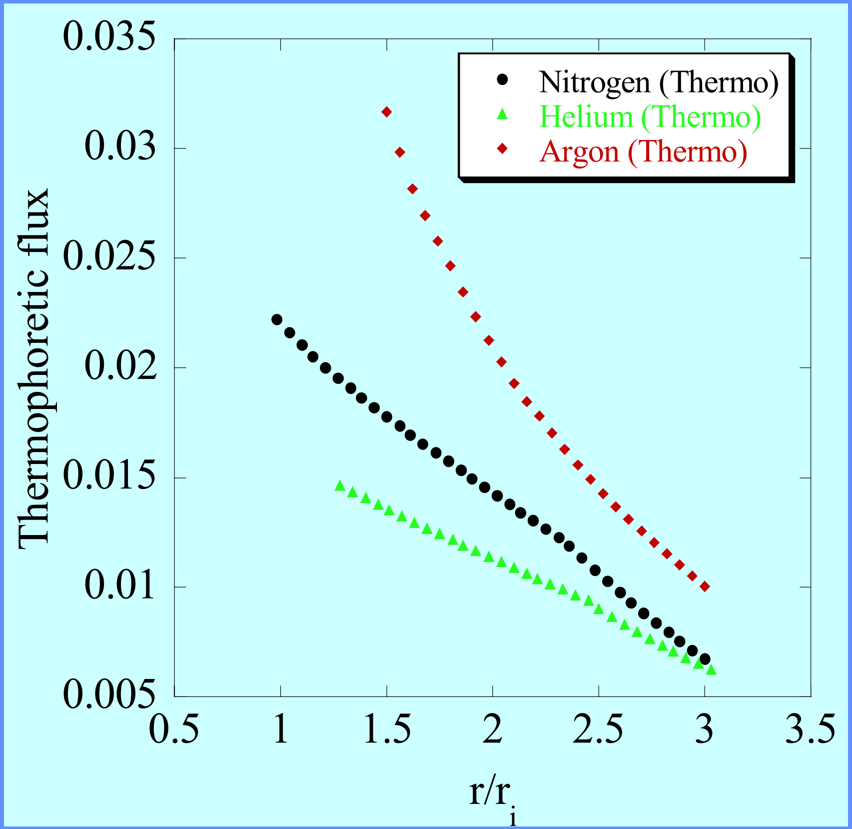
- Residence time and temperature are two major factors that influence soot formation
- Higher residence time and flame temperature in Ar/O_2 flame favor soot production

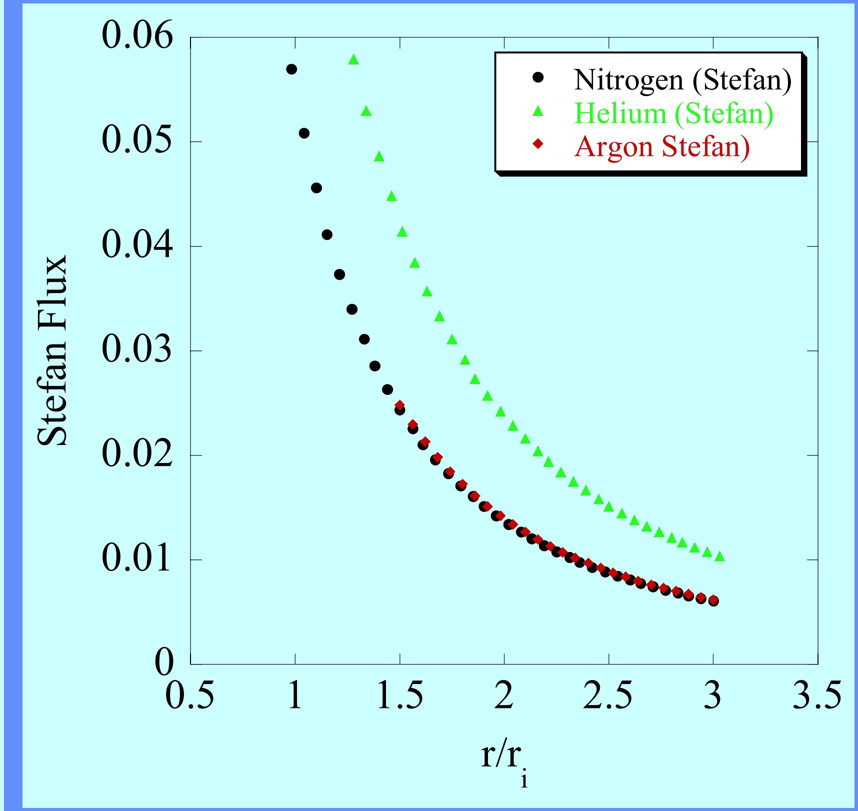
Soot Standoff Ratio



- Sootshell resides closest to the droplet in Ar/O_2
- Stefan induced viscous drag & thermophoretic flux are the major forces on soot particles

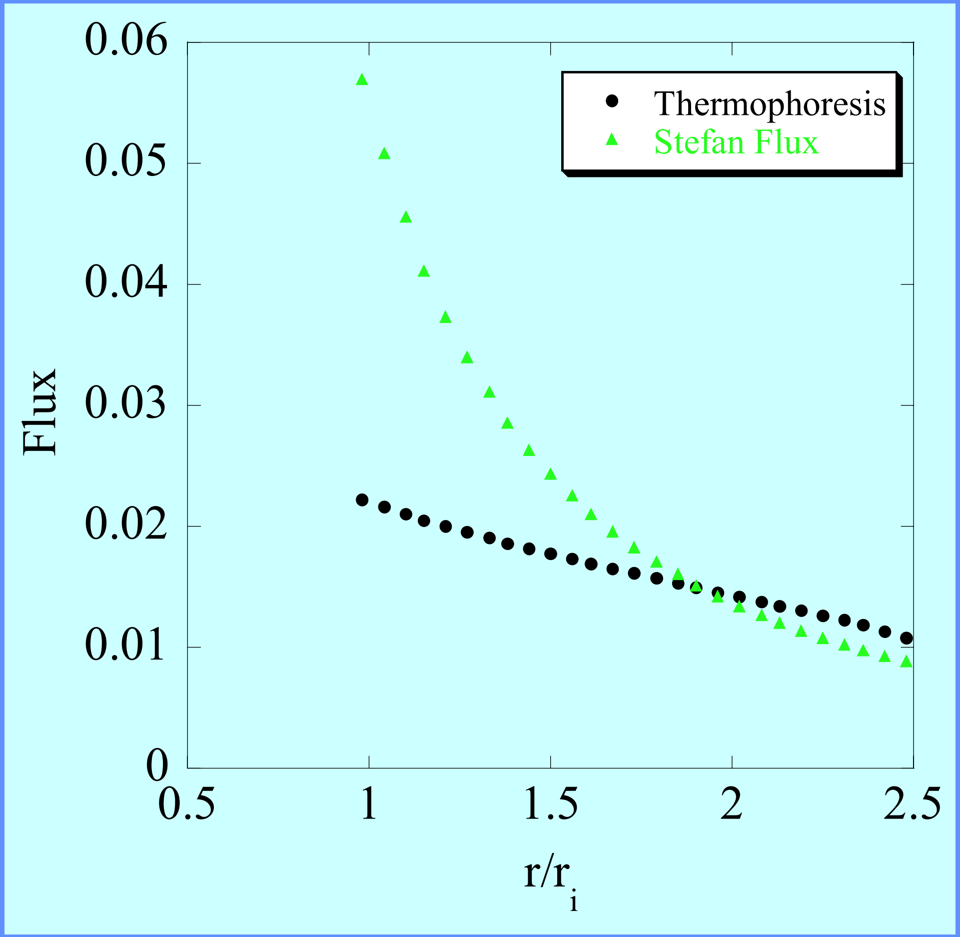
Forces Acting on Soot





- **Stefan Flux is directed away from the droplet while thermophoretic flux is towards the droplet**
- **Argon/O_2 has the highest thermophoretic flux and lowest Stefan flux causing the sootshell to reside closer to the droplet**

Sootshell Location



- **Calculated sootshell location matches well with the experimental measurements (SSR_{exp} =2.1, SSR_{calc} =1.9)**

Conclusions

- An increase in ambient pressure and oxygen concentration leads to higher rates of soot formation.
- Burning rate increases with increasing oxygen index, decreases with initial droplet diameter, but is not affected by ambient pressure Ethanol droplets burns fastest in He/O_2 ambient.
- Soot volume fraction increases non-monotonically with increasing oxygen concentration.
- Ethanol soots most in Ar/O_2 due to higher flame temperature and longer residence time.
- The location of sootshell was affected by the inerts due to the changes in the magnitude of Stefan and thermophoretic flux