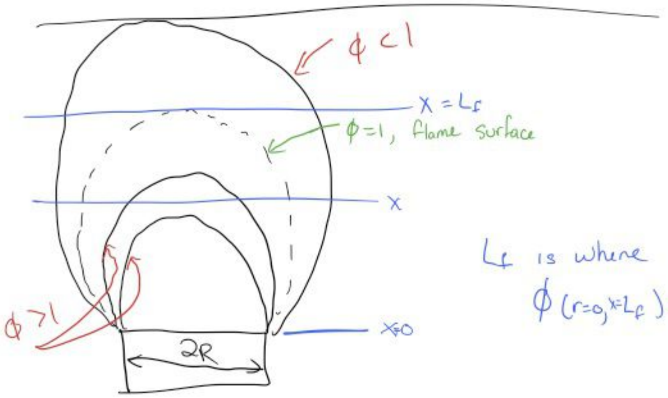
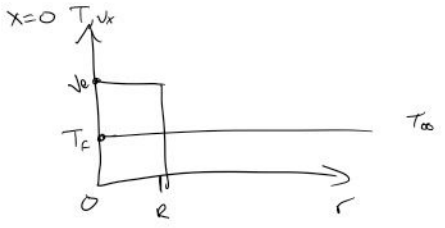
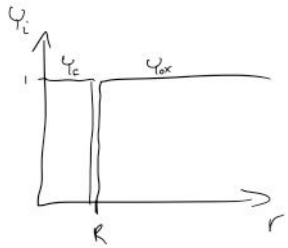
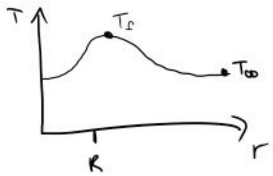


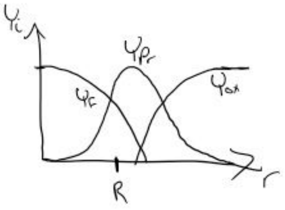
Lf is where $\phi(r=0, x=L_f) = 1$



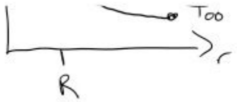


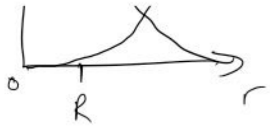
$0 < x < L_f$





$x = L_f$





L_f : flame length depends on Q_F

$$Q_F = v_e \pi R^2$$

$$L_f \approx \frac{3}{8\pi} \frac{Q_F}{D_{AB} Y_{F,stoic}}$$

$CH_4 \rightarrow 1CO_2 \quad 2H_2O \rightarrow 2O_2$

$C_8H_{18} \rightarrow 8CO_2 + 9H_2O \rightarrow 12.5\ O_2$

- orange/yellow appearance → you have soot!

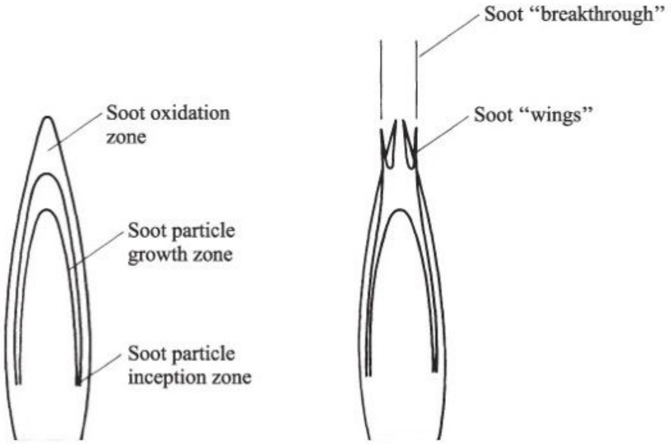


Figure 9.5 Soot formation and destruction zones in laminar jet flames.

Figure 9.6 Laminar ethylene jet diffusion flame. Note soot "wings" at sides of the flame near the tip.

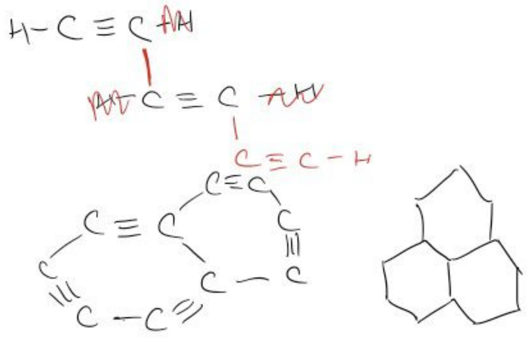
SOURCE: Photograph courtesy of R. J. Santoro.

Soot is formed over a limited T range
of 1300 K → 1600 K

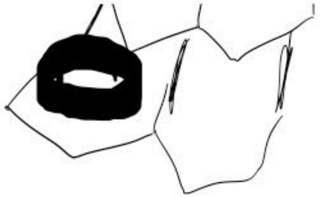
Soot formation:

1) formation of precursor species
2) particle inception
3) Surface growth & particle agglomeration
4) particle oxidation

1) precursor



2) particle inception



3000–10000 a.m.u.

↳ 250–850 carbon atoms

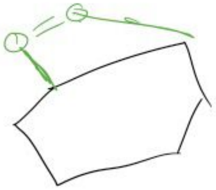
3) growth & agglomeration

1 – add more HC's to existing rings

2 – particles collide

4) oxidation

– travel through ϕ<1 region



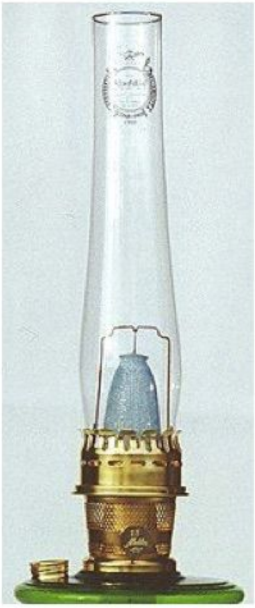
→ CH_2O

HCO

CO_2

if O_2 destroys <u>all</u> particles we call the flame a non-sooting flame

Smoke point – experimentally measured by inc. fuel flow rate until smoke is observed escaping the flame tip



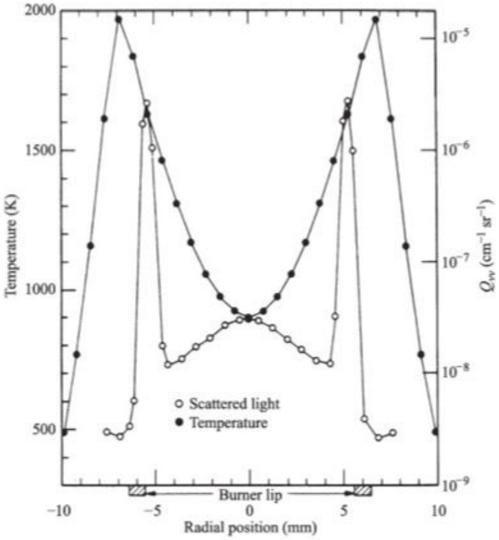
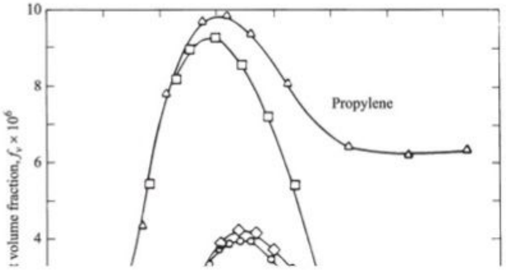


Figure 9.13 Radial profiles of temperature and scattered light for a laminar ethylene jet diffusion flame. Soot is contained in the region where the scattered light intensity is high.

SOURCE: Reprinted from Ref. [1] by permission of Gordon & Breach Science Publishers, © 1987.



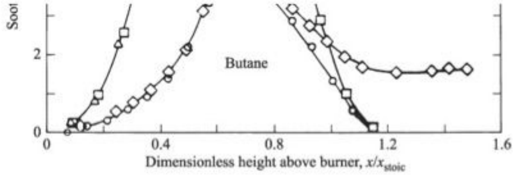


Figure 9.14 Measured soot volume fractions as functions of height above burner for propylene and butane at both sooting and nonsooting conditions.

SOURCE: Reprinted by permission of Elsevier Science, Inc., from Ref. [37]. © 1986, The Combustion Institute.

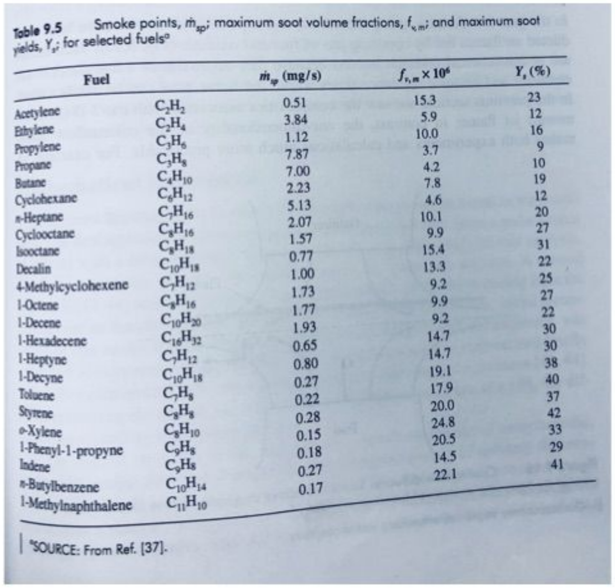


Table 9.5 Smoke points, $\dot{m}_{sp}$; maximum soot volume fractions, $f_{v,m}$; and maximum soot yields, Y_s; for selected fuels[a]

Fuel		$\dot{m}_{sp}$ (mg/s)	$f_{v,m} \times 10^6$	Y_s (%)
Acetylene	C_2H_2	0.51	15.3	23
Ethylene	C_2H_4	3.84	5.9	12
Propylene	C_3H_6	1.12	10.0	16
Propane	C_3H_8	7.87	3.7	9
Butane	C_4H_{10}	7.00	4.2	10
Cyclohexane	C_6H_{12}	2.23	7.8	19
n-Heptane	C_7H_{16}	5.13	4.6	12
Cyclooctane	C_8H_{16}	2.07	10.1	20
Isooctane	C_8H_{18}	1.57	9.9	27
Decalin	$C_{10}H_{18}$	0.77	15.4	31
4-Methylcyclohexene	C_7H_{12}	1.00	13.3	22
1-Octene	C_8H_{16}	1.73	9.2	25
1-Decene	$C_{10}H_{20}$	1.77	9.9	27
1-Hexadecene	$C_{16}H_{32}$	1.93	9.2	22
1-Heptyne	C_7H_{12}	0.65	14.7	30
1-Decyne	$C_{10}H_{18}$	0.80	14.7	30
Toluene	C_7H_8	0.27	19.1	38
Styrene	C_8H_8	0.22	17.9	40
o-Xylene	C_8H_{10}	0.28	20.0	37
1-Phenyl-1-propyne	C_9H_8	0.15	24.8	42
Indene	C_9H_8	0.18	20.5	33
n-Butylbenzene	$C_{10}H_{14}$	0.27	14.5	29
1-Methylnaphthalene	$C_{11}H_{10}$	0.17	22.1	41

[a]SOURCE: From Ref. [37].

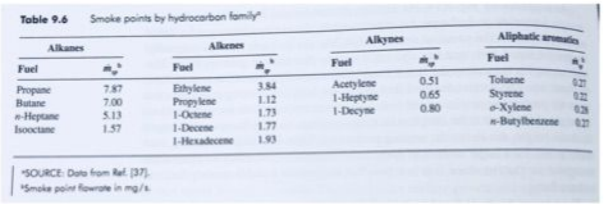


Table 9.6 Smoke points by hydrocarbon family[a]

Alkanes		Alkenes		Alkynes		Aliphatic aromatics	
Fuel	$\dot{m}_{sp}$[b]	Fuel	$\dot{m}_{sp}$[b]	Fuel	$\dot{m}_{sp}$[b]	Fuel	$\dot{m}_{sp}$[b]
Propane	7.87	Ethylene	3.84	Acetylene	0.51	Toluene	0.27
Butane	7.00	Propylene	1.12	1-Heptyne	0.65	Styrene	0.22
n-Heptane	5.13	1-Octene	1.73	1-Decyne	0.80	*o*-Xylene	0.28
Isooctane	1.57	1-Decene	1.77			*n*-Butylbenzene	0.27
		1-Hexadecene	1.93				

[a]SOURCE: Data from Ref. [37].

[b]Smoke point flowrate in mg/s.

jet flame simplified theory

Assumptions:

1) flow is laminar, steady, & axisymmetric, produced by a jet of fuel from a circular nozzle of radius R, which burns in a quiescent, infinite reservoir of oxidizer

2) only have 3 "species" (fuel, oxidizer and products).
   - in the flame zone: only fuel
   - outside the flame: only oxidizer

3) flame sheet approximation: fuel & oxidizer react in stoichiometric proportions at the flame edge. Kinetics infinitely fast, so the flame is an infinitesimally thin sheet.

4) molecular transport: simple binary diffusion (Fick's)

5) thermal energy & species diffusivities are equal

$$Le = \alpha / D_{AB} = 1$$

6) radiation heat transfer negligible

7) only radial diffusion of momentum, thermal energy & species is important. Axial diffusion neglected

8) flame oriented vertically upward

Conservation eqns

mass:

$$\frac{1}{r}\frac{\partial}{\partial r}(r v_r \rho) + \frac{\partial}{\partial x}(\rho v_x) = 0$$

momentum (axial):

$$\frac{1}{r}\frac{\partial}{\partial x}(r \rho v_x v_x) + \frac{1}{r}\frac{\partial}{\partial r}(r \rho v_x v_r) - \frac{1}{r}\frac{\partial}{\partial r}\left(r \mu \frac{\partial v_x}{\partial r}\right) = (\rho_\infty - \rho) g$$

Species:

$$\dot{m}_i''' = 0$$

$$\frac{1}{r}\frac{\partial}{\partial x}\left(r\rho v_x Y_i\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v_r Y_i\right) - \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho D_{AB}\frac{\partial Y_i}{\partial r}\right) = 0$$

i = fuel inside flame bandary

= oxidize outside flame bandary

$$Y_{Pr} = 1 - Y_F - Y_{ox}$$

Energy

Shvab – Zeldovich applicable

$\left(\sum h^{\circ}_{f,i}\,\dot{m}_i'''\right) = 0$ (sheet approximation)

$$\frac{\partial}{\partial x}\left(r\rho v_x \int c_p\,dT\right) + \frac{\partial}{\partial r}\left(r\rho v_r \int c_p\,dT\right) - \frac{\partial}{\partial r}\left(r\rho D_{AB}\frac{\partial \int c_p\,dT}{\partial r}\right) = 0$$

Eqn. of state

$$\rho = \frac{P\,MW_{mix}}{R_u T}$$ (ideal gas)

where $MW_{mix} = \left(\sum Y_i / MW_i\right)^{-1}$