Model Answer

Question ① 《15 marks》

A- Define: Flammability Limits, Smoke Point, Minimum Ignition Energy, Chemical Kinetics, Quenching Distance, adiabatic flame temperature, Calorific Value, Flash Point, Enthalpy of Formation, and Diffusion Flames. (10)

Flammability limits are defined as the concentration range in which a flammable substance can produce a fire or explosion when an ignition source (such as a spark or open flame) is present.

Smoke Point: Measure of the tendency of a liquid fuel to produce soot.

Minimum Ignition Energy (MIE) can be defined as the minimum energy that can ignite a mixture of a specified flammable material with air or oxygen, measured by a standard procedure

Chemical kinetics is the area of chemistry concerned with the speeds, or rates, at which a chemical reaction occurs, the factors that affect rates of reactions, and the mechanisms by which reactions occur.

Quenching Distance is the critical diameter of a circular tube where a flame extinguishes, rather than propagates

Adiabatic flame temperature is defined as the flame temperature achieved with the assumption of no work and no changes in kinetic or potential energy for the given reactants due to complete combustion; thus all liberated energy is absorbed by the products attaining its maximum temperature.

Calorific Value is the amount of energy released in the form of heat due to burning unit mass of fuel, and is measured either as gross calorific value or net calorific value. The difference being the latent heat of condensation of the water vapor generated from the combustion process.

Flash Point: id the lowest temperature at which liquid fuel will produce sufficient vapor to form a flammable mixture with air. Indicates maximum temperature at which liquid fuel can be stored without any fire hazard

Enthalpy of Formation (ΔH_f) is the enthalpy change that occurs when one mole of a compound is formed at standard state (25°C and 1atm).

Auto Ignition Temperature: The lowest temperature required to make the combustion self-sustained without any external aid.

Methane number (MN) is defined as the percentage of methane by volume blended with hydrogen that exactly matches the knocking behavior of the unknown gas mixture under specified operating conditions in a knock testing engine.

B- Discuss the major parameters for boiler overall performance analysis? (5)

1. Combustion Efficiency – It is important to try for perfect combustion efficiency, but many times perfect combustion efficiency is impractical due to the requirements of maintenance efficiency, safety, environmental efficiency, and fuel efficiency.
2. Maintenance Efficiency – Although a brand new burner or boiler may run extremely efficiently with little or no problems, as time goes on, the same boiler slowly begins to lower its efficiency. This is because as a boiler or burner gets older it becomes dirtier and deteriorates. This affects the combustion process greatly and can seriously affect missions and safety. In most cases, as a burner wears down, more excess air will be needed to ensure proper combustion and reduce CO emissions. To ensure that efficiency is maintained when a boiler ages, it is important to closely monitor the amount of O_2 needed to produce proper combustion and CO emissions.
3. Safety – Safety is a major concern when dealing with any form of combustion. The toxic emissions that are released along with the risk of possible explosions can cause great harm. Older parts that are used in the combustion process can create more dangerous conditions. To ensure complete safety it is essential to monitor levels of CO and CxHy (hydrocarbons). It is also necessary to check the amounts of oxygen needed to ensure low levels of CO and hydrocarbons. CO is a toxic gas that can be lethal in higher concentrations. Hydrocarbons contain unburned fuel, which can cause explosions and consequently, great injury.
4. Environmental Efficiency – Toxic compounds such as sulfur dioxide, carbon monoxide, nitrogen oxides, and particles are undesirable emissions that are frequently results of the combustion of fossil fuels. These compounds cause smog, acid rain, and respiratory problems. In effort to reduce these pollutants federal and state laws have been established under the guidelines of the Clean Air Act and the EPA (Environmental Protection Agency). Combustion analysis aids in monitoring these toxic gases and meeting the regulations set forth by the government and EPA.

<u>Question ② (15 marks)</u>

A- What are the major parameters needed to account the boiler heat balance? With the help of a flow diagram that shows the inputs and outputs of both heat and mass, into and out from the boiler respectively (7)

Heat balance sheet accounts.

- The amount of heat inside, Q_i, consists of:
  - Chemical heat of the fuel;
  - Fuel sensible heat;
  - feed water sensible heat;
  - Sensible heat of the air in the boiler.
- The amount of heat out, Q_E, includes:
  - Heat useful;
  - Heat loss through the flue gas sensible heat;
  - Heat lost through chemical combustion incomplete;

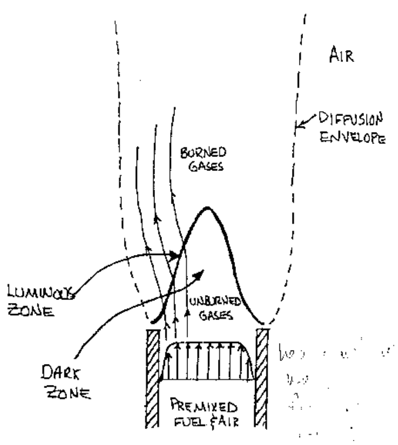
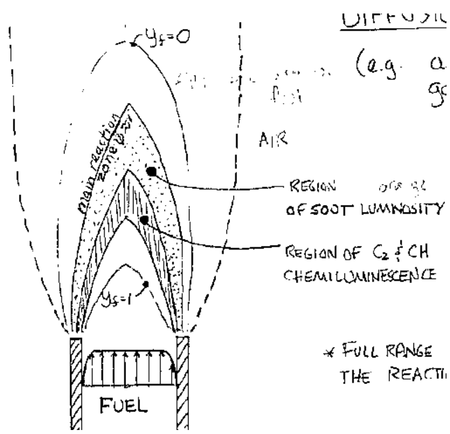
- Heat lost through incomplete combustion machine;
- Heat lost by radiation and convection environment;
- Heat sensitive heat lost through the slag;
- Heat lost by water purged;
- Heat lost through cooling water recovered.

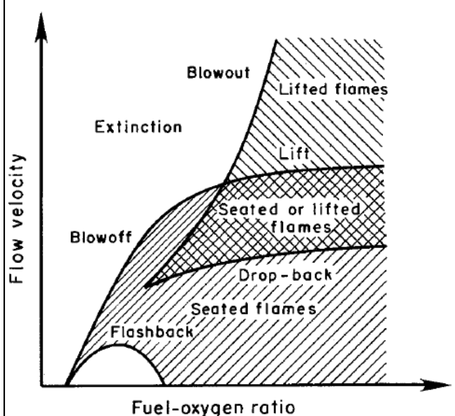
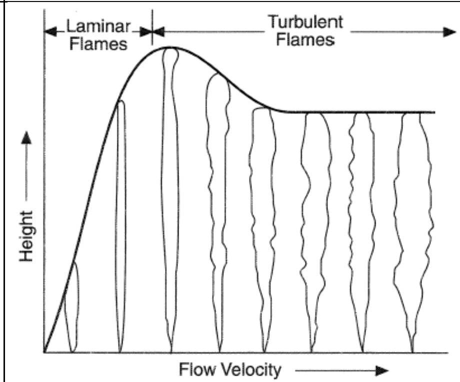
The combustion efficiency cannot be measured directly, but it can be calculated by identifying all of the losses that occur during combustion. It is important to consider all factors including sensible heat losses, unburned gases, radiation, and unburned particles. In most instances, the values of the skin losses and latent heat losses are not taken into account.

The following equation can be used to calculate combustion efficiency:

$$\text{Boiler efficiency} = \frac{Output}{Input} \text{ or } \%\text{Efficiency } = 100\% - \frac{\text{Total Heat losses}}{\text{Fuel heating value}} \times 100$$

B- Differentiate with the help of sketches between premixed and diffusion flames. (8)

parameter	**Premixed**	**diffusion**
Mixing of reactants	Fuel and oxidizer are mixed prior to the burner jet or combustion zone	Fuel and oxidizer are introduced separately into the combustion zone
Motivation of reaction	Rate of burning depends mainly on the chemical kinetics of reaction	Rate of burning depends mainly on the mixing rate between fuel and oxidizer
Flame front	There exists a flame zone through which the fuel and air react each with other at any equivalence ratio within flammability limits. 	There exists a flame front through which the fuel and air react each with other, where the equivalence ratio is always equal unity. 

Flame stability	Flame is unstable at the flammability limits if there is any fluctuation in velocity streams of incoming mixture (Blow-off or flash-back)	The stability of diffusion flames depends mainly on the flow velocity of fuel as well as the mixing rate between fuel and air
Stability chart		

Question ③ (15 marks)

A- What are the factors affecting the laminar burning velocity? (5)

There are two main groups of variables affecting the laminar burning velocity; chemical and physical variables. Chemical variable includes the fuel-oxidant ratio (or the equivalence ratio), fuel type (or the molecular structure of the fuel), and additives and fuel blending, while, the physical variable includes the ignition energy, initial temperature, and pressure.

1- Temperature: the laminar burning velocity has a strong temperature dependence with independence factor of about 2. The general preheating of the unburned gas mixture effect on the burning velocity can be represented in the form of: $S_L = A + B\left(\frac{T_u}{T_o}\right)^{\alpha}$

2- Pressure: From the previous analysis $S_L \propto P^{(n-2)/2}$, for a global reaction order of 2, burning velocity should be independent of pressure. It is found stated, in a similar manner, that both the diffusion and thermal theories of flame propagation predict the following form of pressure dependency: $S_L \propto P^{\beta}$ and β vary from 0 to -0.5 for a monomolecular reaction.

3- Equivalence ration: Generally, the laminar burning velocity has its maximum value at slightly rich mixture and falls down to its minimum value at the flammability limits in like bell-shaped curve, which is approximately about the axis, give equivalence ratio at which the maximum burning velocity occurs.

4- Fuel type: Generally, as the straight chain length (indicating number of carbon atoms in the chain) for alkanes, alkenes, and alkynes increased, the laminar burning velocity decreased, this emphasis the effect of unsaturation: the burning velocity increases in the order alkanes<alkenes< alkynes. All saturated hydrocarbons (alkane or paraffin such as propane and butane) posses approximately the same maximum burning velocity independently of the number carbon atoms in the molecule.

5- Dilution: The influence of the inert gases (diluents) depends upon the heat capacity, diffusion constant and thermal conductivity of the gas. Generally, the diluents reduce the reaction rate and the flame temperature thus reducing the burning velocity. However, the additives have a chemical effect on the burning velocity; it may be another fuel, catalytic agent, or inhibitor.

B- State briefly the factors affecting on the reaction rate? (5)

The factors affecting the reaction rates are:

1. ***Concentrations of reactants***: Reaction rates generally increase as the concentrations of the reactants are increased –more frequent collisions.
2. ***Ionic or molecular nature of reactants in aqueous solution***: Reactions between ions are typically faster than those between molecules – solvated ions are ready for reaction.
3. ***Physical state of the reactants –*** states that promote contact have faster rates; homogeneous vs. heterogeneous.
4. ***Temperature***: Reaction rates generally increase rapidly as temperature is increased – more frequent and higher energy collisions.
5. ***Surface area***: For reactions that occur on a surface rather than in solution, the rate increases as the surface area is increased.
6. ***Catalysts***: Catalysts speed up reactions – by providing an alternate pathway that has a lower Activation Energy requirement.

C- State the main factors affecting fuel atomization and spray pattern. (5)

1- Fluid Properties Affecting the Spray Among a variety of factors affecting droplet size the fluid properties in particular its surface tension, viscosity, and density.
   a. *Surface tension* tends to stabilize a fluid, preventing its breakup into smaller droplets. Everything else being equal, fluids with higher surface tensions tend to have a larger average droplet size upon atomization.

b. A *viscosity* has a similar effect on droplet size as surface tension. Viscosity causes the fluid to resist agitation, tending to prevent its breakup and leading to a larger average droplet size.

c. *Density* causes a fluid to resist acceleration. Similar to the properties of both surface tension and viscosity, higher density tends to result in a larger average droplet size.

2- Operating conditions as the fluid exit velocity and the fluid pressure

3- Geometrical parameters as jet hole diameter, number of holes, and the hole thickness.

The main parameters to describe fuel spray include the spray cone angle, droplet sauter mean diameter and the size distribution.

Question ④ ⦅15 marks⦆

A- If the flammability limits for hydrogen, gasoline, and methane are given, and are stored in a storage room has dimensions of 4 m x 4 m x 4 m. Calculate the amount of each fuel, in kg, that must leak or evaporate into the room to form a flammable mixture. Assume a temperature of 30ºC and a pressure of 1 atm. (5)

	LFL	UFL	Molecular Weight kg/mol
Hydrogen:	4.0%	75%	0.002
Gasoline:	1.3%	7.2%	0.106
Methane:	5.0%	15.0%	0.016

Solution: The room of given dimensions will have a total volume of 4x4x4 = 64 m^3.

Hydrogen: The lower flammable limit is 4% by volume hydrogen in air. Thus, the hydrogen gas required to reach the LFL is

$$(0.04)\left(64 \text{ m}^3\right) = 2.56 \text{ m}^3$$

The molar density of any ideal gas at 1 atm and 30°C = 303K is:

$$\rho = \frac{P}{R_g T} = \frac{1 \text{ atm}}{\left(8.2057\times10^{-5} \text{ m}^3 \text{ atm/mol K}\right)\left(303 \text{ K}\right)} = 40.2 \text{ mol/m}^3$$

The total amount of hydrogen at the LFL is $\left(2.56 \text{ m}^3\right)\left(40.2 \text{ mol/m}^3\right) = 102.9 \text{ mol}$

$$102.9 \text{ mol} = 0.206 \text{ kg}$$

Thus only 0.206 kg of hydrogen needs to leak out in order to explode.

Gasoline: The LFL is 1.3%. The total volume of gasoline vapor required to reach the LFL is

$$(0.013)\left(64 \text{ m}^3\right) = 0.832 \text{ m}^3$$

$$\left(0.832 \text{ m}^3\right)\left(40.2 \text{ mol/m}^3\right) = 33.4 \text{ mol}$$

The total moles of gasoline in this vapor is $33.4 \text{ mol} = 3.54 \text{ kg}$

Methane: The LFL is 5.0%. The total volume of gasoline vapor required to reach the LFL is

$$(0.05)\left(64 \text{ m}^3\right) = 3.2 \text{ m}^3$$

The total moles of methane in this vapor is

$$\left(3.2 \text{ m}^3\right)\left(40.2 \text{ mol/m}^3\right) = 128.6 \text{ mol}$$

$$128.6 \text{ mol} = 2.06 \text{ kg}$$

B- In a test of a gas-turbine combustor, saturated-liquid methane at 115 K is to be burned with excess air to hold the adiabatic flame temperature to 1600 K. It is assumed that the products consist of a mixture of CO2, H2O, N2, O2, and NO in chemical equilibrium. Determine the percent excess air used in the combustion, and the percentage of NO in the products. (10)

$$CH_4 + 2x\,O_2 + 7.52x\,N_2$$
$$\rightarrow 1\,CO_2 + 2\,H_2O + (2x\text{-}2)\,O_2 + 7.52x\,N_2$$

Then	N_2	+	O_2	$\Leftrightarrow$	2 NO	Also	CO_2	H_2O
initial	7.52x		2x-2		0		1	2
change	-a		-a		+2a		0	0
final	(7.52x-a)		(2x-2-a)		2a		1	2

$$n_{TOT} = 1 + 9.52x$$

1600 K: $\ln K = -10.55,\ K = 2.628\times10^{-5}$

$$2.628\times10^{-5}\ K = \frac{y_{NO}^2}{y_{N2}y_{O2}}\left(\frac{P}{P^0}\right)^0 = \frac{y_{NO}^2}{y_{N2}y_{O2}} = \frac{4a^2}{(7.52x\text{-}a)(2x\text{-}2\text{-}a)}$$

From A.9 and B.7,

$$H_R = 1\left[-74\,873 + 16.043(-274.7\text{-}624.1)\right] + 0 + 0 = -89\,292\ \text{kJ}$$

(Air assumed 25 °C)

$$H_P = 1(-393\,522 + 67\,569) + 2(-241\,826 + 52\,907)$$
$$+ (7.52x\text{-}a)(41\,904) + (2x\text{-}2\text{-}a)(44\,267) + 2a(90\,291 + 43\,319)$$
$$= -792\,325 + 403\,652\,x + 181\,049\,a$$

Assume $a \sim 0$, then from $H_P - H_R = 0 \rightarrow x = 1.7417$ and substitute

$$\frac{a^2}{(13.098\text{-}a)(1.483\text{-}a)} = \frac{2.628\times10^{-5}}{4}, \qquad \text{get} \quad a \approx 0.0113$$

Use this a in the energy equation

$$x = \frac{703\,042 - 181\,049\times0.0113}{403\,652} = 1.7366$$

$$\Rightarrow \frac{a^2}{(13.059\text{-}a)(1.4732\text{-}a)} = \frac{2.628\times10^{-5}}{4},\ a = 0.0112 \quad \Rightarrow \quad x = 1.7366$$

$$\%\ \text{excess air} = \mathbf{73.7\ \%}$$

$$\%\ NO = \frac{2\times0.0112\times100}{1+9.52\times1.7366} = \mathbf{0.128\ \%}$$

Good Luck,
Ali M.A. Attia