Combustion related aspects Fundamentals

- Fuels Liquid and Gaseous fuels and key characteristics
- Fuels Stoichiometric and Equivalence Ratios and their relevance
- Heat release in Combustion Processes, Flame temperature and how to enhance the flame temperature
- Ignition of gaseous and liquid fuels
- Gaseous Flame Types Diffusion and pre-mixed and their importance in practical combustion systems
- Ideas Laminar and Turbulent flows and flames
- Chemistry of Premixed and Diffusion flames both in steady state and Limiting mixture situations and the mechanisms of flash back and blow off
- Mixing Fuel Gas with air techniques and implications in practical fuel systems
- Flameless modes of combustion
- An understanding of Liquid fuel spray systems

How do we ignite a fuel jet in ambient atmosphere?



- One can use a naked flame from a match stick or use a spark plug.
- Because the match stick flame is broad, ignition has much better possibility under quiescent conditions.
- However, with surrounding air flow, its chance in causing Ignition is highly uncertain. It may ignite or extinguish
- In the case of spark plug, its position inside the flow matters. If immersed in the fuel stream only, no ignition occurs.
- The spark should be continuous in case of industrial systems unless the ignition sequence is tuned to the entry time of fuel jets or sprays with liquid sprays. In the case of reciprocating engines, it is of a short duration. In the case of gas turbines, it is a continuous duration – for a time up to which the combustion gets initiated.

How does ignition occur?

Diffusion under quiescent conditions, convection also with flow into the fuel jet of fuel-air mixture If premixed



Whether it is a naked flame or spark, the result is a mix of hig temperature ~ 1500 K and reactive radicals - OH, H, CHO

1. Reaction and heat release accompanied by diffusion and convection.

- 2. If it results in higher temperatures, getting generated in fresh zones, we say there is Ignition.
- 3. At this stage, If the ignition source can be withdrawn and steady propagation continues.
- 4. If not, there is ignition failure. This can happen if there is larger diffusion and convection that exothermic reaction cannot sustain high temperature.
- 5. In this case, the ignition energy needs to be raised. When raised adequately, ignition will occur. Experimentally, one determines under quiescent conditions, the energy required to cause ignition.

Table 8.1: Ignition energies $(I.E)$ at $0.1 MPa$				
Fuel	Oxidizer	I.E		
		mJ		
Hydrogen	Air	0.01		
Hydrogen	Oxygen	0.003		
Methane	Air	0.003	Γ	
Ethane	Air	0.4	י נ	
Butane	Air	0.3	Г	
Acetylene	Air	0.03	C	
Methyl alcohol	Air	0.2		
Carbon monoxide	Air	0.05		



 H_2 -air/ O_2 needs smaller amount of energy compared to HCs.

Ignition system in gas turbines, same in large combustors

Locate the igniter here



The igniter should be located in the area where the equivalence ratio is around one, or slightly larger than one. If the spark plug is moved around 5-10 mm towards the leaner side, the ignition probability may decrease from 100 % to 0 %. The best location is in the recirculation zone, where the fuel recirculated back towards the fuel nozzle as this is when the flame kernel spread best.



Is it what that is adopted in practical systems?



The ignition systems using sparking devices are engineered after testing for a number of conditions – initial temperature and humidity of air.

Typical energy levels of these ignition systems is as large as about 1 J for reciprocating engines and 2 J for gas turbine engines (several hundred times the one under quiescent conditions to account for local flow conditions).

Diffusion, premixed fuels?

- Diffusion flames are un-premixed flames fuel meets the oxidant at the flame
- Premixed flames have both fuel and oxidizer mixed in them before being ignited LPG stove or many other combustion systems of LPG.
- Mixing is the slower that chemical reaction in a diffusion flame.
- Chemical reaction controls the burn behaviour of premixed flames since mixing has already occurred.
- Premixed flames burn more cleanly than diffusion flames.
- On the average, nature prohibits combustion, and surely premixed flame purely for sustainability reasons! Otherwise we would not have oxygen for breathing!
- Just ignite a gaseous fuel jet, or a spilled kerosene layer or a candle or fuel wood in an atmosphere of air – These are diffusion flames.

Diffusion flame with increased velocities (flow)



Diffusion to premixed flame transition



Side air vent opened with increased air for ambient air to be drawn in by the fuel jet leading to premixing

Deflagration – diffusion, transition to premixed flame



The steady combustion of the flow of premixed mixture through a Bunsen burner as the flow rate is increased and decreased



Diffusion flame is obtained by causing the flow of a fuel – liquid petroleum gas (LPG) through the Bunsen burner. Air enters by diffusion. As the flow rate is increased the flame height increases linearly. It also lifts off from the edge of the tube. The height then levels off with the flow becoming turbulent. The jet entrains air from outside causing premixing below the base of the flame. Beyond a flow rate, the flame blows off. Blow-off is also termed local extinction



<<LiR



Premixed flames are characterised by a quantity "Burning velocity" –

Velocity of a propagating flame with reference to unburnt conditions





Cold (mixture density x velocity) = Hot (mixture density x velocity)

Cold (velocity x temperature) = Hot (velocity x temperature)



Premixed flames – 2



v₁ – constant volume/pressure, pressure effects



From G. B. Tomlin's thesis

through The flow а Bunsen burner is slowly through decreased tubes of different diameters. The flame blows off in the smallest diameter tubes since the quench distance of the is mixture comparable to the diameter of the tube. It flashes back in the other three tubes.

Flash Back/Blow Off



Premixed flames - 1







- The velocity normal to a steady 1 d flame of the premixed reactants is called the <u>burning velocity</u>
- There are several techniques to measure the burning velocity. It is a function of equivalence ratio, pressure and initial temperature of the reactants.
- The variation of the reactants and temperature through the flame has been obtained.
- Typical flame thickness is 0.5 mm for CH_4 -air, ambient pressure and temperature flame.
- Efforts to get equivalent single step chemistry parameters show that it can be approximate. The activation parameter, $\beta = E/RT_{ad}$, that is taken as infinity in asymptotic analyses is 6.3 for stoichiometric case and it is much lower for hydrogen-air flames.



Fig. 1. Heat release rates with full chemistry and single step reaction for CH_4 -air system.

$$h_r / h_{r, \max} = (1 - \tau) \left(\frac{1}{\phi} - \tau \right) \exp(-E/RT)$$
$$E = \frac{\left(1 + \frac{1}{\phi} - 2\tau_m \right)}{\left(\frac{1}{\phi} - \tau_m \right) (1 - \tau_m)} \frac{R_g T_m^2}{(T_{ad} - T_0)}$$
(18)

where $\tau_m = (T_m - T_0)/(T_{ad} - T_0)$, T_m being the temperature at maximum reaction rate.

The parameters for the lean case are $T_{ad} = 1481$ K, $\beta = 15.3$, and Le nearly unity. For the stoichiometric case, $T_{ad} = 2224.0$ K, $\beta = 6.3$,



Laminar Diffusion flame structure



Turbulent premixed flame behavior



- When the scale of turbulence

 A is large compared to the
 unstrained flame thickness
 the flame is wrinkled by
 turbulence.
- The flame surface area change is taken proportional to turbulent velocity fluctuation, u'
- Because of temperature jump across the flame, viscosity increases and the flow may even become laminar locally.
- Under strong turbulence, the flame structure itself is altered
- Based on these considerations, various correlations are developed.



$$\frac{S_{\rm T}}{S_{\rm L}} = \frac{A_{\rm L}}{A_{\rm T}}, \qquad A_{\rm L}/A_{\rm T} = 1 + u'/S_{\rm L} \qquad S_{\rm T} = S_{\rm L} + u',$$
$$S_{\rm L} = \frac{1}{\varrho_0} \left(\frac{kw}{C_{\rm p}}\right)_{\rm L}^{1/2}, \qquad S_{\rm T} = \frac{1}{\varrho_0} \left(\frac{kw}{C_{\rm p}}\right)_{\rm T}^{1/2}, \qquad S_{\rm T}/S_{\rm L} = (v_{\rm T}/v)^{1/2},$$

 $v_{\rm T} \sim u' l, \qquad S_{\rm T}/S_{\rm L} \sim R_l^{1/2}.$

Koolmogorov scale based Re, Taylor scale based Re and inertial scale based Re

 $R_{\rm k}^4 \approx R_{\lambda}^2 \approx R_1$

 $D_{\rm a} = lS_{\rm L}/\delta_{\rm L}u'$

A simple approach to the height of a diffusion flame



Suppose the flame is enclosed in a cylinder of diameter d and height h. The fuel flow rate is \dot{m}_f . The flame will acquire just enough air for it to burn completely. This means that the air obtained by diffusion should be in stoichiometric proportion with fuel flow. This means $\dot{m}_{air}/\dot{m}_f = 1/f_s$. The flow rate of air is the product of mass flux, and the area, $\pi h d$. The mass flux is given by Fick's law of diffusion as $D_{12}\rho(dY_0/dx)$. We can take take $dY_0 = (Y_{0,\infty} - 0)$, dx = d/2 and write down the relationship for the stoichiometric air-to-fuel flow rate as

$$\pi hd \times 2D_{12}\rho \times \frac{Y_{0\infty}}{d} = \dot{m}_{air} = \frac{\dot{m}_f}{f_s} \tag{10.3}$$

$$h = \frac{\dot{m}_f}{2\pi f_s Y_{0\infty} D_{12} \rho}, \qquad \frac{h}{d} = \frac{ReSc}{8f_s Y_{0\infty}}$$
(10.4)

Behavior of Premixed and Diffusion flames



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- Fuel and air are separated by the flame

 - Diffusion is slow and when the fuel and oxidizer meet, they react at high rates
 - Flame is located where ever the fuel and oxidizer fluxes along a local normal are in stoichiometric proportions.
 - For gaseous fuel injection, flame location adjusts itself depending on the flow rate
 - For liquid or solid fuels, the air-to-fuel ratio (A/F or O/F) for stoichiometry controls the flame stand-off. Since O/F is large as is true for most hydrocarbons the flux demand leads to flame stand-off several times the fuel size.
 - Flame temperature is adiabatic flame temperature affected mildly by stretch and other effects

Role of chemistry in ignition, steady combustion and extinction

- Steady premixed combustion in multi dimensions depends on chemistry much as it does for onedimensional case.
- In one-dimensional case, burning velocity can be taken as representative of chemistry. When stretch and turbulence effects are accounted, most observations can be understood within this framework.
- Burning velocity-justified-single-step-chemistry with activation energy and a frequency factor would be good choice for computations. This is in fact the strategy for modeling solid propellant combustion. It would be adequate for other premixed flame situations as well.
- Unsteady or unstable premixed combustion near limits of flammability can be dealt with using additional features of fluid mechanics as in flame blow off or flash back.
- Diffusive combustion near limits of extinction or ignition need chemistry. This chemistry whether
 reasonably substantive (meaning a fair number of species and a large number of steps) is not necessarily
 identical to what is used for premixed chemistry. There may not be enough demand for clarifying the
 differences yet.
- Steady diffusion limited combustion for determining heat release and burn rates can be taken to relatively independent of the details of chemistry
- Auto-ignition and Ignition in practical systems need to account for conduction of heat or diffusion of species and need to treat both diffusion and reaction processes

Some fuels are more easy to ignite.....is it?, if so why?



Figure 8–5. Dependence of autoignition temperature upon carbon chain length for normal alkanes, C_NH_{2N+2} , at atmospheric pressure [26].

Methane has the highest T_{ign} followed by higher alkanes. Why so?

Larger molecules decompose more readily into reactive fragments than smaller ones. Hydrogen, the high reactive molecule is more difficult to auto-ignite compared to several liquid hydrocarbons!

All these mean that chemistry matters with regard to ignition. It is not entirely short duration high energy inspired reaction chemistry either. There are energy extraction processes due to flow including turbulence – a dynamic energy balance deeply influenced by chemistry.

Easier ignition does not mean faster combustion. Burning velocity of premixed hydrogen-air mixture is about 5 times more than straight chain hydrocarbon. <u>Different mechanisms are at play – early time dependent breakdown vs. steady back</u> diffusion of reactive intermediates.

Flammability limits

$\frac{1}{1000}$							
Fuel	Oxidiser	Lean Limit %(Volume of fuel)	Rich Limit %	${\rm O/F}_{stoi}$			
Hydrogen	Air	4.0	75.0	29.5			
Hydrogen	Oxygen	4.0	95.0	66.0			
Methane	Air	4.5	14.0	9.5			
Ethane	Air	3.0	12.4	5.6			
Propane	Air	2.1	9.1	4.0			
Butane	Air	1.8	8.4	3.1			
Acetylene	Air	2.5	100.0	7.8			
Methyl alcohol	Air	6.7	36.0	12.2			
Carbon monoxide (Moist)	Air	12.0	76.0	29.5			

Table 7.1. Flammability limits (0.1 MPa, 300 K)

Why are there such limits?

Because the heat release rate is unable to compete with the heat loss rate

We must note that heat release rate is Proportional to burning velocity² and burning velocity drops down towards both the limits

Turbulence, and diffusion limited flows

- There are many perceptions of difference between laminar and turbulent flows.
- It is commonly understood that pipe flows are turbulent beyond a Reynolds number, *Re* (= pud/μ) – typically 2300, where as the correct statement would be that turbulence cannot be sustained below a certain Re, say 2300.
- Any unsteady flow with fluctuations is not a turbulent flow. It could simply be an unsteady laminar flow.
- A flow with fluctuations like white noise fluctuations with the same amplitude at all frequencies is not a turbulent flow.
- A flow in which the fluctuations have a power spectrum (variation of the square of fluctuating velocity with frequency) involving all frequencies (not simply connected to any specific geometrical feature) is turbulent.
- In a turbulent flow, the fluctuating velocity draws energy from the mean field and dissipates it through fluctuations until the final dissipation occurs through viscosity.
- A buoyancy driven flow field (like buoyant jets) can also be turbulent. Here the convective motion gets sustained buoyancy.

Energy cascading in turbulent flows

Big whorls have little whorls that feed on their velocity, and little whorls have smaller whorls and so on to viscosity in the molecular sense.





Data On Turbulent Premixed mixtures

Comparison of turbulent flame speed correlations for HC fuels at elevated pressures, GT2016 – 57804 by Burke, E M, Guthe, F Monaghan, R F D



Figure 5 Turbulence and flame conditions for the data displayed in Table 3 plotted on a Borghi diagram modified by Peters [17].



Figure 11 Predicted trends for Flame D (CH₄ with T = 300 K, P = 0.1 MPa) with u' = 1.89 using correlation parameter to minimize



Figure 6 Predicted trends for Flame J (CH₄ with T = 300 K, P = 0.1 MPa) with Φ = 0.7 using correlation parameter to minimize MAPE for DG 1



Figure 7 Predicted trends for Flame J (CH₄ with T = 300 K, P = 0.1 MPa) with Φ = 1.0 using correlation parameter to minimize MAPE for DG 1

<u>The conclusion of several authors is that the correlations for turbulent flame speed</u> are not satisfactory. Modeling of the role of turbulence needs improvement.

For complex premixed flows, a simple approach is to use BML model in which the local temperature of an averaged combination of temperatures at unburnt condition and fully burnt condition, the averaging procedure evolved through conservation equations. It is turbulence that controls the averaging process.

Briefly, on liquid fuels, hydrocarbons and alcohols

- Liquids when ignited, burn because they vaporise and meet the oxidizer (air, usually) at the flame.
- The heat transferred from the flame causes the liquid to vaporise. They are directly related. With m
 ^{''} as the mass flux from the surface (g/m²s), we write
- $\dot{m}'' L = q'' = h_g (T_f T_s)$, so that $\dot{m}'' = h_g (T_f T_s) / L$; It leads to $\dot{m}'' = (h_{g/}c_p) c_p (T_f T_s) / L \sim B (h_{g/}c_p)$, where h_g is the heat transfer coefficient and B = Spalding's transfer number
- The mass flux with small thickness is about 11 g/m²s.

Heat transfer From the fire



Extinction in flames



No wind Region in green Has high temperature With wind Region in green has the fire blown off

Extinction in lifted flames is a much researched Subject. The precise causes have been debated. Our view: Due to local premixed flame having a higher velocity than the burning velocity



The essential elements of both the cases – of a pan fire having no flame in the region identified when wind blows past it and the case of a candle flame blowing off are the same. The convection upsets the balance between various fundamental aspects of energy conservation between convection, conduction and radiation locally that when wind occurs, the balance is in favour of a condition with temperature = ambient temperature. Otherwise it is high.

This is classically called ignition-extinction problem discussed in combustion literature.

Flameless combustion mode – Moderately intense low oxygen dilution (MILD, as it is called)









Flameless mode – how does it work?

The cone is found unnecessary and optimization of chamber dimensions will help achieving flameless mode without the cone.

- As different from conventional mode demanding that fuel and oxidant (air/oxygen) be mixed well, the fuel and air streams are kept separate, but injected at Higher speeds – 20 to 100 m/s or more.
- 2. This leads to Entrainment of the hot burnt gases amounting to recirculation of the product gases.
- 3. This makes both he fuel and air jets hotter as they flow and dilute so that the combustion process can get initiated only when the average temperature goes up to values of about 1200 K.
- 4. This process reduces the fluctuations in all the fluid variables and so, the noise level is lower, the emissions of NO_x and CO will be lower. It is greatly used in Oxy-fuel combustors to reduce NO_x emissions

Porous radiant burner



- Keep the inflow such that the flame does not occur before the porous combustion bed
- 1. Increase the loading such that flame extinguishes even at stoichiometry quench distance
- 2. Keep the stream speed much larger than burning velocity







Emissions – NOx, CO in porous burner



Rich

Principles of emission reduction

- 1. Emissions from LPG/liquid fuel combustion are CO_2 , CO, NO_x , SO_x , HC
- 2. CO₂ reduction occurs because of reducing the fuel usage for the same output (efficiency improvement)
- 3. CO is a slow reacting compound. It can be reduced by better mixing air/oxidant with the fuel in the combustion zone (unless you use flameless combustion mode), perhaps at a slightly leaner side of the stoichiometry.
- 4. NO_x is a compound produced at high temperatures (in excess of 1200°C) when air is at a condition more than stoichiometry. Its lower end appears under slightly fuel rich condition.
- 5. The behavior of CO and NO_x are at variance with each other
- 6. SO_x is inevitable due to fuel containing sulphur. Furnace oil is therefore a dirty fuel!
- Some industrial systems use flue gas recirculation (FGR) and some selective catalytic reduction (SCR) using urea-water mixture with a catalyst to reduce NO_x by large fraction

Emissions – general features



Techniques required to reduce NO_x

NO_x production increases with temperature, But not that much under fuel rich conditions. This is because its generation is controlled by Zeldovich mechanism:



Flue gas recirculation technique to reduce NO_x emissions

Ducts bringing in flue gas into the combustion chamber to reduce the emissions



Liquid combustion vs. Gaseous fuel combustion

- 1. Gaseous fuels can be introduced with increasing and large velocities into space and hence a large volume that can mix with air and conflagrate on ignition.
- 2. If one delivers liquid, it will create a large pool over the ground surface. When ignited it will burn away at a maximum rate of 80 g/m²s (maximum pool burn flux!) because the burn flux depends on the heat transfer by convection and radiation. If one wants to increase the flux and so burn rate, one needs to atomize the fuel as done in reciprocating engines and gas turbines.
- 3. By reducing the size through atomization, the area is increased many fold N ($\pi/4$ d²) = ($\pi/4$ D²), D = diameter of a pan say 1 to several meters and d = droplet diameter ~ 20 to 50 micrometers, the value of N is N = (D/d)² which is very large.

Burn rate ratio

- \dot{m} (pool) = \dot{m}'' ($\pi/4$)D². The maximum flux in pool fires is about 80 g/m²s.
- \dot{m} (droplet) = 4 π (k/cp)_g d ln (1 + B), where is the ratio of thermodynamics-to-specific heat ratio in the g-phase. Thus the ratio of burn rates is
- $\dot{m}(droplets)/\dot{m}(pool) = N 4 \pi (k/cp)_g d \ln (1 + B) / [80 ((\pi/4)D^2] ~ (Nd/D^2)[(k/cp)_g \ln (1 + B)]/5$
- We already know N = $(D/d)^2$. Therefore, $\dot{m}(droplets)/\dot{m}(pool) \sim (1/d)[(k/cp)_g ln (1 + B)]/5$

Thus by decreasing the drop diameter, the burn rate can be increased. This is what that is taken benefit of and that is why one atomizes the drop to very fine sizes.

All gas turbine engines use finely atomised fuel,

So also reciprocating diesel engines



Spray Physics and Characterization





Figure 14 Breakup model of diesel fuel jet (modified from ref. [22])

FIGURE 8.3.2

View of the typical conventional CI-engine spray targeting from the bottom. The images of the nonevaporative spray were obtained in an engine with a transparent piston top, using a fast camera and a pulsed laser for illuminating the sprays from the same side as the camera. (From Cronhjort, A. and Wählin, F., *Appl. Opt.*, 43(32), 5971, 2004. With permission.)

(6) Mean diameter of spray: The Sauter mean diameter X_{SMD} is the most popular mean diameter. The definition is;

$$X_{SMD} = \frac{\sum_{i} n_i X_i^3}{\sum_{i} n_i X_i^2} \tag{1}$$

where n_i is numbers of X_i diameter droplet. The Sauter mean diameter is a representative diameter corresponding to equivalent surface of spray and could show the average evaporation characteristics of a spray. Typical empirical equations of the Sauter mean diameter of diesel spray was as follows [11].

$$\frac{x_{SMD}}{D_n} = MAX \left[\frac{x_{SMD}^{LS}}{D_n}, \frac{x_{SMD}^{HS}}{D_n} \right]$$
(2)

$$\frac{x_{SMD}^{LS}}{D_n} = 4.12 \cdot Re^{0.12} \cdot We^{-0.75} \cdot \left(\frac{\mu_l}{\mu_a}\right)^{0.54} \cdot \left(\frac{\rho_l}{\rho_a}\right)^{0.18}$$
(3)

$$Re = \rho_l U_l D/\mu_l$$
(4)

$$\frac{x_{SMD}^{HS}}{D_n} = 0.38 \cdot Re^{0.25} \cdot We^{-0.32} \cdot \left(\frac{\mu_l}{\mu_a}\right)^{0.37} \cdot \left(\frac{\rho_l}{\rho_a}\right)^{-0.47}$$
(4)

$$We = \rho_l U_l^2 D/\sigma$$

Where, MAX[A,B] means the larger value of the two. μ is viscosity of liquid (*l*) and air(*a*), and ρ is density. Positive index of *Re* (Reynolds number) and negative index of *We* (Weber number) meant that both of shear force in a nozzle and jet stability were dominant factors on X_{SMD} . However, applicable range of nozzle diameter D_n was unclear and it was one of fundamental issues of liquid atomization. X_{SMD} of a traditional type diesel spray was ranging into 25µm-35µm, and that of 10µm-20µm was attained with a high-pressure injection.

Breakup Form	d10/di	V6/VI	Range in We No.
into film)			We<80
I large breakup	0.3	0.3	80 <u><</u> We<600
III small breakup	0.1	0.5	We≥ 600



Figure 17 Fuel film breakup model for impinging diesel spray [29][31]

From: Arai, Physics behind diesel sprays, ICLASS 2012, 12th triennial int. conf. liq. atomization and spray systems

Spray characteristics – general features



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FIGURE 6.40

Influence of ambient air pressure on radial fuel distribution. (From Ortman, J., and Lefebvre, A.H., Journal of Propulsion and Power, 1(1), 11–15, 1985. With permission.)

- SMD is the actual spray volume to spray surface area. Mean drop sizes are close to 30 microns.
- Drop size distribution describes the fractional volume in a small diameter range.
- The amount of liquid distribution across the face shows that it is double peak matching with the influence of the swirl.
- The combustion process is largely governed by drop vaporization. Chemical kinetics of combustion
 will be dominant at outer limits high altitudes (12 13 km) and moderate speeds (M~0.85) when
 the pressure in the combustion chamber will be low ~ 2 to 5 atm.



Flame is treated as a thin sheet. Reactions occur no where else excepting at this sheet. Rates are represented by Dirac delta function. The mass and heat flux balance at the surface of the fuel and the think flame lead to the solution to the problem

$$\dot{m}_F = \frac{4\pi k_g r_s}{c_{pg}} \ln(1 + B_{o,q}).$$

The d² law:
$$d^2 = d_0^2 - K t$$
, $t_b = d_0^2/K$

 d_o = drop diameter, K = Burning constant

A 1 mm droplet will take ~ 1 s to burn
A 100 μm droplet will take ~ 10 ms to burn;
A 20 μm drop will take 200 to 400 μs to burn

 $K = \frac{8k_g}{\rho_l c_{pg}} \ln(1 + B_{o,q}).$

B_{0,q} = Transfer number ~ 8 to10 for Hydrocarbons

Summary

- 1. A large number of flow related topics involving premixed and diffusion flames
- 2. Novel modes of combustion including flameless mode.
- 3. There are other techniques called rich-quench-lean combustion mode used in gas turbines more significantly. They are not always simple to use in industrial modes