

Module 3: Laminar Premixed Flames

[| Objectives |](#) [Scope |](#) [Reading Assignments |](#) [Assignment Schedule |](#)

Objectives

By the end of this module, students should be able to:

- Define what is meant by Premixed Flame
- Understand the Hugoniot Curve
- Understand the basic theory for flame speed in a premixed system
- Identify various methods used to measure flame speed
- Explain what factors can influence flame speed
- Explain the factors that can affect the stability of Laminar Premixed Flames
- Define flammability limits
- Understand pressure effects of flammability limits
- Understand flame stabilization at low velocities
- Define Flashback and Blow-off
- Define Flame Quenching

Scope

- Review the Hugoniot Relation
- Analysis of the basic structure of premixed flames
- Analysis of premixed flame speed and variables that effect the speed
- Analysis of flammability limits

Reading Assignments

- **Turns:** Chapter 8, Chapter 16
- **Drysdale:** Chapter 3

Assignment Schedule

Five problems worth 2 points each (10 total) are to be completed and submitted online. There are also two extra credit problems available (4 points). See the last page of this module for more details.

There are also discussion exercises (3.1, 3.2, and 3.3) that will count towards your class participation grade.

Laminar Premixed Flames Introduction

We can now use the knowledge that we have gained in the first two modules to begin talking about flames. As presented in the introduction, our discussion of flames will begin with developing an understanding of laminar, premixed flames. First, let us review what we mean by “laminar, premixed” flames.

“Laminar” vs. turbulent flow – laminar describes the nature of the gaseous flow field in which the flame is occurring. Of particular importance is the fact that thermal transport in the vicinity of the flame can be assumed to occur largely by conduction rather than by convection.

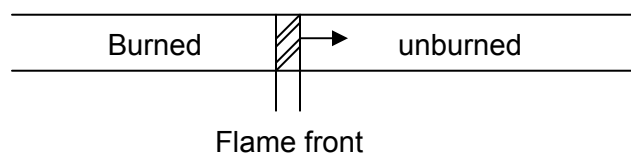
“Premixed” vs. diffusion flame – as we discussed in Module 1, in premixed flames reactants are completely mixed prior to entering the flame zone. By comparison, diffusion flames depend on mixing of the fuel and air at the flame front by diffusion.

In Module 2, we talked about homogeneous thermal explosions and chain branching explosions as a way to achieve rapid release of the heat of combustion of a fuel-oxidizer system. However, for most fuel-oxygen combinations at room temperature and atmosphere pressure, the system is unreactive. As we now know, despite the large (negative) heat of reaction associated with fuel-oxidizer reactions, at room temperature the kinetics of such reactions are simply too slow for them to occur spontaneously in a self-sustaining manner. We learned that if the mixture was heated sufficiently or sufficient radicals were introduced, an explosion would occur. In most cases, this “explosion” corresponds to a self-sustaining flame which propagates at subsonic velocity. Such a flame propagation is usually referred to as a “deflagration.” However, if the explosion leads to a supersonic flame propagation, the result is a “detonation.”

If we begin with a fuel/oxidizer mixture and a local ignition source is applied to the mixture which raises the temperature or concentration of radicals, a region of rapid reaction and high heat release will propagate through the mixture provided the mixture is within “flammability limits.”

We will hold our discussion of local thermal ignition and flammability limits until later in this Module. Right now let us focus on the structure of a laminar, premixed flame.

Consider a long tube containing a flammable fuel/oxygen mixture as shown below. If an ignition source is applied at one end, a combustion wave will propagate down the tube from the burned gases into the unburned gases.



For a tube that is open at both ends, the velocity of propagation of this flame front (sometimes referred to as a flame wave), V , is typically in the range of 20 – 200 cm/sec. For most hydrocarbon/air combinations this flame speed is approximately 45 cm/sec.

The flame wave velocity is controlled primarily by transport processes, i.e. heat conduction and the diffusion of radicals. This low speed (i.e. subsonic) flame propagation is called a “Deflagration”. Note, that the range of V 's given above is much less than the sound speed.

If the tube is closed at the ignition end, the flame will accelerate in the tube as it propagates. Eventually it will transition from subsonic to supersonic. This supersonic process is called a “Detonation.” In a detonation, the shock wave which occurs at supersonic velocity raises T and P of the mixture to create an explosive reaction and energy release to sustain wave propagation.

To better understand the structure of this flame wave phenomenon (whether subsonic or supersonic) we will apply the principals of fluid mechanics. As usual when analyzing a fluids problem, we will start with the conservation equations.

Conservation Equations

$$A_1 \rho_1 u_1 = \rho_2 u_2 A_2 = \dot{m} \quad (\text{continuity})$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2 \quad (\text{momentum})$$

$$\underbrace{C_p T_1 + \frac{1}{2} u_1^2}_{H_1} + q = \underbrace{C_p T_2 + \frac{1}{2} u_2^2}_{H_2} \quad (\text{energy})$$

Also we can use the ideal gas equation of state. However, note that the final state equation is not independent of the initial state equation.

$$\begin{aligned} p_2 &= \rho_2 R T_2 \\ (p_1 &= \rho_1 R T_1) \end{aligned} \quad (\text{not independent})$$

Thus, we have a system of 4 equations, 5 unknowns. However, by assuming $A_1 = A_2 = 1$ in the continuity equation and combining continuity and momentum we can obtain a fifth equation given as:

$$p_2 - p_1 = \rho_1 u_1^2 - \rho_2 u_2^2 = \frac{(\rho_1 u_1)^2}{p_1} - \frac{(\rho_2 u_2)^2}{p_2} = \left(\frac{1}{p_1} - \frac{1}{p_2} \right) \dot{m}^2$$

or

$$(\rho_1 u_1)^2 = \cancel{m}^2 = \left[\frac{\frac{p_2 - p_1}{1} - \frac{1}{\rho_1} - \frac{1}{\rho_2}}{\rho_1} \right] \quad \text{This is the definition of a so-called Rayleigh line.}$$

If we remember that the Mach number, M, is defined as the local gas velocity divided by the local speed of sound, C, such that $M_1 = \frac{U_1}{C_1}$ where $C_1 = \sqrt{\gamma R_1 T_1} = \sqrt{\gamma \left(\frac{p_1}{\rho_1} \right)}$

Where $\gamma = \frac{C_p}{C_v}$ gives

$$\frac{\gamma \rho_1^2 u_1^2}{\gamma \rho_1 p_1} = \frac{\frac{p_2}{p_1} - 1}{1 - \frac{\rho_1}{\rho_2}}$$

$$\gamma M_1^2 = \frac{\left(\frac{p_2}{p_1} - 1 \right)}{\left[1 - \frac{\left(\frac{1}{\rho_2} \right)}{\left(\frac{1}{\rho_1} \right)} \right]}$$

or

Recall

$$C_p - C_v = R$$

And

$$\gamma = \frac{C_p}{C_v}$$

so

$$C_p - \frac{C_v}{C_p} C_p = R$$

Or

$$C_p - \frac{1}{\gamma} C_p = R$$

So

$$C_p = \frac{R}{1 - \frac{1}{\gamma}} = \frac{\gamma}{\gamma - 1} R$$

Then the energy equation gives

$$C_p T_1 + \frac{1}{2} U_1^2 + q = C_p T_2 + \frac{1}{2} U_2^2$$

using equation of state $T_1 = \frac{p_1}{\rho_1 R_1}$, then

$$\frac{C_p}{R_1} \frac{p_1}{\rho_1} - \frac{C_p}{R_2} \frac{p_2}{\rho_2} = \frac{1}{2} (U_2^2 - U_1^2) - q$$

or

$$\frac{\gamma}{\gamma - 1} \left(\frac{p_2}{\rho_2} - \frac{p_1}{\rho_1} \right) - \frac{1}{2} (U_1^2 - U_2^2) = q$$

but

$$U_1^2 - U_2^2 = \frac{p_2 - p_1}{\rho_1} + \frac{\rho_2}{\rho_1} U_2^2 + \frac{\rho_2 - p_1}{\rho_2} - \frac{\rho_1}{\rho_2} U_1^2$$

so we get

$$\frac{\gamma}{\gamma - 1} \left(\frac{p_2}{\rho_2} - \frac{p_1}{\rho_1} \right) - \frac{1}{2} (p_2 - p_1) \left(\frac{1}{\rho_1} + \frac{1}{\rho_2} \right) = q$$

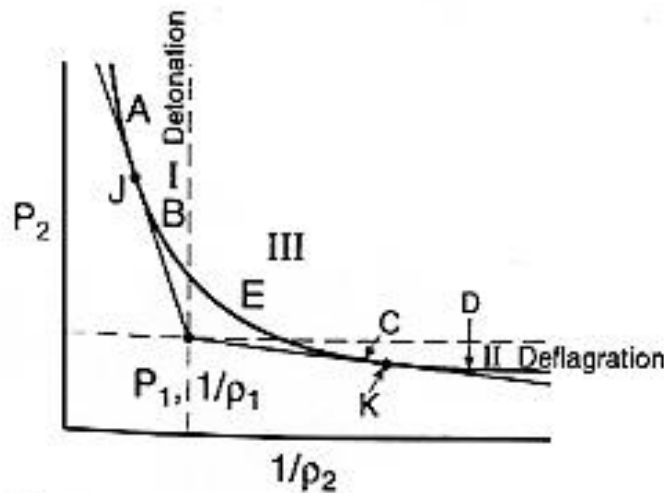
(Rankine) – Hugoniot Relation

For the premixed flame wave process described above, this equation defines the relationship between the initial state (unburned gases) and the final state (burned gases) for a given heat of combustion, q . For a fixed q and a given P_1 and ρ_1 , the Rankine-Hugoniot equation describes a curve on a plot of p_2 versus $1/\rho_2$ that corresponds to a family of solutions to this equation. As we will see below, one region of the solution leads to deflagrations while the other region leads to detonations.

Hugoniot Curve

As shown in Figure M3-1 below, for fixed q : the Rankine-Hugoniot relation leads to a curved line on plot of p_2 vs $1/\rho_2$. Also shown on the plot are tangent lines to the upper and lower branches of the curve. The tangent points are called the “Chapman-Jouguet” points. These points help divide the curve into three regions.

Figure M3-1: Hugoniot Plot



(From *Combustion* 3rd Ed. by Glassman, page 121)

Region I in the figure correspond to final states where the pressure and density are greater than the initial pressure and density. This is the region of detonations and the flame wave propagation velocity is supersonic. The tangent point J is the upper Chapman-Jouguet point. Region II arises when the final pressure and density are lower than the initial state. These regions correspond to deflagrations and the flame wave propagation velocity is subsonic. The tangent point K is the lower Chapman-Jouguet point. Region III is a region that, although mathematically valid as a solution to the Rankine-Hugoniot relation, is not physically valid (since U_1 would be imaginary). Although, in theory, a range of detonations and deflagrations can occur, in practice, only the solution corresponding to the Chapman-Jouguet point (point J) is observed for detonations and only solutions corresponding to the Chapman-Jouguet (point K) and less (area C on the curve) are observed for deflagration.

Note, $M_2 = 1$ for both Chapman-Jouguet points; thus, since flow cannot go from subsonic to supersonic in a constant area duct, no values greater than Chapman-Jouguet point are allowed for deflagrations.

For deflagrations, the rate of heat release of the fuel-air mixtures provides the 5th equation that determines where the subsonic region in the final state exists. This point along the weak deflagration region of the curve defines the deflagration velocity. This deflagration velocity is by definition the laminar flame speed. That is, the laminar flame speed is the speed at which a flame wave will propagate through a given fuel-air mixture in a tube with both ends open.

At this point, it is worthwhile to discuss the term “explosion” in light of our newfound understanding of deflagrations and detonations. If a fuel-air mixture is confined, such as a natural gas leak in a home, and an ignition source is present, a flame wave will propagate through the mixture. As we all know this generally leads to an “explosion” which destroys the home. However, in almost all cases, this is not a detonation. It is only a confined deflagration. That is, the rate of propagation of the flame in this situation will be subsonic. And, although the pressure inside the home will rise for a period of time until it is vented, generally, the process will stay subsonic. This has an important implication for most explosions we encounter in Fire Protection. If an explosion is caused by a deflagration, since the process is subsonic, the pressure will rise uniformly everywhere in the vessel (e.g. the closed portion of the house in which the mixture is contained). As a result, the explosion will not vent closest to the source of ignition, but rather it will vent wherever the weakest part of the structure containing the explosion is (for many houses this means the doors or windows blow out first).

This phenomenon can be understood by remembering that the speed of sound is the speed at which pressure waves propagate through a gas. Therefore, in a deflagration, the pressure waves propagate significantly faster than the flame does. As a result, the pressure rises approximately uniformly within the volume containing the deflagration.

Discussion Exercise 3.1:

Assume a propane torch with a one pound supply bottle leaks into a large conference room and premixes with air (within its flammability limits) before it is ignited by an electrical motor for an HVAC unit. If the conference room measures 40 meters by 25 meters by 4 meters in height will the “explosion” blow out the windows? The walls? (Assume windows break at 0.5 psig and that cinderblock walls fail at 2 psig). Discuss with your fellow students the level of hazard that you believe such a propane bottle constitutes.

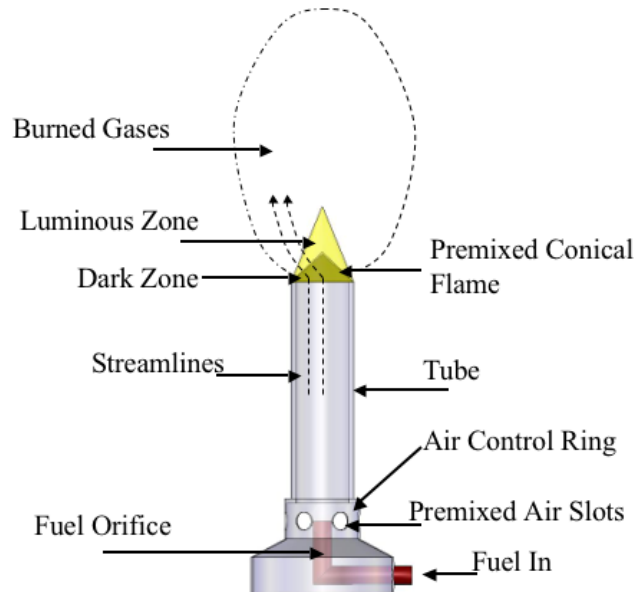
Instructions:

Determine the level of hazard this constitutes. Once determined, post your findings and discuss it with fellow students. Answering the problem is the beginning of this exercise. Discuss the implications and how this applies to you in your field of Fire Protection Engineering. There is a topic ‘M3-Explosion’ in the discussion area created for this discussion.

Laminar Flame Structure

We are now ready to look at the structure of the flame zone itself. We can start by remembering the simple Bunsen burner flame from Module 1.

Figure M3-2: Schematic of Bunsen Burner

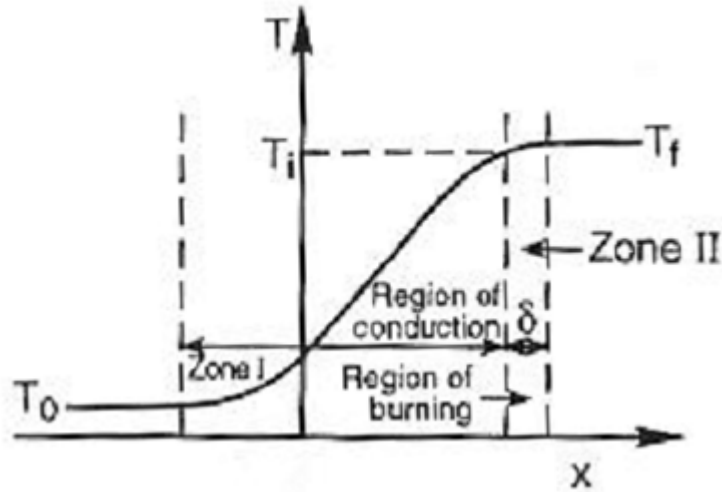


This burner flame is a simple laminar premixed flame. The air and fuel are mixed in the tube and flow together out the top of the burner where they enter the premixed flame zone. The flame itself is conical in shape with a dark zone under the flame cone and a luminous region that defines the flame zone itself. The burned gases flow upward out the top of the flame accelerated by the heat release in the flame zone. If we isolate a section of the flame front, we can analyze it to understand more precisely the structure of the premixed flame. We will do this analysis following the theory of Mallard and Le Chatelier with the ultimate goal of understanding the structure of the flame and the variable that determine the flame speed for a laminar premixed flame (i.e. the velocity of travel of the deflagration).

Laminar Flame Speed

Mallard and Le Chatelier developed a “Two zones” theory of a laminar, premixed flame. In their theory, the flame is divided into a preheat region (or region of conduction), Zone I, and a burning region, Zone II, as shown in Figure M3-3 below. Note that the burning zone has a thickness, δ , defined as the laminar flame thickness.

Figure M3-3: Mallard-Le Chatelier Description



(From *Combustion* 3rd Ed. by Glassman, page 126)

In their theory, the flame moves by conducting heat from the burning zone to the preheat zone. In order for the flame to be self-sustaining, the amount of heat conducted from the burning zone must be sufficient to raise the temperature of the unburned fuel/air mixture to its ignition temperature. Thus, they theorized that in Zone I the gases are heated from their initial temperature, T_0 , to their ignition temperature, T_i , by heat from the combustion reaction conducted from Zone II into Zone I. The excess energy released from the combustion reaction then further raises the temperature of the gases from T_i to the flame temperature T_f . They analyzed this process by linearizing the temperature change in Zone II and by setting the sensible heat necessary to raise the unburned gases from T_0 to T_i equal to the heat conducted from the flame into Zone I. The energy balance then is given by

$$\dot{m} C_p (T_i - T_0) = \lambda \frac{(T_f - T_i)}{\delta} A$$

Where λ = thermal conductivity

If we treat this flame propagation as a 1-D problem then the mass flow rate in the preheat region is given by:

$$\dot{m} = \rho A u = \rho A s_L$$

where $s_L = u$ is defined as the laminar flame speed.

So the energy balance around the flame becomes

$$\rho s_L C_p (T_i - T_0) = \lambda (T_f - T_i) / \delta$$

or

$$\boxed{S_L = \frac{\lambda}{\rho C_p} \frac{(T_f - T_i)}{(T_i - T_o)} \frac{1}{\delta}} \quad (M3-1)$$

but the flame thickness, δ , is unknown. However, we can use chemical kinetics to get an expression for δ as follows. The flame thickness is given by the flame speed times some measure of the reaction time. This reaction time is given by the inverse of the reaction rate, so

$$\delta = S_L \cdot \tau = S_L \frac{1}{\left(\frac{d\varepsilon}{dt}\right)} = \frac{S_L}{RR},$$

If we substitute the expression for δ into equation (M3-1) and solve for S_L then we get

$$S_L = \left(\frac{\lambda}{\rho C_p} \frac{T_f - T_i}{T_i - T_o} (RR) \right)^{1/2} \sim (\alpha RR)^{1/2}$$

where $\alpha = \frac{\lambda}{\rho C_p}$

If we eliminate RR by using the fact that $RR = S_L / \delta$ then we get

$$\boxed{\delta = \frac{\alpha}{S_L}}$$

That is, the flame thickness is equal to the thermal diffusivity divided by the laminar flame speed.

Since for typical Hydrocarbons

$$S_L = 40 \text{ cm/sec.}$$

Then

$$\delta \approx 0.1 \text{ cm} = 1.0 \text{ mm}$$

And

$$\tau = \frac{\alpha}{S_L^2} \approx 1-5 \text{ milliseconds}$$

Note

$$\boxed{S_L \propto (\alpha RR)^{1/2}}$$

If we look at the reaction rate,

$$RR = \frac{d\varepsilon}{dt} = k\varepsilon^n p^{n-1} = Ae^{-E/RT} \varepsilon^n p^{n-1}$$

So

$$S_L \sim \left\{ \frac{1}{\rho} p^{n-1} \right\}^{1/2} \sim (p^{n-2})^{1/2}$$

Since for most Hydrocarbon fuels, the reaction rate is overall second order, i.e., $n = 2$, then S_L is approximately independent of pressure.

Also note, that since the reaction rate term is dominated by the exponential term in the Arrhenius expression,

$$S_L \sim \left(e^{-E/RT} \right)^{1/2}$$

if $T_i \approx T_f$ then

$$S_L \sim \left(e^{-E/RT_f} \right)^{1/2}$$

this leads to the conclusion that a higher T_f produces a faster S_L .

Summary

Review: Mallard and Le Chatelier

Thermal theory (2 zones):

- preheat
- flame

Result:

$$S_L = \left(\frac{\lambda}{\rho c_p} \frac{T_f - T_o}{T_i - T_o} \frac{dE}{dt} \right)^{1/2}$$

$$S_L \sim (\alpha RR)^{1/2}$$

$$\delta \sim \frac{\alpha}{S_L}$$

$$S_L \sim (p^{n-2})^{1/2} \sim p^0$$

$$S_L \sim \left(e^{-E/RT_f} \right)^{1/2}$$

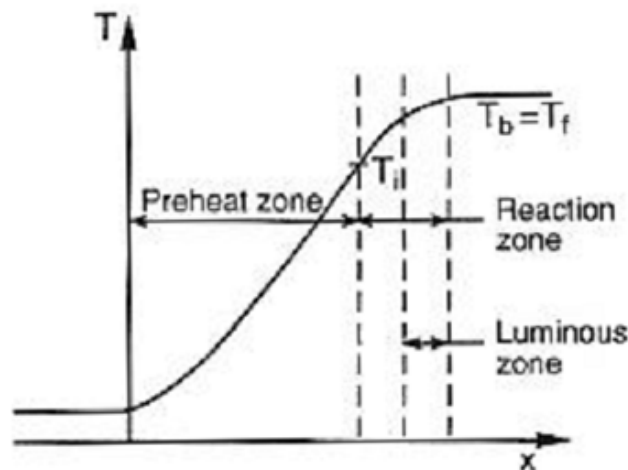
Flame Speed Measurements

In order to measure the speed of a laminar flame it is often necessary to define the exact location of the flame. The flame can be located by a number of different measurement techniques. The first and most obvious is the luminous zone of the flame. However, some other techniques can also be used to define the flame zone. They include the optical methods of shadowgraph and Schlieren, which measure the second derivative and the first derivative, respectively, of the temperature gradient, and interferometry, which measures the temperature or density of the gas.

Ways to locate flame

- a) luminous zone
- b) shadowgraph (2nd derivative)
- c) Schlieren (1st derivative)
- d) Interferometry (temperature or density)

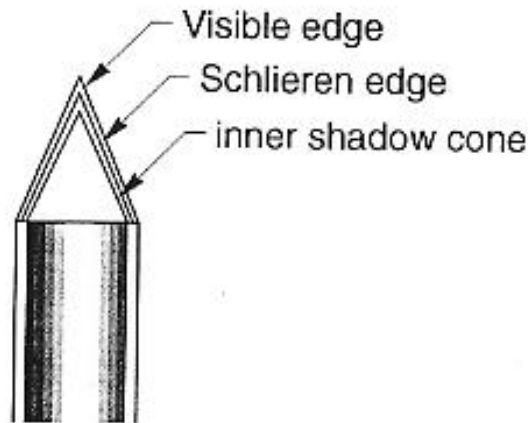
Figure M3-4: Temperature regimes in a laminar flame



(From *Combustion* 3rd Ed. by Glassman, page 149)

For a Bunsen Burner (see Figure M3-5 below), these different measures of the flame zone give slightly different definitions of the flame area and, as we will see below, lead to slightly different measures of the flame speed.

Figure M3-5: Optical fronts in a Bunsen burner flame



(From *Combustion* 3rd Ed. by Glassman, page 150)

Methods of flame speed measurement

Burner method

S_L – varies

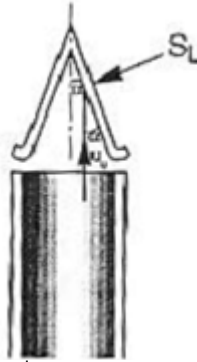
Early method:

$$S_L = \frac{Q}{A} \sim \text{cm/sec}$$

also use cone angle, then:

$$S_L = U_U \sin \alpha$$

Figure M3-6: Velocity vectors in a Bunsen core flame



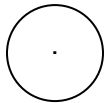
(From *Combustion* 3rd Ed. by Glassman, page 152)

Cylindrical tube

1. horizontal tube open at one end
2. ignite at open end
3. flame is curved

$$S_L A_f = U_m \pi R^2$$

Soap bubble method



gas in soap bubble ignited at center $p = \text{constant}$

balance gives

$$S_L \times A \times p_o = u_r \times A \times p_f$$

or

$$S_L = u_r \left(\frac{p_f}{p_o} \right)$$

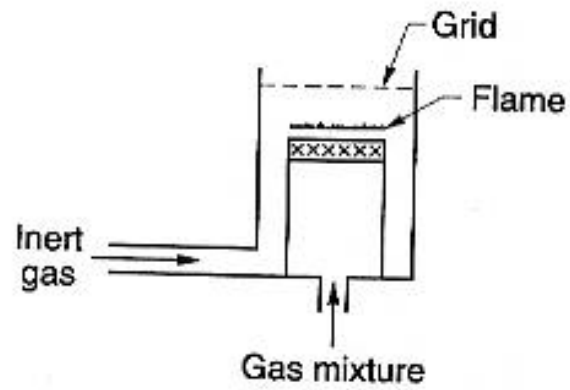
Spherical bomb

Constant volume – p changes must follow p and flame

$$S_L = \left[1 - \frac{R^3 - r^3}{3p\gamma_u r^2} \frac{dp}{dr} \right] \frac{dr}{dt}$$

Flat Flame burner

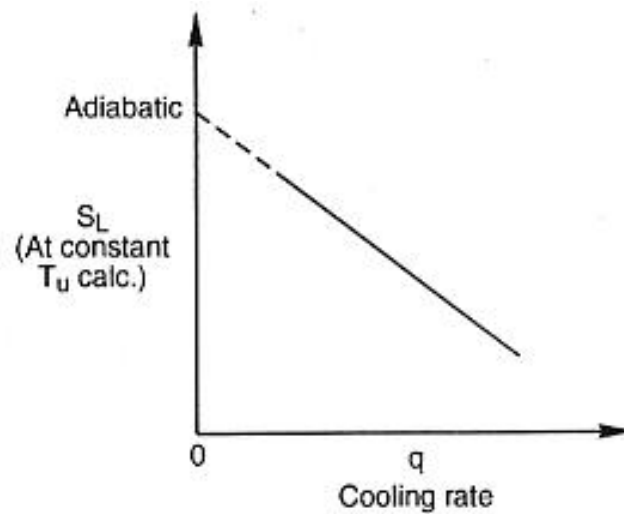
Figure M3-7: Flat flame burner apparatus



(From *Combustion* 3rd Ed. by Glassman, page 154)

Cool burner

Figure M3-8: Cooling effect in flat flame burner apparatus



(From *Combustion* 3rd Ed. by Glassman, page 155)

Discussion Exercise 3.2:

A stoichiometric fuel-air mixing flowing in a Bunsen burner forms a well-defined conical flame. The mixture is then made leaner. For the same flow velocity in the tube, does the cone angle become larger or smaller than the angle for the stoichiometric mixture? Explain.

Instructions:

In the discussions space, there is a topic 'M3-Flow Velocity'. Post your explanation/opinion there. Be sure to provide support for your answer. Compare and discuss your findings with those of other students.

Effects on Flame Speed

Showed previously

$$S_L = \left[\frac{\lambda}{pc_p} \frac{T_f - T_o}{T_i - T_o} \frac{dE}{dt} \right]^{1/2} \sim (\alpha RR)^{1/2}$$

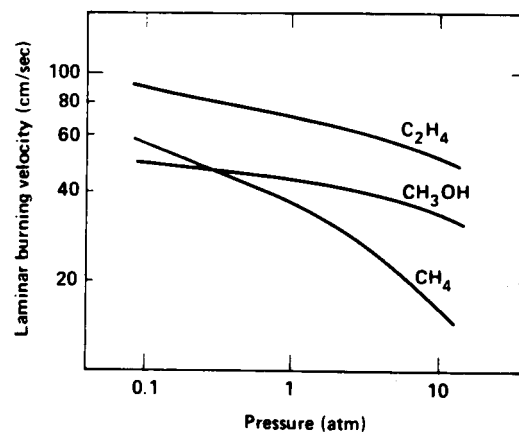
$$\sim \left(e^{-E/RT} \right)^{1/2} \sim (p^{n-2})^{1/2}$$

n is overall order of reaction.

For second order $S_L \sim p^o$

For most hydrocarbons (hc), $n \longrightarrow 1.5 - 2.0$ (1.75), so there is a slight decrease in S_L with p.

Figure M3-9: Variation in laminar flame speeds



(From *Combustion* 3rd Ed. by Glassman, page 157)

Competition between:

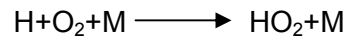
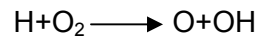
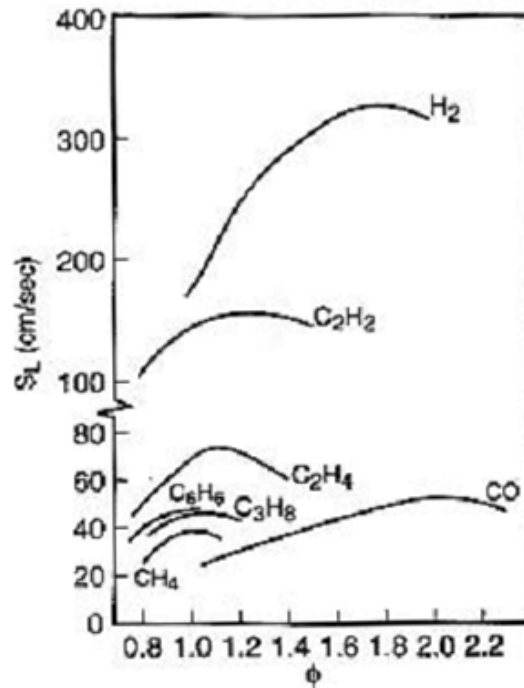


Figure M3-10: Variation in laminar flame speeds

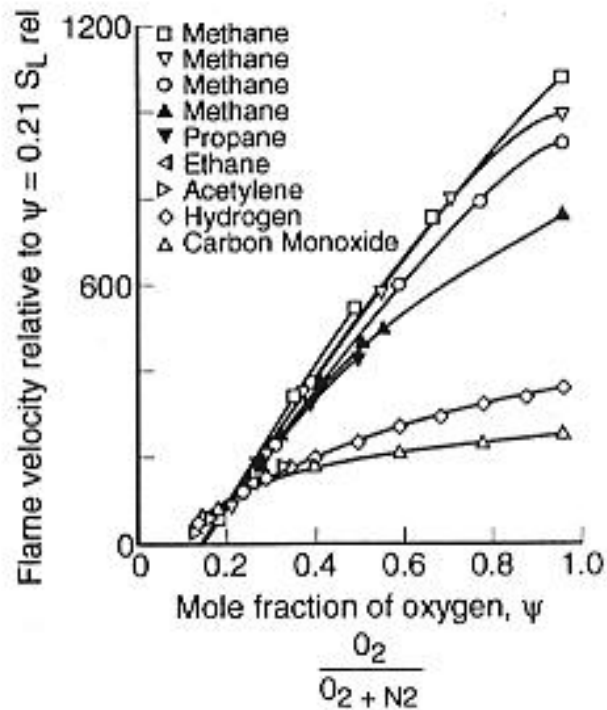


(From *Combustion* 3rd Ed. by Glassman, page 158)

S_L vs ϕ

- T max at ϕ slightly greater than 1.0
- So is S_L max
- For H_2 increase in thermal different pushes
- Max S_L richer
- Variation of S_L for hc follows T_f

Figure M3-11: Relative effect of oxygen concentrations on flame speed



(From *Combustion* 3rd Ed. by Glassman, page 159)

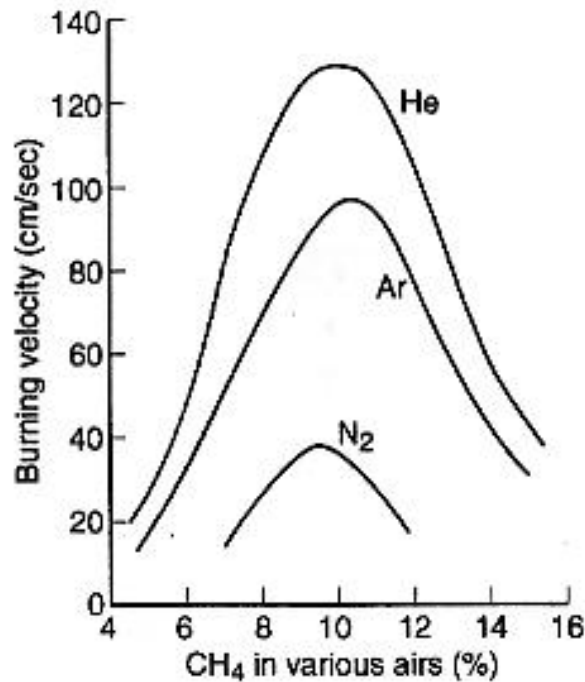
S_L vs $\frac{O_2}{O_2 + N_2}$

- should expect hc factor of 5 higher
- should expect CO/H₂ factor of 5 lower
- CO has limited OH
- hc radical pool increases with O₂

S_L vs T_i

small changes in T_i give small changes in T_f but since $S_L \sim e^{-E/RT_f}$ can have large effect.

Figure M3-12: Methane laminar flame velocities



(From *Combustion* 3rd Ed. by Glassman, page 160)

S_L vs dilluent (N₂, AR, He)

AR and N₂ have the same diffusivity, but

$$Cp_{N_2} > Cp_1AR$$

and

$$CpAR = Cp_{He}$$

but

$$\alpha_{He} > \alpha_{AR}$$

Note: attempts to modify flame speed by addition of low temperature intermediate produces results that are the same as excess fuel. Thus, S_L is controlled by high temperature reactions.

For CO added H₂, H₂O increases, then decreases by ~5% due to OH

Anti-knocks: no effect on flame speed reduce marginal radicals

Halogens: reduce marginal radicals

Stability of Laminar Flames

Limits due to loss of heat in gas phase:

- reduced temperature
- no feed back

Limits due to quenching at wall

- loss of heat & radicals

Limits due to mixture flow

- Flashback
- Blow-off
- Turbulence

Flammability Limits: Introduction

- As a function of ϕ
- Measured by self sustained propagation
- Often ignites by spark or flame
- controlled by heat gain vs heat loss

Factors Affecting Flammability Limits

- size of tube
- energy of spark
- direction of propagation

Table M3-1: Flammability Limits of Some Fuels in Air

	<i>Lower (lean)</i>	<i>Upper (rich)</i>	<i>Stoichiometric</i>
Methane	5	15	9.47
Heptane	1	6.7	1.87
Hydrogen	4	75	29.2
Carbon Monoxide	12.5	74.2	29.5
Acetaldehyde	4.0	60	7.7
Acetylene	2.5	100	7.7
Carbon Disulfide	1.3	50	7.7
Ethylene Oxide	3.6	100	7.7

(From *Combustion* 3rd Ed. by Glassman, page 163)

Flammability Limits broaden with T initial

Note: Lower limits approximately 50% of stoichiometric

Upper limits approximately 3 times stoichiometric

Lower limit is the same for O₂ and air (mixing O₂ like N₂)

But upper limit is much greater in O₂ because of temperature

Table M3-2: Comparison of Oxygen and Air Flammability Limits

	<i>Lean</i>		<i>Rich</i>	
	<i>Air</i>	<i>O₂</i>	<i>Air</i>	<i>O₂</i>
H ₂	4	4	75	94
CO	12	16	74	94
NH ₃	15	15	28	79
CH ₄	5	5	15	61
C ₃ H ₈	2	2	10	55

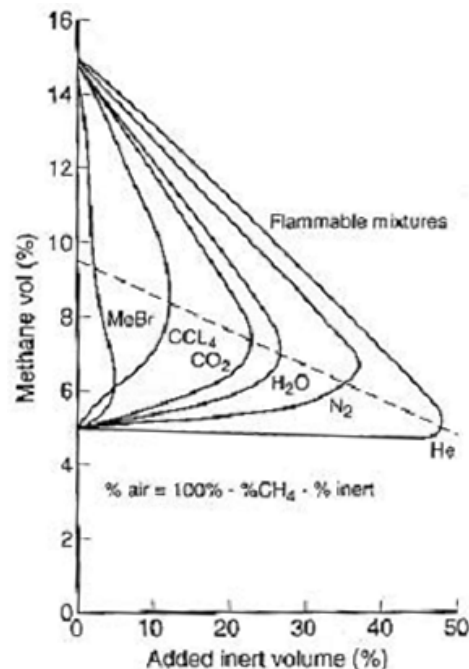
(From *Combustion* 3rd Ed. by Glassman, page 164)

Effect of diluent type on flammability limit.

CO₂ > N₂ > He or AR

The trend follows specific heat, C_p

Figure M3-13: Limits of flammability of various methane-inert gas-air mixtures



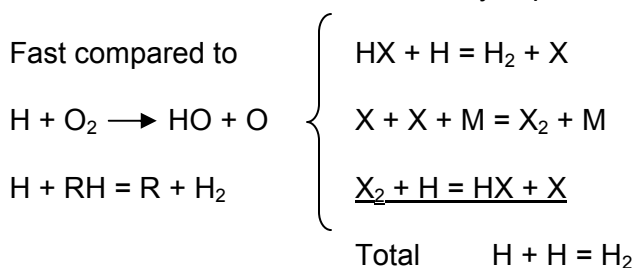
(From *Combustion* 3rd Ed. by Glassman, page 165)

Rich limits are more resistive to diluents than lean limits.

Halogens

The effect of halogen compounds on Flammability limits is substantial. The addition of only a few percent of can make some systems nonflammable. This is not only due to the diluent effect of the added gas, but also due to the ability of the halogens to act as catalysts in reducing the H atom concentrations in the chain branching sequence.

In the following comparison, X represents a halogen atom (F, Cl, Br, or I). The right side of the comparison is much faster than the reactions on the left side. This competition between reactions reduces the rate of the very important $\text{H} + \text{O}_2$ reaction.



Discussion Exercise 3.3:

Explain briefly why halogen compounds are effective in altering flammability limits.

Instructions:

There is a topic 'M3-Halogens' in the discussion area. Post your explanation there. Compare and discuss your explanation with that of other students.

Pressure Effects on Flammability Limits

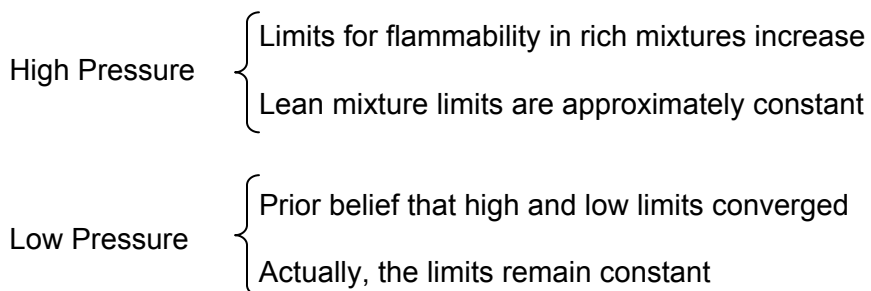
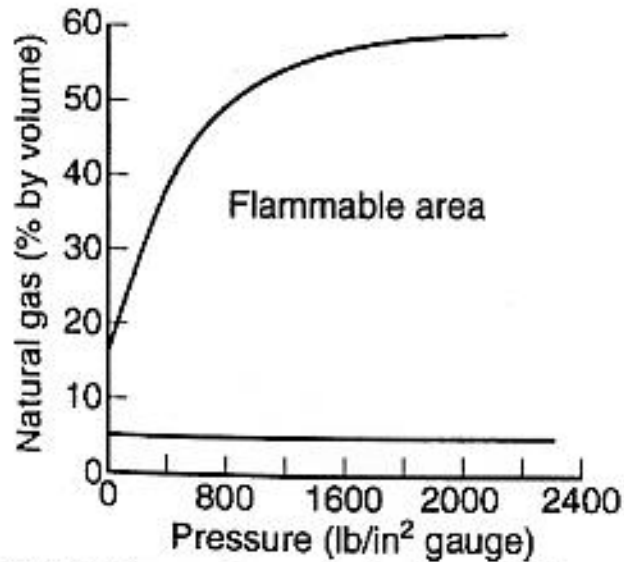
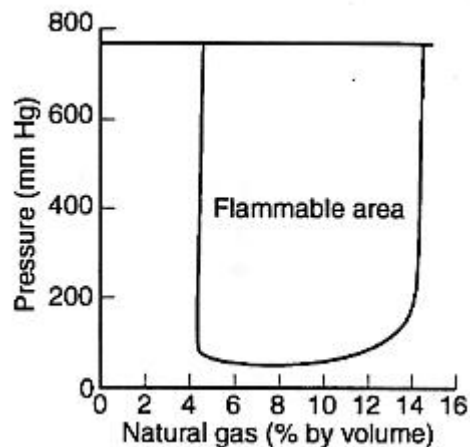


Figure M3-14: Effect of pressure increase



(From *Combustion* 3rd Ed. by Glassman, page 167)

Figure M3-15: Effect of reduction of pressure



(From *Combustion* 3rd Ed. by Glassman, page 168)

Flame stabilization at low velocities

If the flow velocity > flame speed, then flame will be forced out of tube and it becomes a burner flame.

The flame is then stabilized by the burner lip, which acts as sink for heat and radicals.

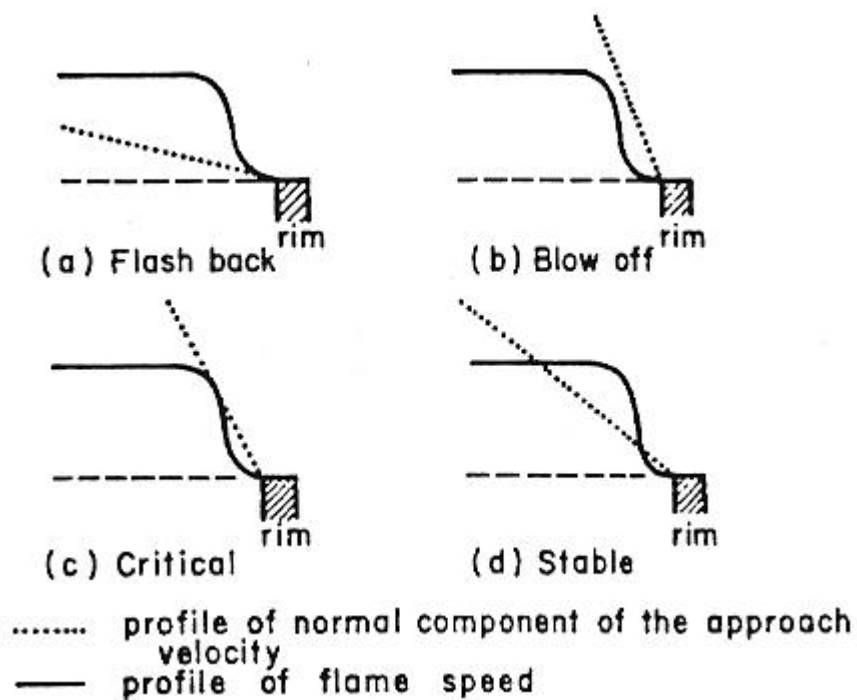
As flow increases, the flame cone angle decreases, but the flame is stabilized by the lower velocity near the lip of the burner. Eventually, as the flow continues to increase, the flame will “blow-off.”

If the velocity is decreased, the flame will propagate into the tube. This is referred to as “flashback.”

Thus, the flame is only stable within certain velocity limits!

Flashback and Blow-off

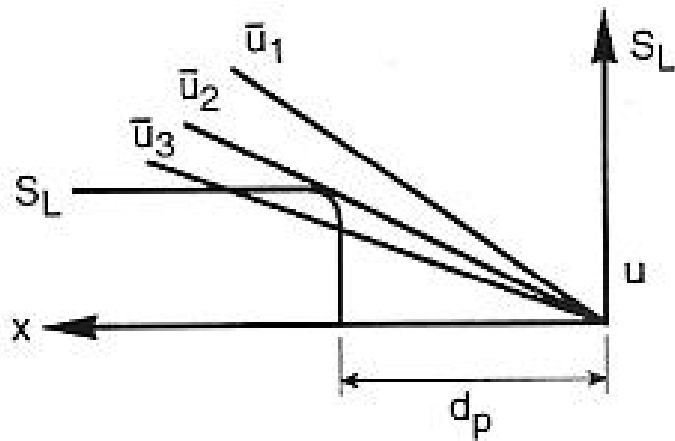
Figure M3-16: Stability of flame front near the rim of a Bunsen burner



Gradient for flashback is given by:

$$g_F = \frac{S_L}{d_p} \text{ where } S_L \text{ is the flame speed and } d_p \text{ is the penetration distance.}$$

Figure M3-17: Burning velocity and gas velocity inside a Bunsen tube



(From *Combustion* 3rd Ed. by Glassman, page 175)

inside tube for:

- $\bar{u}_1 > S_L$ flame blows out of tube
- $\bar{u}_2 = S_L$ flame begins flashback
- $\bar{u}_3 < S_L$ flame flashes back

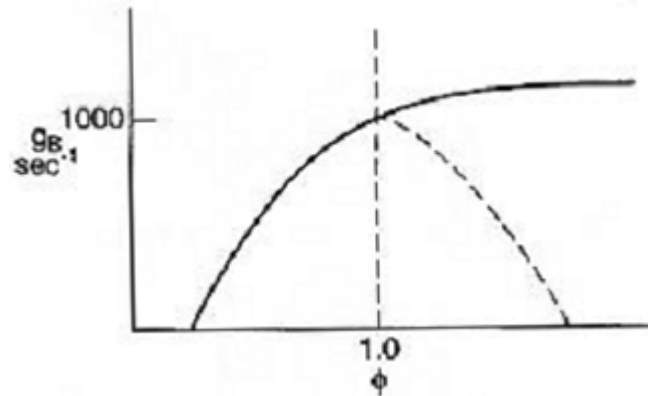
For blow-off:

- As u increases, the equilibrium position moves away from rim
- More dilution slows flame but eventually it blows off.

$$G_B = \lim_{r \rightarrow R} \left(-\frac{du}{dr} \right)$$

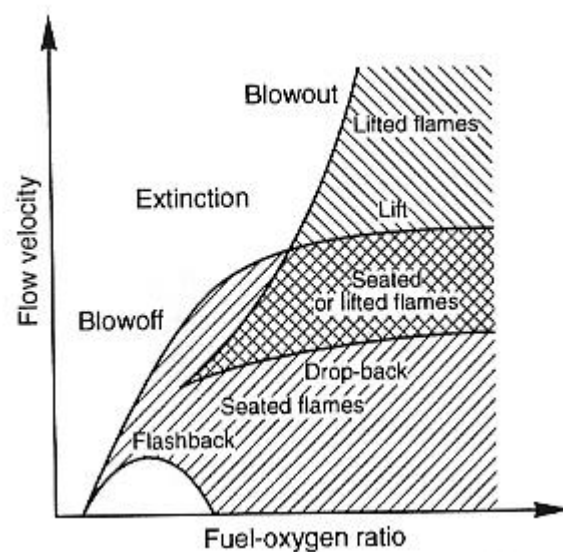
for Poiseuille flow $g_{B,F} = \frac{8\bar{u}}{d}$

Figure M3-18: Typical curves of the gradient of flashback and blowoff, respectively



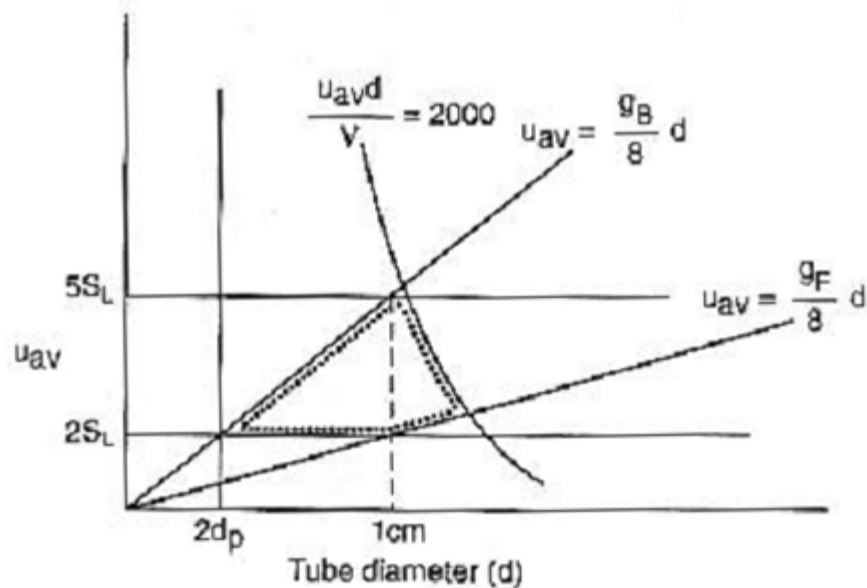
(From *Combustion* 3rd Ed. by Glassman, page 177)

Figure M3-19: Seated and lifted flame regimes for Bunsen burners



(From *Combustion* 3rd Ed. by Glassman, page 178)

Figure M3-20: Stability and operation limits of a Bunsen burner

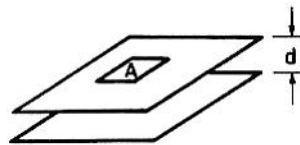


(From *Combustion* 3rd Ed. by Glassman, page 179)

Flame Quenching

The quenching diameter, (d_T) is the smallest diameter of a Bunsen burner that just lets flame flashback. To look at quenching as a heat loss phenomenon, let us look at parallel plates:

Figure M3-21: Parallel Plates



Quenching occurs when $\dot{q}_{RXN} = \dot{q}_{LOSS}$

$$\dot{q}_{RXN} = \phi_o(RR)(A\phi) Q_{RXN}$$

$$\dot{q}_{LOSS} = \lambda A \frac{dT}{d\lambda}$$

If T_q is lowest flame temperature for propagation and T_o is wall temperature, then

$$2 \left(A \lambda \frac{T_q - T_o}{d/2} \right) = \phi_o Q_{RXN} RR A d$$

or

$$d^2 = \frac{4\lambda(T_q - T_o)}{\phi_o RR Q_{RXN}}$$

but

$$Q_{RXN} = C_p (T_f - T_o)$$

so

$$d^2 = \frac{4\lambda}{\phi_o C_p RR} \left(\frac{T_q - T_o}{T_f - T_o} \right)$$

or

$$d \sim \left(\frac{\alpha}{RR} \right)^{1/2}$$

remembering

$$S_L \sim (\alpha RR)^{1/2}$$

then

$$\frac{S_L}{d} \sim RR$$

and

$$S_L d \sim \alpha$$

Note: as $RR \rightarrow 0$ $d \rightarrow \infty$ which is not true so assumption breaks down for low RR

Note: d_p = depth of penetration

$$d_p = \frac{1}{2} d \text{ (parallel plates)}$$

note for more reactive fuels d decreases.

$$\text{i.e.} \quad d_{H_2} < d_{HC}$$

there is also the affect of diluents

$$d_{He} > d_{AR} > d_{N_2} > d_{cd_2}$$

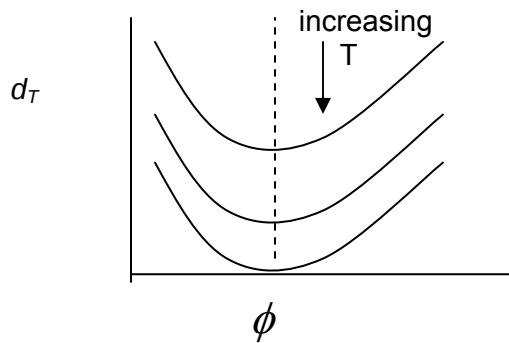
because

$$\alpha_{He} > \alpha_{AR} > \alpha_{N_2} > \alpha_{CO_2}$$

also

$$d_T \sim \left(\frac{1}{\phi} \right)^{1/2}$$

so



Also, d_T increases as P decreases

$$\alpha = \frac{\lambda}{pc_p} \sim \frac{1}{p}$$

$$RR \sim p_n$$

so

$$d \sim \left(\frac{\alpha}{RR} \right)^{1/2} \sim \left(\frac{1}{pn+1} \right)^{1/2}$$

for Hydrocarbons:

$$d \sim \frac{1}{p} \quad 2^{\text{nd}} \text{ order}$$

The effect of low p must also take into consideration the effect of radicals. As p decreases, the mean free path increases, so more radical quench. This enters into the analysis through the RR term.

Module 3 Assignment

In completing this assignment, you should show all work. The approach that you use is the essential part of developing a solution, where obtaining the correct answer in these assignments is only of modest importance.

Formats for submitting assignments

Problems that are due on the same date can be completed in one document and submitted as one electronic file. You may complete your assignment in the following formats: word processed (.doc, .rtf, pdf, etc.) or scanned.

Due Dates:

See class schedule for due date.

Total Points: 10

All problems can be found in the m3_problems.doc in the assignment for module 3.