الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الثالثة

هندسة الاحتراق

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Combustion engineering

The nature of combustion

Combustion or burning is the sequence of exothermic chemical reactions between a fuel and an oxidant accompanied by the production of heat and conversion of chemical species. The release of heat can produce light in the form of either glowing or a flame. Fuels of interest often include organic compounds (especially hydrocarbons) in the gas, liquid or solid phase.
In a complete combustion reaction, a compound reacts with an oxidizing element, such as oxygen or fluorine, and the products are compounds of each element in the fuel with the oxidizing element. For example:

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$$
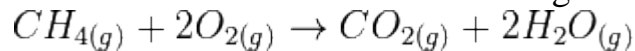
A simple example can be seen in the combustion of hydrogen and oxygen, a reaction commonly used to fuel rocket engines:

$$H_{2(g)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(g)}$$
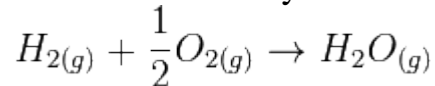
The result is water vapor, with a standard enthalpy of reaction at 298.15 K and 1 atm of −242 kJ/mol.
equilibrium, a wide variety of major and minor species will be present, such as carbon monoxide, hydrogen and even carbon (soot or ash). As actual combustion reactions come to air, which is 78 percent nitrogen, will also create small amounts of several nitrogen oxides, commonly referred to as NOx.increasing surface area to increase reaction rate is a method used in engineering practice for example liquid spray combustors which are used in burners ,diesel engines increases in surface area can also produce undesirable results such as accidental explosions .Another common method of causing fast reaction is to increase the temperature.

Complete combustion
In complete combustion, the reactant burns in oxygen, producing a limited number of products. When a hydrocarbon burns in oxygen, the reaction will primarily yield carbon dioxide and water. When elements are burned, the products are primarily the most common oxides. Carbon will yield carbon dioxide, sulfur will yield sulfur dioxide
. NOx species appear in significant amounts above about 2,800 °F (1,540 °C), and more is produced at higher temperatures. The amount of NOx is also a function of oxygen excess.
In most industrial applications and in fires, air is the source of oxygen (O2).
In air, each mole of oxygen is mixed with approximately 3.76 mol of nitrogen.

Combustion engineering

Incomplete combustion
Incomplete combustion will only occur when there is not enough oxygen to allow the fuel to react completely to produce carbon dioxide and water. It also happens when the combustion is quenched by a heat sink, such as a solid surface or flame trap.

For most fuels, such as diesel oil, coal or wood, pyrolysis occurs before combustion. In incomplete combustion, products of pyrolysis remain unburnt and contaminate the smoke with noxious particulate matter and gases. Partially oxidized compounds are also a concern; partial oxidation of ethanol can produce harmful acetaldehyde, and carbon can produce toxic carbon monoxide.

The quality of combustion can be improved by the designs of combustion devices, such as burners and internal combustion engines. Further improvements are achievable by catalytic after-burning devices (such as catalytic converters) or by the simple partial return of the exhaust gases into the combustion process.,

Smoldering
Smoldering is the slow, low-temperature, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel. It is a typically incomplete combustion reaction. Solid materials that can sustain a smoldering reaction include coal, cellulose, wood, cotton, tobacco, and dust. Common examples of smoldering phenomena are the initiation of residential fires on upholstered furniture by weak heat sources and the persistent combustion of biomass behind the flaming fronts of wildfires.

Rapid combustion
The Bunsen burner used inheating, sterilization, and combustion. The gas can be natural gas (which is mainly methane) or a liquefied petroleum gas, such as propane, butane, or a mixture of both. The Bunsen burner consists of a metal tube on a base with a gas inlet at the lower end of the tube, which may have an adjusting valve; openings in the sides of the tube can be regulated by a admit as much air as desired. The mixture of air and gas (optimally about 1 part gas to 3 parts air) is forced by gas pressure to the top of the tube, where it is ignited with a match. It burns with a pale blue flame, the primary flame, seen as a small inner cone, and a secondary, almost *colorless* flame, seen as a larger, outer cone, which results when the remaining gas is completely oxidized by the surrounding air

boiler

Steam generator or boiler is an integral component of a steam engine when considered as a prime mover. However it needs be treated separately, as to some extent a variety of generator types can be combined with a variety of engine units. A boiler incorporates a firebox or furnace in order to burn the fuel and generate heat. The generated heat is transferred to water to makesteam, the process of boiling. This producessaturated steam at a rate which can vary according to the pressure above the boiling water. The higher furnace temperature, the faster the steam production. The saturated steam thus produced can then either be used immediately to produce power via a turbine and alternator, or else may be further superheated to a higher temperature

internal combustion engine

The internal combustion engine is anengine in which thecombustion of a fuel(normally afossil) occurs with an oxidizer (usually air) .the mixture of air and petrol vapor is compressed and ignited by an electric spark and the essential chemical reaction is the oxidation of hydrocarbon molecules .
It is essential that the combustion of the fuel in the cylinder of an internal combustion engine should proceed in a regular way .After the reaction is initiated by a spark ,a flame should spread rapidly and smoothly through the gas mixture and the expanding gas drives the piston down the cylinder.

. In an internal combustion engine (ICE) the expansion of the high-temperature and high-pressure gases produced by combustion apply directforce to some component of the engine. The force is applied typically to pistons, turbine
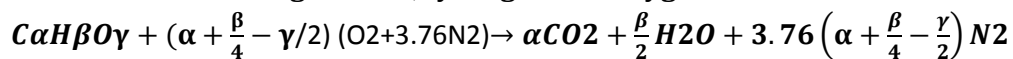
blades, ornozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy.

Stoichometry calculations

1.for hydrogen-air reaction

$$H2 + a(O2$$
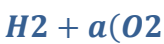
2.for a fuel containing carbon ,hydrogen and oxygen which is burned to completion:

$$C\alpha H\beta O\gamma + (\alpha + \frac{\beta}{4} - \gamma/2) \, (O2+3.76N2) \rightarrow \alpha CO2 + \frac{\beta}{2} H2O + 3.76 \left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right) N2$$

Where α, β, γ are the number of
carbon ,hydrogen and oxygen atoms in a molecule of fuel ,alternatively
α , β, γ *are the mole fractions of the carbon, hydrogen and oxygen from*

*the uitimate a*analysis of the fuel .the mole of stoichiometeric air per mole and fuel are :-

The stoichiometeric fuel/air ratio by weight is $Fs = \dfrac{mf}{mas} = \dfrac{Mf * nf}{Ma * nas} = \dfrac{Mf}{29\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right)*4.76}$

The percent excess air is the actual air used minus the stoichiometric air all divided by the stoichiometeric air times 100.

Percent theoretical air is the amount of air actually used divided
by the stoichiometeric air:-

Hence

For example 110 % theoretical air is alean   mixture with 10%excess air and 85%theoretical air is a rich mixture which is 15% deficient in air .

Some times equivalence ratio as the fuel/air mass (f) divided by the stoichiometeric fuel/air ratio (fs) used in stead of excess air to describe a combustible mixture the equivalence ratio

Excess air is directly related to equivalence ratio

Example 1
For a stoichiom*etric hydrogen air* reaction at 1 atm pressure find

a/the fuel

b/the mas

c/the part

Solution:-

Basis=1 Kgmole   H2

From an (H) balance 2=2b→ $b = 1$

From an (O) balance   2a=b→a=1/2

N2=

The mas

The partial pressure of water vapour in the products is obtained from the mole fraction.
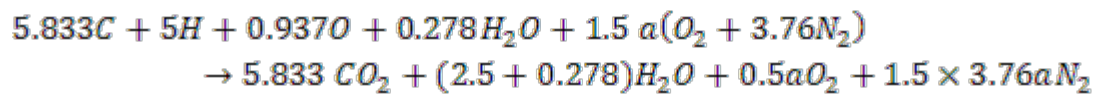
$$XH2O = \frac{1}{mol}$$

Example 2

Bituminous coal is burned to completion with 50% excess air. Find the fuel to air ratio (f) and the dry and wet analysis of the products .the as-received ultimate analysis of the coal is 70% with carbon,5% hydrogen 15 %O2, 5% moisture and 5 ash.

Basis for 100Kg of coal

species	M(kg)	M(kg/kgmole)	N(kmole)
C	70	12	5.833
H	5	1	5
O	15	16	0.937
H20	5	18	0.278

$5.833C$

$$5.833C + 5H + 0.937O + 0.278H_2O + 1.5\ a(O_2 + 3.76N_2)$$
$$\rightarrow 5.833\ CO_2 + (2.5 + 0.278)H_2O + 0.5aO_2 + 1.5 \times 3.76aN_2$$

Solvingforafromanoxygenatombalance

$$a = 5.833 + (5/4) - (0.937/2)$$

$$f = \frac{100}{(6.614) \times 1.5 \times (1 + 3.76) \times 29} = 0.073$$

species	N	Xi	Xidry
CO_2	5.833	0.1185	**0.1256**
H_2O	2.778	0.0564	
O_2	3.307	0.0672	**0.0712**
N_2	37.303	0.7579	**0.8032**

Combustion engineering

Home work:-Q1:- *stationary gas turbine engine operates at full   (3590 kw) at an equivalence ratio of 0.236 with an air flow of 15.9 kg/s .the equivalent composition of the fuel (natural gas)is C1.16 H4.32.determine the full mass flow rate and the operating air-fuel ratio for the engine.*

Q2:- *a natural gas fired industrial boiler operates with an oxygen concentration of 3 mole percent in the flue gases .determine the operating air-fuel ratio and the equivalenceretreat natural gas as methane.*

Q3:-$Naturalgas(97\%$ CH_4,$3\%N_2 byvolumeisburnedwith200\%excessairif85\%frommethanechange$ $toCO_2 and10\%toCOand\ 5\%notburned.determinedtheoperatingair$-$fuelratio.theequivalenceratioandthecompositionoffluegas.$

Chemical energy

Latent heat of vaporization

In many combustion process ,a liquid –vapor phase change is important .for example a liquid fuel droplet must first vaporize before it can burn. And if cooled sufficiently ,water vapor can condense from combustion products formally ,we define the latent heat of vaporization hfg as the heat required in a constant –pressure process to completely vaporize a unit mass of liquid at given temperature .

The latent heat of vaporization is also known as the enthalpy of vaporization.

Heat of reaction

To understand the heat of reaction, consider the reaction of a fuel and air mixture of mass m. for a constant –volume combustion with heat transfer Qv taken as negative if out of the system the first law gives.

m[(u2-u1)+(u2-u1)]=Qv

Where subscripts s and c refer to sensible and chemical energy

To is the reference temperatur

(Cr)r is the specific heat of the reactant mixture.

*If the heat transfer is just large enough to bring the products temperature back to the reactant temperature ,and if this temperature is taken as the reference temperature To for the sensible energy then (u2-u1)=0 by definition ,and Qv is the chemical energy released by the reaction. The quantity$[(1 + f)/](-Qv/m)$ is the lower heat value (LHV) of the fuel for constant –volume combustion .if the water in the products is condensed .the value of $[(1 + f)/](-Qv/m)$ becomes the higher heating value (HHV)of the fuel for constant volume combustion.

If the reaction takes place at constant pressure and the total heat transfer is Qp, then the energy equation becomes

If   T1=T2=To   ,then Qp is the chemical energy released for the constant pressure case ,if the moles of gaseous products Np are larger than moles of gaseous reactants Nr then some of the chemical energy is expended to push side the ambient pressure .thus ,for reactant and products which are ideal gases .

The heat of reaction may be calculated for reactions taking place at temperature other than To, and for cases where the initial and final temperature are not equal, by use of the heat of reactant data taken at To. Consider the reaction at constant pressure with reactant temperature T1 and product temperature T2 assume, for example T2>T1>To.To use the Qp(To) value ,imagine that first the reactants are cooled from T1 to To, then the reaction takes place at To, and finally the products are heated from To toT2 .

Where r referee to the reactants if to the products and hs is the sensible enthalpy.

Note that Qp(To)is negative for an exothermic reaction.

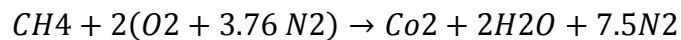***Example***

The higher heating value of gaseous methane and air at 25c is 55.5mj/kg. find the heat of reaction at constant pressure of a stoichiometric mixture of methane and air if the reactant and products are at 500k.

Solution

The reaction is

$$CH4 + 2(O2 + 3.76\ N2) \rightarrow Co2 + 2H2O + 7.5N2$$

Analysis of reactants and products using sensible enthalpies appendix yields

Reactants	Xi	His(Mj/kgmole)	MJ	Yi
CH4	0.095	3.2	16	0.055
O2	0.19	6.07	32	0.22
N2	0.715	5.91	28	0.725

Nr=1+2(4.76)=10.52Mr=ΣXiMi=27.6 kg/kgmole

Hsr=ΣXihsi=6.61 MJ/kgmolehsr=6.16/27.6=223 kj/kg

The fuel –to air mass ratio is f=0.055/(0.22+0.725)=0.05

Example:

In a flow calorimeter 24 mg/s of graphite particulate reacts completely with oxygen initially at 25 CO to form carbon dioxide at 1atm and 25C .the rate at heat absorbed by the calorimeter water is 787 W .find the heat of formation of CO2.

Solution:-

Since for carbon M=12 and since one mole of C yields one mole of CO2 is formed.

Nco2=(0.024 gc/s)*(1 gmole CO2/gmole C) =0.002 gmole CO2/s

12 gc/gmole C

The energy balance

(Nh)r =(Nh)p+q

And since the sensible energies are all zero at the reference temperature at 25C0and since the C and O2are in their standard states so that the heats of formation are zero.

0=(N Δh)co2+q

(Δh)co2 =-787 W/0.02 gmole/s=-39.35 MJ/Kgmole

Combustion engineering

Example

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Solution

The reaction is :- $CH4 + 2(O2 + 3.76\ N2) \rightarrow CO2 + 2H2O + 7.52N2$

Analysis of reactants and products using sensible enthalpies from appendix yield

Reactants	Xi	his(MJ/kgmole)	Mj	Yi(kg)
CH4	0.095	8.2	16	**0.055**
O2	0.19	6.09	32	**0.22**
N2	0.715	5.91	28	**0.725**

Nr=1+2(4.76)=10.52   Mr=ΣXiMI=27.6 kglkgmole

hsr=ΣXihsi= 6.16 MJ/kgmole   hsr=6.16/27.8 KJ/kg

the fuel to air mass ratio is f=0.055/(0.22+0.725)=0.0582

Products	Xi	His	Mj
CO2	0.095	8.31	44
H2O	0.19	6.92	18
N2	0.715	5.91	28

since the water vapour dose not Np=10.52 ,hsp=6.33 MJ/kgmole , Mp=27.6 kg/kgmole   ,hsp=229 KJ/kg condense ,the lower heating value is used

=-2747 KJ/kg fuel reactants

Qp=-2747+(229-223)=-2741 KJ/kg reactants

The negative sign indicates that the heat flow out of the system.

E<u>xample</u>

a. Determine the upper and lower heating values at 298 K of gaseous n-decane $C_{10}H_{22}$, per kmole of fuel and per kg of fuel. The molecules weight of n-decane is 142.284.

A. for 1 mole of $C_{10}H_{22}$ the combustion equation can be:-

$$C_{10}H_{22}\,(g) + 15.5\,(O_2 + 3.76\,N_2) \rightarrow 10CO_2 + 11H_2O(l \text{ or } g) + 15.5 \times 3.76 N_2$$

For either the upper or lower heating value

$$\Delta H_c = -\Delta H_R = H_{reac} - H_{prod}$$

Where the numerical value of Hprod depends on whether the H2O in the produced liquid (determining higher heating value) or gases (determining lower heating value). the sensible enthalpies for all species involved are zero since we desire ΔHc at the reference state(298k). furthermore, the enthalpies of formation the O2 and N2 are also zero at 298k .

$$H_{reac} = \sum_{reac} N_i h_i \quad and \quad H_{prod} = \sum_{prod} N_i h_i$$

$$\Delta H_{c\,H_2O(l)} = HHV = 1\,h_f - \left[10\,h_{f\,CO_2} + 11 h_{f\,H_2O(l)}\right]$$

Fromables $h_{f_{H_2O (g)}} = hf_g$ - $h_{f_{H_2O (l)}}$ =-241.847-44010=-285857kJ/kmole

$$\Delta H_{c\ H_2O(l)} = 1\left(-244.659\frac{kJ}{kmole}\right) - [10(-393{,}546\frac{kJ}{kmole} + 11(-285.857\frac{kJ}{kmole}$$
$$= 6830096$$

$$\Delta h_c{}^* = \frac{\Delta H_c}{N_{C10}} = \frac{6830096}{1\text{kmole}} = 6830096\frac{kJ}{\text{kmole}}$$

$$\Delta h_c = \frac{\Delta h_c{}^*}{MwC_{10}H_{22}} = \frac{6830096}{142284} = 48003$$

For the lower heating value we use $h_{f_{H_2O(g)}} =$ -241847kJ/kmole

In place $h_{f_{H_2O(l)}} = -285857\ kg/kmole$

$$\Delta h_c{}^* = 6345986\ \frac{kJ}{kmole}$$

$$\Delta h = 44601\ kJ/kg$$

Flames

Diffusion Flames

Diffusion flames take place when the sources of fuel and oxidizer are physically separate so that the energy release is limited primarily by the mixing process .There is no fundamental flame speed as in the case of premixed flames , and the flames are not one dimensional Chemical kinetics plays a secondary role in the behavior of diffusion flames .Diffusion flames occur with flowing gases ,with vaporization of liquid fuels ,and with devolatilization of solid fuels . A candle flame shown in figure 4 is an example of a diffusion flames .Wax is melted , flows up the wick and vaporized . Air flows upward due to natural convection .The reaction zone is between the air and the fuel zones Air diffuses inward and fuel diffuse outward .In hydrocarbon flames , soot particles are produced giving rise to luminosity.

Laminar premixed flames

A combustion reaction started at a local heat source in a quiescent fuel-air mixture at ambient conditions will propagate as a laminar flame .chemical reaction take place in a relatively thin zone ,and the flame moves at a fairly low velocity .For stoichiometric hydrocarbon mixtures in ambient air the flame is approximately 1mm thick and moves at about ($0.5 \ m/s$).The pressure drop through the flame is very small (1Pa),and the temperature in the reaction zone is high (2200-2600 k).
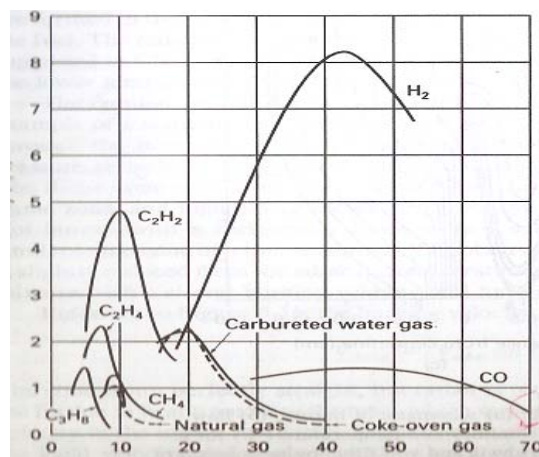
Effect of stoichiometry on laminar burning velocity .

The effect of fuel concentration on the laminar burning velocity is shown in figure 1 for various fuels .it can seen that the laminar burning velocity for a particular fuel can vary by a factor**3** depending on the fuel/air ratio. The rich and lean limits of flammability are also shown in this figure laminar flames will not occur above or below these limits .Hydrogen has the highest velocity and widest limits of flammability while methane has the lowest burning velocity and the narrowest

limits. The maximum burning velocities are found just to the rich side of stiochiometric .The fame temperature is highest near the stoichiometric and the lowest near the flammability limits figure 2.Higher laminar burning velocity is associated with a higher flame temperature

The effect of nonreactive additives such as nitrogen or argon is to reduce the flame temperature and the laminar burning velocity .The most common diluents addition is product of combustion for example in power plants a fraction of the combustion products are sometimes recirculated with the inlet air to reduce the amount of No produced by decreasing

 Fig(1)The effect of fuel concentration on the laminar burning velocity

the flame temperature. similarly in internal combustion engines a fraction of the residual products from the previous cycle mix with the new charge Other additives may react directly for example is the addition of small amounts of water(0.23%)to a CO-O2 mixture which increases the burning velocity by a factor of 8 .this is due to the formation of OH radical.
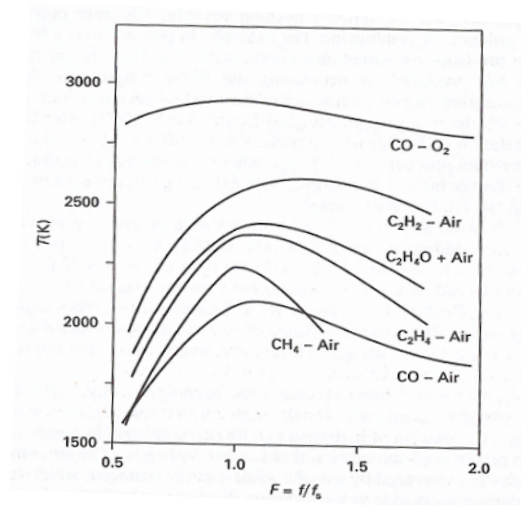
fig(2)Flame temp as a function of equivalence

Effect of reactant pressure and temperature on laminar burning velocity

For each premixed fuel-air mixture there is a characteristic laminar burning velocity .The burning velocity is defined as the flame relative to the unburned reactants The laminar burning velocity depends on fuel type fuel-air mixture ratio and initial temperature and pressure of the reactants . For slow burning mixtures (VL<0.6 m/s)the burning velocity decreases with increasing pressure . the observed pressure dependence can be expressed as a power law ,$(VL=ap^{ß})$, where **p** is the pressure in atmospheres and ß varies from(0 to – 0.5) for example , the burning velocities for propane – air mixtures at various pressures are shown in figure 3 for fast –burning mixtures (VL>0.6 m/s), the value of ß either zero or slightly positive . increased pressure increases the flame temperature because there is less dissociation , and hence the burning velocity however , less dissociation means less active radicals are available to diffuse upstream to enhance flame propagation . both effects are important .

The burning velocity increases with the temperature of the reactants , provided the reactants do not partially react prior to the flame passage . The observed temperature dependence can also be expressed as a power law . and the burning velocity increases as the second or third power of the absolute temperature. for example , the maximum burning velocity for propane-air goes from **40cm/s** to **140 cm/s** as the reactant temperature is increases from 300K to 617 K .

Ln[p(Kpa)]
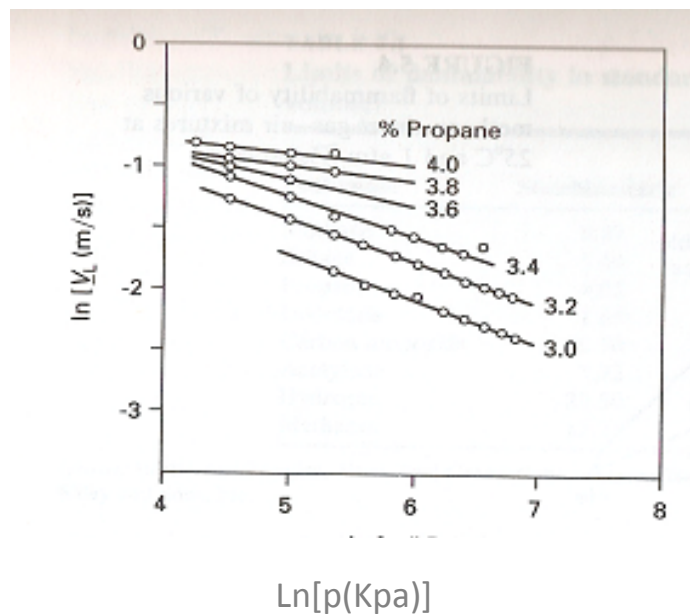
Fig(3) Influence of pressure on laminar burning velocity

Structure of CH4-Air flame

The structure of a premixed flame in fig (5)shows the temperature distribution and selected species mole fraction profiles (the principal C-containing CH4,CO,and CO2) through a1-atm ,stoichiometric , CH4-Air flame .Here we see the disappearance of the fuel, the appearance of the intermediate species CO and burnout of the CO to form CO2 .the CO concentration has its peak value at approximately the same

location where the CH4 concentration goes to zero , whereas the CO2 concentration at first lags the CO concentration but the continues to rise as the CO is oxidized .Figure (6) shows that C- intermediate species CH3,CH2O AND HCO,are produced and destroyed in a narrow interval (0.4-1.1mm)
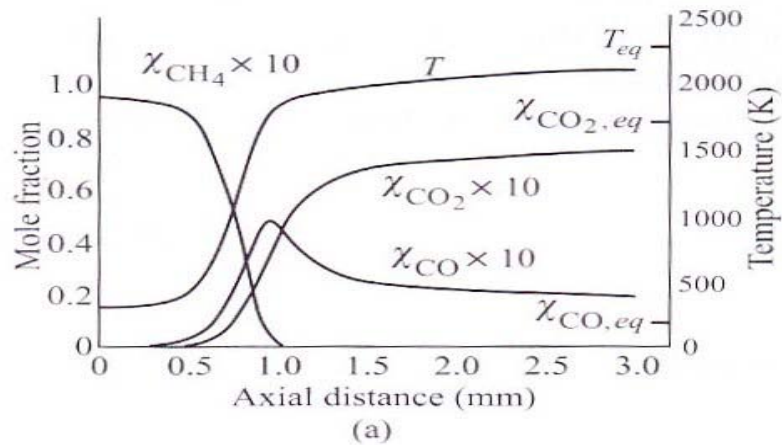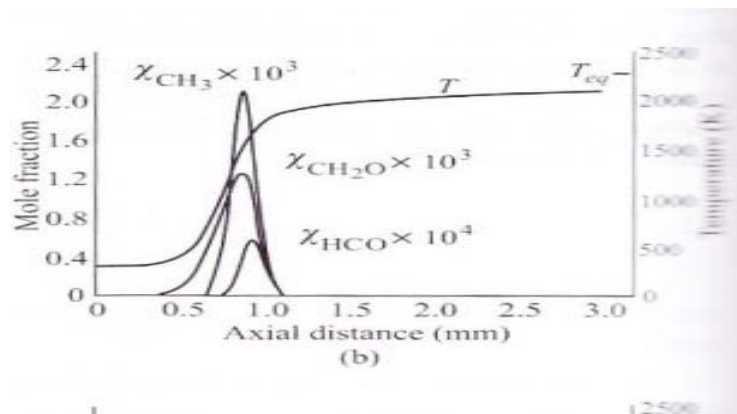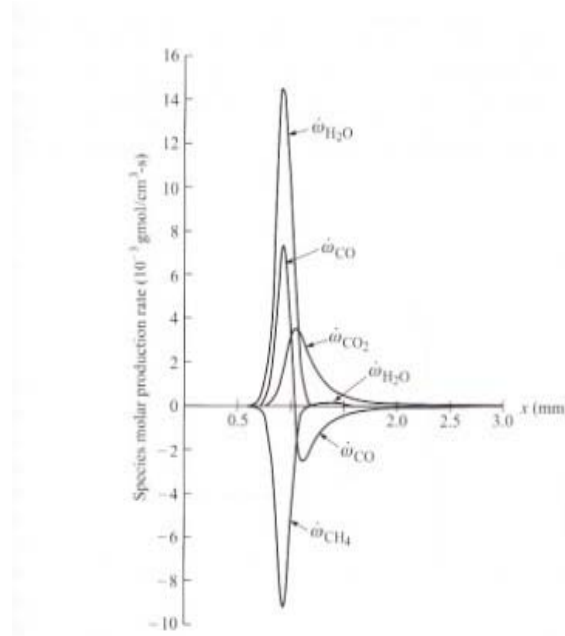

fig (5)

Fig(6)

Figure (7) provides additional insight into the CH4---CO---CO2 sequence by showing the local molar production (destruction) rates for these species. We see that the peak fuel destruction rate nominally corresponds with the peak CO production rate and the CO2 production rate initially lags that of CO .Even before the location where is no longer any CH4 to produce additional CO , the net CO production rate becomes negative ,I,e., CO is destroyed .The maximum rate of CO destruction occurs just

downstream of the peak CO2 production rate .The bulk of the chemical activity is contained in an interval extending from about 0.5 mm to 1.5 mm .

Fig(7)

FLAME SPEED CORRELATIONS FOR SELECTED FUELS

Metghalchi and Keek experimentally determined laminar flame for various fuel-air mixtures over a range of temperatures and pressures typical of conditions associated with reciprocating internal combustion engines and gas-turbine combustors.

$$S_L = S_{L,\text{ref}} \left(\frac{T_u}{T_{u,\text{ref}}} \right)^{\gamma} \left(\frac{P}{P_{\text{ref}}} \right)^{\beta} (1 - 2.1 Y_{\text{dil}}),$$

(1)

For $T_u >$ 350 K . The subscript ref refers to reference conditions defined by $T_{u.ref} = 289K$ and P =1 atm .

$$S_{L,\text{ref}} = B_M + B_2 (\Phi - \Phi_M)^2 \qquad (2)$$

Where the constants B_M, B_2, and Φ_M depend on fuel type and are given in table 1 The temperature and pressure exponents, γ and β, are functions of the equivalence ratio, expressed as

$$\gamma = 2.18 - 0.8(\Phi - 1)$$

$$\beta = -0.16 + 0.22(\Phi - 1).$$

The term Y_{dil} is the mass fraction of diluents present in the air-fuel mixture. Recirculation of exhaust or flue gases is a common technique used to control oxides of nitrogen in many combustion systems and in internal combustion engines, residual combustion products mix with the incoming charge under most operating conditions.

Table 1 values for B_M, B_2, and Φ_M

Fuel	Φ_M	B_M cm/s	B_2 cm/s
Methanol	1.11	36.92	-140.51
Propane	1.08	34.22	-138.65
Isooctane	1.13	26.32	-84.72
RMFD-303	1.13	27.58	-78.34

Example (1)

Compare the flame speed of gasoline-air mixture with Φ = 0.8 for the following three cases:

1. At reference conditions of T = 298 K and P = 1 atom.
2. At conditions typical of a spark-ignition engine operating at wide-open throttle: T = 685 K and P = 13.38 atom.
3. Same as condition 2 above, but with 15 percent (by mass) exhaust-gas recirculation .

Solution

We will employ the correlation of Metghalchi and Keck, equation (1),. The flame speed at 298 K and 1 atom is given by:

$$S_{L,\text{ref}} = B_M + B_2(\Phi - \Phi_M)^2$$

where, from Table 8.3,

$$B_M = 27.58 \text{ cm/s,}$$
$$B_2 = -78.38 \text{ cm/s,}$$
$$\phi_M = 1.13.$$

Thus,

$$S_{L,\text{ref}} = 27.58 - 78.34(0.8 - 1.13)^2,$$

$$\boxed{S_{L,\text{ref}} = 19.05 \text{ cm/s}}$$

To find the flame speed at temperatures and pressures other than the reference state, we employ equation below

$$S_L(T_u, P) = S_{L,\text{ref}} \left(\frac{T_u}{T_{u,\text{ref}}}\right)^\gamma \left(\frac{P}{P_{\text{ref}}}\right)^\beta$$

where

$$\gamma = 2.18 - 0.8(\Phi - 1)$$
$$= 2.34$$
$$\beta = -0.16 + 0.22(\Phi - 1)$$
$$= -0.204.$$

Thus,

$$S_L(685 \text{ K}, 18.38 \text{ atm}) = 19.05 \left(\frac{685}{298}\right)^{2.34} \left(\frac{18.38}{1}\right)^{-0.204}$$

$$= 19.05(7.012)(0.552)$$

S_L = 73.8 cm/s

      With dilution by exhaust gas recirculation the flame speed above is reduced by the factor $(1\text{-}2.1Y_{dil})$

S_L(685K,18.38atm) =73.8(1-2.1(0.15))

S_L=50.6 cm/s

AdiabaticFlameTemperature

    A. Сonstant pressure combustion

   *B. Constant volumecombustion*

Combustion engineering

We define two adiabatic flame temperature: one for constant–pressure combustion and one for constant volume. If a fuel–air mixture burn adiabatically at constant pressure. the absolute enthalpy of the reactants at the initial state T=298K, P=1atm equal the absolute enthalpy of the final state T=T_{ad}, P=1 atm

$$H_{reac(T,P)} = H_{prod(Tad,P)}$$

Or, equivalently on a per mass of mixtures basis

$$H_{react(Ti,P)} = h_{prod(Tad,P)}$$

The equation above defines what is called the constant pressure adiabatic flame temperature. The definition is illustrated graphically in fig. Conceptually, the adiabatic flame temperature is simple; however, evaluating this quantity required knowledge of the composition of the combustion products .at typical flame temperatures ,the products dissociate and the mixture comprises many species.
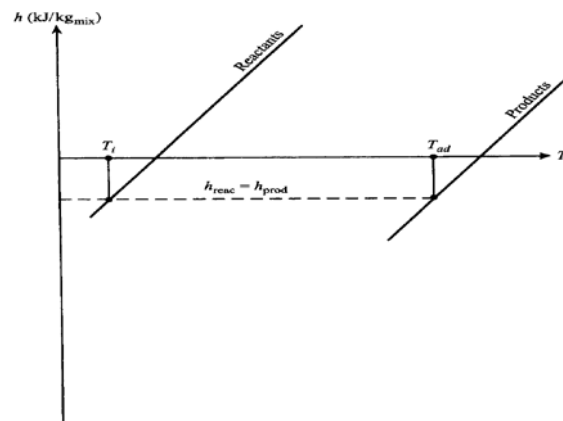
D   Illustration of constant-pressure adiabatic flame temperature on h–T

Estimate the constant pressure adiabatic flame temperature for the combustion of stoichiometeric CH_4-air mixture. the pressure is 1 atm and the initial reactant temperature   is

298k.

1. complete combustion theproduct mixture consists onlyof CO_2, H_2O and N_2

2. Theproduct mixtureenthalpyestimatedusingspecificheatsevaluatedat 1200 =0.5(T1+Tad)where Tad isguessed to beabout 2100k.

Solution

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$
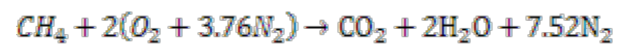
$$NCO_2 = 1 \quad , NH_2O = 2 \quad , NN_2 = 7.52$$

Specificheat 1200k	Enthalpyformation(298k)	Species
	hf_i(ki/kmole)	(kj/kmole.k)
CH_4		
CO_2	-	
H_2		
N_2		
O_2		

$$H_{react} = \sum_{reac} N_i h_i = H_{prod} = \sum_{prod} N_i h_i$$

$$H_{react} = 1(-74831) + 2(0) + 7.52(0) = -74831 \; kJ$$

$$H_{prod} = \sum Ni[hf_i + cp_i(T_{ad} - 298)]$$

$$= 1[-393546 + 56.21(T_{ad} - 298)] + 2[-241.845 + 4387(T_{ad} - 298) + 7.52[0 + 33.71(T_{ad} - 298)]$$

Equating H_{react} to H_{prod} and solving to T_{ad} yields

$$T_{ad} = 2318 \; k$$

For constant –volumeadiabatic flametemperature

$$U_{react}(T_{init}, P_{init}) = U_{prod}(T_{ad}, P_f)$$

WhereUis the absoluteorstandardized internalenergyofthemixture.

SincemostcompilationsorcalculationsofthermodynamicspropertiesprovidevaluesforH(orh)ratherthan u wecan rearrangeequabove

$$H_{react} - H_{prod} - V(P_{init} - P_f) = 0$$

We can apply the ideal-gas law to eliminate the PV term is

$$P_{init} V = \sum_{reac} N_i R_u T_{ad} = N_{reac} R_u T_{init}$$

$$P,V = \sum_{Prod} N_i R_u T_{ad} = N_{prod} R_u T_{init}$$

Thus $H_{react} - H_{prod} - R_u (N_{react} T_{init} - N_{prod} T_{ad}) = 0$

$$M_{mix}/N_{reac} = Mw_{reac}$$

$$M_{mix}/N_{prod} = Mw_{prod}$$

$$H_{react} - h_{prod} - R_u(\frac{T_{init}}{Mw_{react}} - \frac{T_{ad}}{Mw_{prod}}) = 0$$

Example:-

Estimatetheconstantvolumeadiabaticflametemperatureforastoichiometeric CH_4-air mixture.using thesameassumption as in previous exampleinitial conditions areP= 1atm and theinitial reactant temperatureis 298k. solution:-

wenote,howeverthattheCP,valuesshouldbeevaluatedatatemperaturesomewhat greaterthan1200ksincetheconstantvolumeTadwillbehigherthanthe constant pressure

$T_{ad}H_{react} - H_{prod} - R_u(N_{react} T_{init} - N_{prod} T_{ad}) = 0$

Or

$$\Sigma_{reac} N_i h_i = \Sigma_{prod} N_i h_i - R_u(N_{react} T_{init} - N_{prod} T_{ad}) = 0$$

$H_{react} = 1 \times -74831 + 2(0) + 7.52(0) = -74831 \, kj$

$$H_{Prod} = 1[(-393546) + 56.21(Tad - 298)] + 2[-241845 + 4387(Tad - 298)]$$
$$+ 7.52\{0 + 33.71(Tad - 298)]$$

$$= -877236 + 397.5(T_{ad} - 298)$$

$N_{prod} \ T_{ad}) - 8.315(10.52)(298 - Tad)$ *And* $Ru(N_{react} \ T_{init}$

Where $N_{react} = N_{prod} = 10.52 \, kmole$

$$Reassembling\ by\ H_{react} - H_{prod} - Ru(N_{react}\ T_{init} - N_{prod}\ T_{ad}) = 0$$

FLAME SPEED CORRELATIONS FOR SELECTED FUELS

Metghalchi and Keek experimentally determined laminar flame for various fuel-air mixtures over a range of temperatures and pressures typical of conditions associated with reciprocating internal combustion engines and gas-turbine combustors.

$$S_L = S_{L,ref}\left(\frac{T_u}{T_{u,ref}}\right)^{\gamma}\left(\frac{P}{P_{ref}}\right)^{\beta}(1-2.1Y_{dil}),$$

(1)

For T_u > 350 K . The subscript ref refers to reference conditions defined by $T_{u.ref} = 289K$ and P =1 atm .

$$S_{L,ref} = B_M + B_2(\Phi - \Phi_M)^2 \qquad (2)$$

Where the constants B_M, B_2, and Φ_M depend on fuel type and are given in table 1 The temperature and pressure exponents, γ and β, are functions of the equivalence ratio, expressed as

$$\gamma = 2.18 - 0.8(\Phi - 1)$$

$$\beta = -0.16 + 0.22(\Phi - 1).$$

The term Y_{dil} is the mass fraction of diluents present in the air-fuel mixture. Recirculation of exhaust or flue gases is a common technique used to control oxides of nitrogen in many combustion systems and in internal combustion engines, residual combustion products mix with the incoming charge under most operating conditions.

Table 1 values for B_M, B_2, and Φ_M

Fuel	Φ_M	B_M cm/s	B_2 cm/s
Methanol	1.11	36.92	-140.51
Propane	1.08	34.22	-138.65
Isooctane	1.13	26.32	-84.72
RMFD-303	1.13	27.58	-78.34

Example (1)

Compare the flame speed of gasoline-air mixture with Φ = 0.8 for the following three cases:

1. At reference conditions of T = 298 K and P = 1 atom.
2. At conditions typical of a spark-ignition engine operating at wide-open throttle: T = 685 K and P= 13.38 atom.
3. Same as condition 2 above, but with 15 percent (by mass) exhaust-gas recirculation .

Solution

We will employ the correlation of Metghalchi and Keck, equation (1),. The flame speed at 298 K and 1 atom is given by:

$$S_{L,\text{ref}} = B_M + B_2(\Phi - \Phi_M)^2$$

where, from Table 8.3,

$$B_M = 27.58 \text{ cm/s},$$
$$B_2 = -78.38 \text{ cm/s},$$
$$\phi_M = 1.13.$$

Thus,

$$S_{L,\text{ref}} = 27.58 - 78.34(0.8 - 1.13)^2,$$

$$\boxed{S_{L,\text{ref}} = 19.05 \text{ cm/s}}$$

To find the flame speed at temperatures and pressures other than the reference state, we employ equation below

$$S_L(T_u, P) = S_{L,\text{ref}} \left(\frac{T_u}{T_{u,\text{ref}}} \right)^{\gamma} \left(\frac{P}{P_{\text{ref}}} \right)^{\beta}$$

where

$$\gamma = 2.18 - 0.8(\Phi - 1)$$
$$= 2.34$$
$$\beta = -0.16 + 0.22(\Phi - 1)$$
$$= -0.204.$$

Thus,

$$S_L(685\ \text{K}, 18.38\ \text{atm}) = 19.05 \left(\frac{685}{298} \right)^{2.34} \left(\frac{18.38}{1} \right)^{-0.204}$$

$$= 19.05(7.012)(0.552)$$

S_L = 73.8 cm/s

With dilution by exhaust gas recirculation the flame speed above is reduced by the factor $(1\text{-}2.1Y_{dil})$

$S_L(685\text{K}, 18.38\text{atm}) = 73.8(1\text{-}2.1(0.15))$

S_L = 50.6 cm/s

$Tad = 2889k$

Homework

1. *Determine the enthalpy of formation in Kj/kmole for methane given the lower heating value of 50016 kj/kg at 298k.*

2. *determine the absolute enthalpy of the mixture for a temperature of 1000k .express your result in kj/kmole of mixture. (CO=0.095 , CO_2=6 , H_2O=7 , N_2=34, NO=0.005) BY mole*

3. *the higher heating value for liquid octane (C_8H_{18}) at 298k is 47893 kj/kg and heat of vaporization is 363 kj/kg. determine the enthalpy of formation at 298k for octane vapour.*

4. *Determine the adiabatic flame temperature for constant pressure combustion of a stoichiometeric propane–air mixture assuming reactants at 298k.*

Gas- Fired Furnace combustion

Energy Balance and Furnace Efficiency

The fuel and air flow rates required foe a given heat output are collected from an energy and mass balance for a control volume placed around the combustion chamber heat exchanger- mixer

$$N_a h_a + N_f h_f = q + q_L + \sum_{J=1}^{J} N_j h_j$$

Where p stands for product in term of the sensible enthalpy fuel heating value and enthalpy of vaporization of water . The energy balance

For complete combustion 100% combustion efficiency

q = useful heat output

Example

Propane is burned to completion in a furnace with 5% excess air the fuel and air are at 77^0F. If 5% of the heat is lost through the walls of the furnace and the combustion product exit the furnace to the stack at 340^0F . What is the useful heat output of the furnace per pound of propane.

Solution

$C_3H_8 + 1.05*5(O_2 + 376N_2) \rightarrow 3CO_2 + 4H_2O + 1.05*3.76N_2 + 0.05*5O_2$
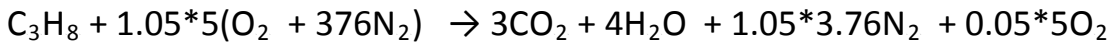
From table HHV 21670 Btu/lb or 953480 Btu/lbmole

products	N_J / N_f	K Btu/lbmole	K Btu/lbmole fuel
CO_2	3	2.528	7.584
H_2O	4	2.142	8.568
O_2	0.25	1.882	0.47
N_2	19.74	1.83	36.282

From equation of energy balance over furnace

The useful heat output is 82.4% of the higher heating value and 89.5% of the lower heating value.

Furnace Efficiency

The efficiency of the furnace is defined as the ration of the useful heat output to the energy input. In general for any type of fuel.

The furnace efficiency can be increased by the following measures

1- Decrease the temperature of the exhaust products
2- Reduce the excess air which will reduce the moles of products per mole of fuel and also reduces the blower power.
3- Reduce the extraneous heat loss
4- Reduce the blower power requirements

Where $\dfrac{N_P}{N_f} = \dfrac{N_P}{N_c} * \dfrac{N_c}{N_f} = \dfrac{N_c/N_f}{x_{CO_2}+x_{cc}}$

Example

Stack gas analysis of a natural gas- fired furnace gave the following volumetric analysis 4% O_2 , 10% CO_2 , 17 H_2O, 86% N_2 all on a dry basis the fuel was 84% CH_4 and 16%C_2H_6 by volume and the higher heating value was 23.3 Btu/Ibm. The fuel and air entered the furnace at 77^0F and the stack gas temperature was 340^0F. No blower was used and heat losses were neglected. What is the operating efficiency of this furnace and what is the excess air.

Solution

The wet product analysis by volume is

4/1.17 = 3.42%O_2 ,   8.55% CO_2 ,   14.53% H_2O , 73.05% N_2

The moles for carbon in the fuel per mole of fuel N_c/N_2 = 0.84 + 0.16*2 = 1.16

H_{sp} = 0.0342 * 1.882 + 0.0855*2.525 + 0.1453 *2.142 +0.735 *1.838 =1.94 kBtu/Ibmole

The molecular weight of fuel is

M_f = 0.84 *16 +0.16*30 = 18.24 Ibmole/Ibmole

The molar higher and lower heating values are

HVV = 233* 18.24 = 425

LHV = 425 − 0.1453 * 1.03*13.6*18 = 388.4

Homework

Calculate the flame temperature producted from burnt methane with air at 600^0C

Example

A laminar flame propagates through a propane-air mixture with an equivalence ratio of 0.9 pressure of 5atm and temperature of 300K. The flame velocity is 22 cm/s .Find a)the gas temperature b) the velocity and c)the pressure behind the flame.

Take: $h_p = h_r = -0.1267*10^6$ kJ/kg , $\rho_r = 5.97$ kg/cm^3 , $M_r = 28.318$kg/Kmole

$\qquad$ a) $T_p = 2200K$ $\rho_p = 0.784$ $\qquad$, $M_p = 28.23$kg/kmol

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ b) $\rho_r v_r = \rho_p v_p$

$C_3H_8 + (5/0.9)(O_2 + 3.76)N_2$ or 1mole at C_3H_8 , 5.56mole of O_2 and 20.89 mole of N_2

$$v_p^- = \frac{v_r^- \rho_r}{P_p} = 0.22 * \frac{5.97}{0.784} = 1.67 \ m/s$$ this the velocity relative to the flame front

$\qquad$ c) $P_p - P_r = \rho_r(v)^2 - (\rho_p v_p)^2 = 5.97(0.22)^2 - 0.784(1.67)^2$ = -1.9 Pa = -0.0000187 atm $P_p = 4.99981$atm

efer to the mixture of reactants and subscript refer to the mixture of products. Conservation of mass, momentum and energy across the flame front are given by

Combustion of liquid fuels

Spray formation and droplet behavior

Oil fired furnaces and boiler, diesel engines, and gas turbines utilize liquid fuel sprays in order to increase the fuel surface area and thus increase the vaporization and combustion rate. For example breaking up a 3 mm sphere of liquid into 30μm drops results in 1 million drops . The droplet mass burning rate is approximately proportional to diameter squared, and the increase in burning rate is 10000 times if we assume that the large single droplet and 1 million small droplets burn under the same ambient conditions.

In spray combustion the liquid fuel injection into a combustion chamber, the liquid undergoes atomization which cause the liquid to breakup into a large number of droplet of various sizes and velocities . Depending on the density and the ambient conditions, some of the droplets may continue to shatter and some may be recombine in droplet collisions. During this time vaporization take place. Fuel vapor produced by vaporization mixes with the surrounding gas ,combustion of the vapor- air mixture occurs. The hot products of combustion mix with the vapor and droplets.

If enough time or combustor length is enough ,the entire amount of fuel will be converted to combustion products. Carbon produced in the combustion process may either continue to oxides to produce final gaseous or may agglomerate to form exhaust particulates.

Spray region divided into

1-The spray formation region .

2-The vaporization region .

3-The combustion region .

In some sprays the breakup region will overlap the vaporazition

Types of spray

1- simple pressure nozzles

simple pressure nozzles either with 4-10 small holes or a pintle are used in predominantly in diesels.

2-Air or steam atomization

Air or steam atomization nozzles are used in burners and furnaces. The burner lance consists of two concentric tubes, a one-piece nozzle and a sealing nut. The media supplies are arranged so that the steam is supplied down the centre tube and the fuel oil through the outer tube. Consequently, the steam space is completely isolated from the oil space.The steam atomizer consists of an atomizer body that has a number of discharge nozzles arranged on a pitch circle in such a way that each oil bore meets a corresponding steam bore in a point of intersection. Oil and steam mix internally forming an emulsion of oil and steam at high pressure. Oil burners with internal mix steam atomizing are tolerant to viscosity changes, do not require high fuel oil pump pressures, and are frugal in the use of steam .
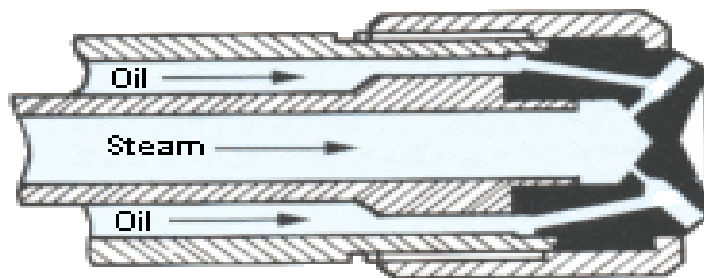
Fig(1) steam atomization

3-Swirl types nozzles

A-Tangential

Liquid enters under pressure and is forced through an offset orifice and into a swirl chamber. As the liquid leaves the orifice the droplets follow a trajectory influenced by the orifice shape and the swirl chamber design. The result is a consistent spray angle and uniform droplet distribution.   Droplet size and spray distribution are very predictable and not dependent upon a laminar flow. The "free passage" of vaneless full cones are determined by the largest particle size that can pass through the

incoming orifice. Vaneless full cones provide the largest free passage that the capacity allows.

Fig(2) **Tangential nozzle**

B-Axial

Liquid enters under pressure and is forced through a stationary turbine vane located inside the nozzle. As the liquid leaves the orifice the droplets follow a trajectory influenced by the orifice shape and vane design .The result is a consistent spray angle and uniform droplet distribution.
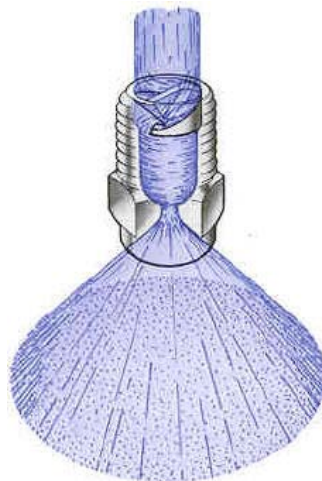

 Fig(3)

BREAKUP REGIMES

Diesel engine sprays are usually of the full cone type .The disintegration of liquid jets is described by two main mechanisms. The first mechanism is the breakup of the intact liquid core into droplets and is called primary breakup length, which is defined as the length of the intact liquid core. The second mechanism is the breakup of droplets into smaller ones, which is called secondary breakup. Here the size of the droplets is a characteristic parameter. Both breakup length and droplet size are dependent on the properties of the liquid and the surrounding gas. At least as important is the relative velocity between the liquid and the surrounding gas.

The primary breakup is the most important mechanism in fuel injection system, because it determines the size of the droplets that separate from the liquid core, hence therefore also determines evaporation behavior and it marks the starting point for further breakup into smaller droplets (secondary breakup). It is also far more difficult to analyze primary breakup both experimentally and numerically. In the following the breakup regimes are treated in more detail, but just for clearness the scheme in Fig. can be kept in mind to have the big picture right.

figure ( ) full cone spray
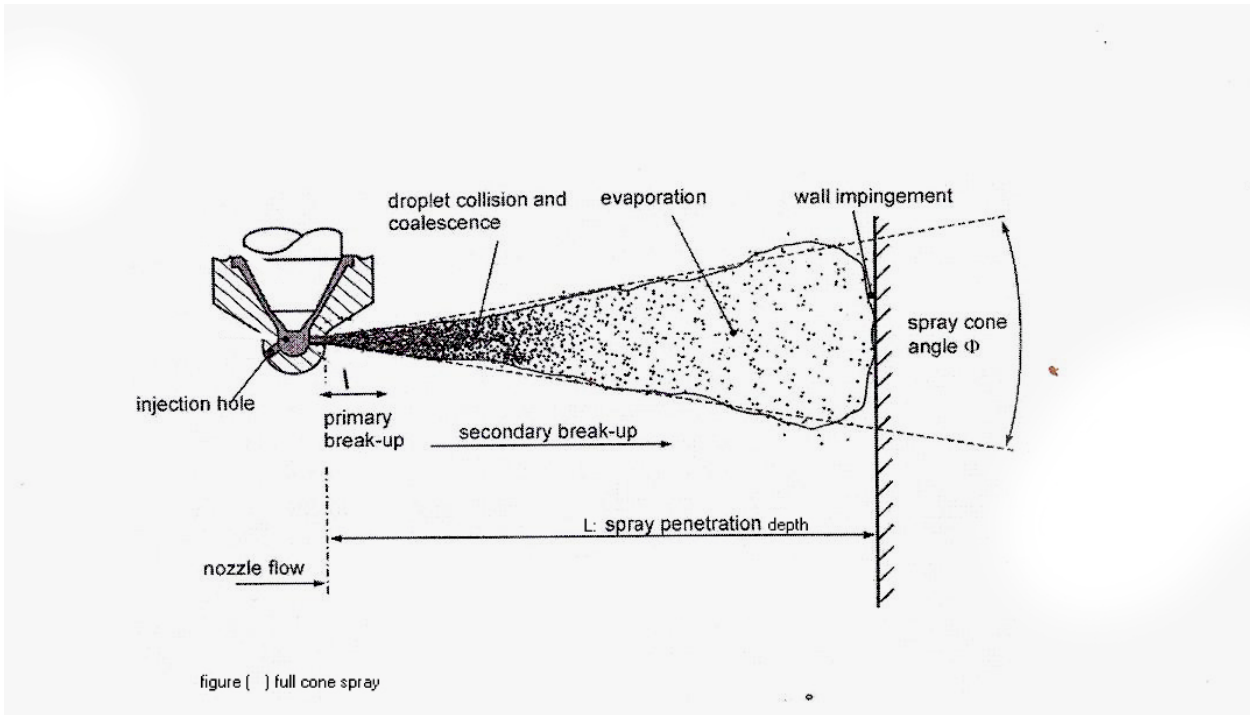
Primary Breakup

The primary breakup mechanism concerns the breakup of the intact liquid core and can be divided into four regimes. NamelyRayleigh regime, the first and second wind-induced regimes and last the atomization regime. In order to make a quantitative classification of the regimes the Ohnesorge number **Oh** is introduced:

$$Oh = \frac{\sqrt{We_l}}{Re_l}$$...

Herein the number We_l and the Reynolds number Re_l are defined as:

$$We_l = \frac{u^2 \, D \, \rho_l}{\sigma}$$

$$Re_l = \frac{u \, D \, \rho_l}{\mu_l}$$

ρ is the density, σ is surface tension, μ is the dynamic viscosity, u is the jet velocity and **D** is the diameter of the nozzle. The subscript l denotes the properties of the liquid. The

Weber number is the ratio between inertial or aerodynamic and surface tension forces. The Reynolds number is the ratio between inertial and viscous forces. Substitution of

and   into   gives:

$$Oh = \frac{\mu_l}{\sqrt{\sigma \, \rho_l \, D}}$$

Thus, the Obnesorge number is ratio between viscous forces and surface tension forces. Now all relevant liquid properties are incorporated, so the various regimes can be classified in the space $\boldsymbol{Oh}$ as function of the jet velocity, or alternatively $\mathbf{Re}_l$. In this figure the four regimes and the relevant zone for diesel injection applications are indicated.

Now the four regimes are described in more detail by increasing jet velocity. Rayleigh regimeBreakup at low jet velocity due to axisymmetric oscillations initiated by liquid inertia and surface tension forces. $D_{droplet} > D_{nozzle}$,the breakup length L_{jet} is long and by increasing jet velocity u also L_{jet} increases.

First wind-induced rigime Liquid inertia and surface tension forces are amplified by aerodynamic forces. The relevant Weber number for this regime is:

$$We_g = \frac{u^2 \, ref \, D \, \rho_g}{\sigma}$$

Here u_{ref} is the relative velocity between liquid and surrounding gas and the subscript g denotes the gas properties. $D_{droplet} \approx D_{nozzle}$, $L_{jet} > D_{nozzle}$ and by increasing jet velocity u the breakup length $\boldsymbol{L_{jet}}$ decreases.

Second wind-induced regime The flow in the nozzle is turbulent. Instable growth of short wavelength surface waves initiated by the turbulence and amplified by aerodynamic forces. $D_{droplet} < D_{nozzle}$ and increasing jet velocity $\boldsymbol{u}$ the breakup length $\boldsymbol{L_{jet}}$ decreases.
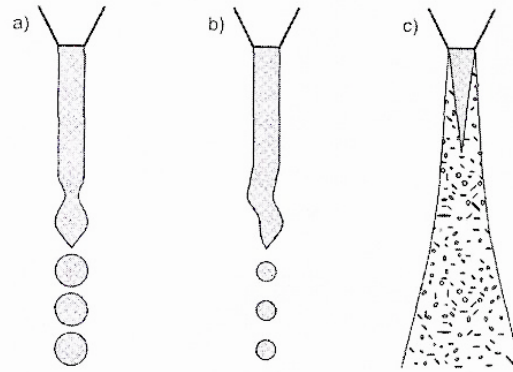
Figure   *Schematic representations of the primary breakup regimes: (a) Rayleigh regime, (b) wind-induced regime, (c) atomization regime [Sti03]*

Atomization regime   Breakup surface directly at the nozzle hole, so the intact core length L_{jet} goes to zero . Conical spray develops immediately after leaving the nozzle. $D_{droplet}$ <<D_{nozzle} .
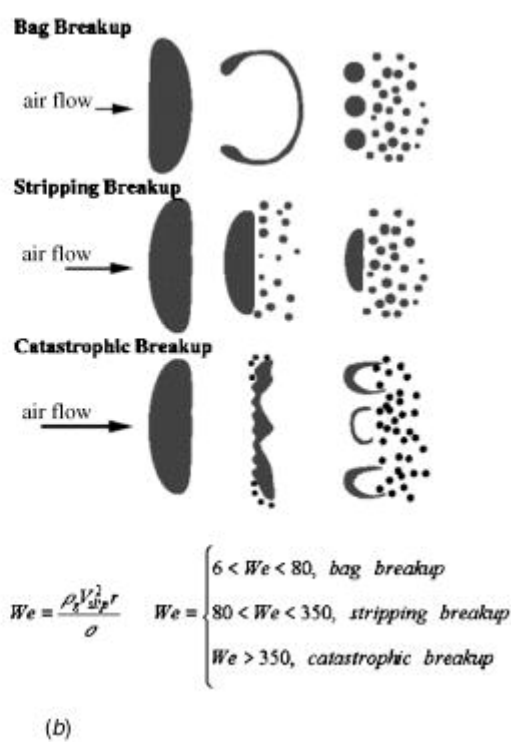
Secondary Breakup

The secondary breakup mechanism concerns the breakuo due to aerodynamic forces that are induced by the relative velocity between the droplets and the surrounding gas .on the gas-liquid interface growth of waves occur ,while in the same time surface tension counteracts the disintegration process .Similar to the first wind induced regime for the liquid core the gas Weber number is the relevant dimensionless quantity to identify the process.

$$We_l = \frac{u^2 \, D \, \rho_l}{\sigma}$$

Decreasing the droplet diameter **D** raises the surface tension force σ this the critical relative takes place.

P_back: back pressure (low)

d: nozzle diameter

U_{inj} $\dot{m}$ θ: spray angle

P_{nozzle}: nozzle opening pressure (high)

U_{inj}: nozzle injection velocity

$\dot{m}$: spray mass flow rate

L: spray penetration depth (function of time)

secondary breakup

primary breakup

(a)

Bag Breakup

air flow

Stripping Breakup

air flow

Catastrophic Breakup

air flow

$$We = \frac{\rho_g V_{slip}^2 r}{\sigma} \qquad We = \begin{cases} 6 < We < 80, & bag\ breakup \\ 80 < We < 350, & stripping\ breakup \\ We > 350, & catastrophic\ breakup \end{cases}$$

(b)

Solid Fuels

Solid fuel refers to various types of solid material that are used as fuel to produce energy and provide heating usually released through combustion . Solid fuels include wood , charcoal, peat, coal and pellets made from wood and other grains. Solid fuels

have been used by humanity for many years to create fire. Coal was the fuel source which enabled the industrial revolution, from firing furnaces, to running steam engines. Wood was also extensively used to run steam locomotives. Both peat and coal are still used in electricity generation today.

The use of some solid fuels (e.g. coal) is restricted or prohibited in some urban areas, due to unsafe levels of toxic emissions. The use of other solid fuels such as wood is increasing as heating technology and the availability of good quality fuel improves. In some areas, smokeless coal is often the only solid fuel used. In Ireland, peat briquettes are used as smokeless fuel. They are also used to start a coal fire.

wood

wood may be burned directly as a fuel or it may be converted into charcoal or producer gas .the principal chemical component of wood are cellulose and lingo cellulose .The major non inflammable component is water which contains 25%-50% .Ash is very small usually less than 0.6% the calorific value of pure of pure cellulose is 16 MJ/Kg .the formation of wood in nature is an endothermic process absorbing approximately 21MJ/Kg this is liberated during combustion

combustion characteristics of wood

1-Easily ignited and burnt below 50% moisture.

2-Does not burn readily in large pieces of layers of semi fused ash forming on the surface

3-produces a long non smoky flame when burned in excess air

peat

Peat is a brown fibrous mass of partially decayed plant material that has accumulated in situ under waterlogged conditions .World resources of peat are estimated at $1200*10^8$ tons .Moisture contains 25%water for cut peat and average values dry basis 16-20 MJ/Kg .

combustion characteristics of peat

1-Low C,V. and high proportion of moisture reduces furnace temperature and efficiency .

2-Low bulk density 350 Kg/m3 reduces capacity of furnace and increases storage and transport capacity.

3-friable nature causes appreciable losses on handling.

Drying of solid fuels

The drying and sorting apparatus for preparation of solid fuel and other solid materials having substantial surface moisture. Ambient air is preheated by indirect heat exchange or other unfired means sufficiently to provide heat needed by the downstream process. The air is then passed up vertically through a bed containing the solid materials, heating and fluidizing them along with the surface moisture. When in a fluidized state, the smaller/lower density particles rise to the top of the bed. At least a portion of the surface moisture on the particles is evaporated. The quantity and temperature of the air flow is sufficient to retain the evaporated surface moisture in the vapor phase. Feedstock of solid materials is added to an intermediate location of the bed. The larger more dense fluidized particles are removed from bottom locations of the bed. The smaller less dense fluidized particles are removed from top location of the bed. The temperature and vapor holding capacity of the air leaving the bed is substantially higher than at ambient conditions. The air is again heated by indirect or unfired means downstream of the bed for reducing relative humidity of the air substantially below saturation prior to passage through a bag house for fine particle collection after which the air along with the superheated water vapor is discharged to atmosphere.