Benha University
Benha Faculty of Engineering
Mechanical Engineering Department
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Combustion Technology (M 1431)
First Semester – Final Exam
Time: 3 h
Date: 11/01/2016

Model Answer.

1) A- Define: Methane Number, Enthalpy of combustion, Chemical Kinetics, Quenching Distance, and Minimum Ignition Energy.

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.

Enthalpy of combustion $\bar{h}_c$ is defined as the difference between the enthalpy of the products and the enthalpy of the reactants when *complete* combustion occurs at a *given temperature and pressure*.

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.

Minimum Ignition Energy (MIE) is the minimum energy that can ignite a mixture of a specified flammable material with air or oxygen, measured by a standard procedure; the minimum amount of energy required to cause ignition.

B- Discuss the major physical and chemical properties required to characterize solid fuels?

The most important physical properties of solid fuels include:
- Size or particle size distribution
- Shape of particles
- Porosity of particles

The chemical properties of solid fuels include identifications of their composition and molecular structures that involve a substantial variety of inorganic and organic compounds. The largest portions are organic and arranged in hydrocarbon chains where, apart from C, H, O, and N, several other atoms are present, such as S, Fe, Ca, Al, Si, Zn, Na, K, Mg, Cl, heavy metals, etc.

C- What do you know about calorimetry and its types for fuel heating value determination?

A calorimeter is a devise used for determining the heat of reaction. Both constant-volume (bomb calorimeters) and flow-through devices are employed for this purpose.

For a reactor operating at steady state, the fuel is burned completely with air. For the products to be returned to the same temperature as the reactants, a heat transfer from the reactor would be required. From an energy rate balance, the required heat transfer is:

$$\frac{\dot{Q}_{CV}}{\dot{n}_f} = \bar{h}_c = H_P - H_R = \sum_P n_j \bar{h}_j - \sum_R n_i \bar{h}_i$$

Main types include:

1- Styrofoam coffee-cup calorimeter, which is often used in laboratories to measure the heat of reaction in aqueous solution, which occurs at constant pressure. This type of calorimeter measures the enthalpy change (ΔH) of a reaction. The heat produced by the reaction is absorbed by the solution (the reaction's surrounding), which can be calculated from the mass, its specific heat, and the temperature change of the solution using the expression: q_{soln} = m C_p ΔT

2- A "bomb-calorimeter" is a type of calorimeter used to measure the amount of heat produced in a combustion reaction. It measures the heat of reaction carried out at constant volume.

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The amount of heat produced is calculated by measuring the heat absorbed by the calorimeter, which is

$q_{comb.} = - q_{cal}$; and $q_{cal.} = h_{cal} \times \Delta T$

where h_{cal} is the heat capacity of the calorimeter

In a bomb calorimeter the fuel is burned in a high pressure O_2 environment. The surrounding water is constantly stirred and any change in temperature is measured with the thermometer. Instead of using the specific heat of water, in this case we look at the specific heat of the whole calorimeter – heat capacity; as stated in above equation.

2) A- State and differentiate between coal types.

Coal can be classified according to composition as:

1. Anthracite, with wt. daf (weight fractions at dry and ash-free basis) volatile between 1.8 and 10%, carbon between 91 and 94.4, carbon C/H (elementary carbon and hydrogen ratio) between 23.4 and 46, and combustion enthalpy between 34.4 and 35.7 MJ/kg

2. Bituminous, with daf volatile between 19 and 44.6%, carbon between 77.7 and 89.9, C/H between 14.2 and 19.2, and combustion enthalpy between 32 and 36.3 MJ/kg

3. Subbituminous, with daf volatile between 44.2 and 44.7%, carbon between 73.9 and 76, C/H between 14.3 and 14.6, and combustion enthalpy between 29 and 30.7 MJ/kg

4. Lignite, with daf volatile around 47, carbon around 71, C/H around 14.5, and combustion enthalpy around 28.3 MJ/kg and ultimate analysis of a typical subbituminous coal.

Typical composition based on the two analysis is shown in table below for subbituminous coal. Moisture and mainly ash contents play an important role regarding the quality of fuels. For instance, some coals may reach 40% in ash content, which leads to problems for ignition of particles.

Typical proximate analysis of a subbituminous coal		Typical ultimate analysis of a subbituminous coal	
Component	Mass % w.b.	Component	Mass %, d.b.
Moisture	5.00	C	73.2
Volatile	38.00	H	5.1
Fixed carbon	47.60	O	7.9
Ash	9.40	N	0.9
High heat value (MJ/kg) (dry basis)	30.84	S	3.0
		Ash	9.9

B- State main ignition and quenching criteria with emphasize on main ways to extinguish flames?

Ignition and Quenching Criteria the following two rules-of-thumb governing ignition and its converse, flame extinction are provided;

Criterion I - Ignition will only occur if enough energy is added to the gas to heat a slab of that gas to the adiabatic flame temperature.

Criterion II - The rate of liberation of heat by chemical reactions inside that slab must approximately balance the rate of heat loss from the slab by thermal conduction.

There are many ways in which a flame can be extinguished, such as:

1- flames extinguishes while passing through narrow passageways. This phenomenon is the basis for many practical flame-arresting devices since 1815.

2- The addition of diluents, such as water, which have primarily a thermal effect, or chemical suppressants, such as halogens, which alter the chemical kinetics.

3- Blowing the flame away from the reactants is also effective in extinguishing flames, as is easily demonstrated with a weakly burning Bunsen-burner flame. A more practical

application is the blowout of oil-well fires with explosive charges; although, in this case, the flames may have a strongly nonpremixed character, rather than being premixed.

C- State briefly how the combustion reaction proceed kinetically? Use, as an example, the reaction of hydrogen with oxygen to form water

In summary, combustion reactions can be described at the molecular level by giving the elementary reactions that comprise the combustion mechanism of the fuel of interest. The overall reaction proceeds via the highly reactive intermediates, the **radicals** O, OH and H reactants in which one radical creates two or more further radicals (e.g. $H + O_2 \rightarrow OH + O$) are termed **chain branching**. These reactions which result in the net disappearance of radicals (e.g. $H + OH + M \rightarrow H_2O + M$) are termed **chain termination**. Intermediate in character are **chain propagation reactions** (e.g. $OH + H \rightarrow H_2O + H$). The termination reactions are all **termolecular** in that a third body, M, is required to remove the energy released in combination. For example the global reaction of hydrogen will be:

$$2H_2 + O_2 \rightarrow 2H_2O$$
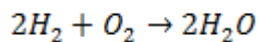
The following elementary reactions are important:

$$H_2 + O_2 \rightarrow HO_2 + H$$
$$H + O_2 \rightarrow OH + O$$

$$OH + H_2 \rightarrow H_2O + H$$

$$H + O_2 + M \rightarrow HO_2 + M$$
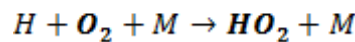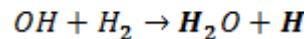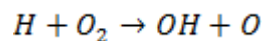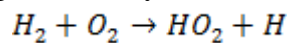
3) A- State different parameters affecting the fuel atomization and the main spray characteristics.

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 the nozzle diameter, number of holes, and the hole thickness.

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

B- What are the 5-Ms burner performs parameters? Hence classify the burner types based on the operating modes.
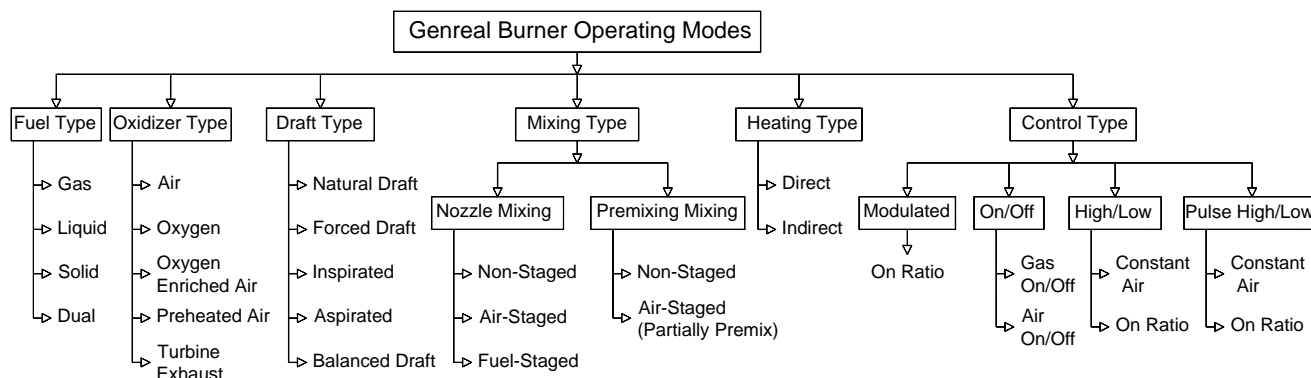
5-Ms burner performance parameters are:

1- **Meter the fuel and air into the flame zone**; throughout the use of system metering orifices.
2- **Mix the fuel and air to efficiently utilize the fuel**, the mixing of fuel/air means to bring fuel (reactant) into close molecular proximity with air (oxidant).
3- **Maintain a continuous ignition zone for stable operation**. It is necessary to provide reliable and continuous ignition of the fuel/air passing through burner over the specified range of operating conditions. This achieved in burner by specific location at which the fuel/air nearly stoichiometric with velocity equal or below that of the flame speed and so providing a continuous "ignition zone" the flame from this zone is used to ignite the remaining fuel/air mixture.
4- **Mold the flame to provide the proper flame shape**. There are critical restrictions on the shape, size, and consistency of the generated flame. The proper flame pattern is generated

by the combination of the fuel injection pattern and the burner tile and the flame holder that control the air flow.

5- Minimize pollutant emissions

According to the operating modes, the burners can be classified based on:

1- Fuel type (gaseous, liquid, solid, mixed/dual ,….)
2- Oxidizer (air, oxygen, oxygenated,….)
3- Draft (natural, forced, aspirated, inspirated, balanced,…)
4- Mixing type (premised, nozzle, ..)
5- Heating type (direct or indirect)
6- Control type (modulated, on/off, high/low, pulses high/low)

Genreal Burner Operating Modes

| Fuel Type | Oxidizer Type | Draft Type | Mixing Type | Heating Type | Control Type |

Fuel Type: Gas, Liquid, Solid, Dual
Oxidizer Type: Air, Oxygen, Oxygen Enriched Air, Preheated Air, Turbine Exhaust
Draft Type: Natural Draft, Forced Draft, Inspirated, Aspirated, Balanced Draft
Mixing Type: Nozzle Mixing (Non-Staged, Air-Staged, Fuel-Staged), Premixing Mixing (Non-Staged, Air-Staged (Partially Premix))
Heating Type: Direct, Indirect
Control Type: Modulated (On Ratio), On/Off (Gas On/Off, Air On/Off), High/Low (Constant Air, On Ratio), Pulse High/Low (Constant Air, On Ratio)

Schematic layout for the different operating modes of burners

C- What are the main factors affecting the flammability limits.

1- **Flammability Limits and Temperature**, when external temperature goes up, the lower flammability limits will decrease while the upper flammability limits increase.

2- **Flammability Limits and Pressure.** Generally, pressure has only a slight effect on LFL except at low pressure (<50 mmHg absolute), where flames do not propagate, while the UFL increases considerably as the initial pressure increases. Raising the initial pressures of the fuel-gas system can generally broaden its flammability limit range, put differently, lowering LFL and raising UFL.

3- **Flammability Limits and Oxygen Concentration.** Normally, the LFLs in a variety of oxygen concentrations are almost the same as in air. Since the LFL is a fuel-lean condition, excess oxygen is available at 21% and any further excess oxygen is simply acting as a diluent. The molar heat capacities of oxygen and nitrogen are similar, and consequently the LFL value is not changed by going to a 100% oxygen atmosphere. However, the UFLs increase sharply with increasing oxygen concentrations.

4- **Flammability Limits and Inert Gases.** Any flammable material present in air must be present at a concentration higher than the LFL and lower than the UFL for a fire or explosion occurrence. To control the fire and explosion, inert additives (that is, substances which are neither fuels nor oxidizers) are sometimes added to mixtures in order to decrease their flammability limits or make the mixture entirely outside the range of flammability. For moderate amounts of inert additives, the effect is mainly on the UFL.

5- **Flammability Limits and Experimental Apparatus Sizing.** The flammability limits are relatively dependent on the experimental apparatus sizes: (i) For a cylindrical vessel of small diameter with a large height, the flammability limits are primarily determined by the quenching effect of the wall; (ii) For cylindrical vessels of small heights, the flammability limits are affected by hot gas accumulation at the vessel ceiling, unburnt gas heating, self heating of the

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incipient flame, and the quenching effect of the walls; (iii) if the vessel size is large enough, all of these effects become negligible, the experimental values of flammability limits may approach the values that would be obtained in free space.

6- **Flammability Limits and Ignition Energy.** Flammable gas/vapor mixtures need initial ignition energy to combust. Different from ignition limits, the flammability limits are essentially independent of the ignition source strength, therefore considerably greater spark energies are required to establish flammability limits than those required for limits of ignitibility.

7- **Flammability Limits and Propagation Direction.** It was observed that the flammability limits are wider for upward than for downward flame propagation, and the horizontal limit lies between the upward and downward limits.

8- **Flammability Limits and Turbulence.** When fan - stirring was introduced into a test chamber, it was found that the LFL rose while UFL fell with fan speed and consequently with the turbulence velocity. The effect requires a sizable stirring speed, however, to become significant. The narrowing effect on observed flammability limits has been interpreted as being an MIE impact.

4) A- Liquid octane (C_8H_{18}) at 25°C and 1 atm is burned with air entering the combustion chamber at 300°C. The volumetric analysis of the products on a dry basis is 5.2% CO_2, 0.33 % CO, 11.24 % O_2, and 83.23 % N_2. Determine (a) the percentage of theoretical air used, (b) the heat transfer from the combustion chamber per kmol of C_8H_{18} if the combustion products leave at 600 K, and (c) the total entropy change per kmol of C_8H_{18}

B- A first order reaction B → Products is 40 % complete at the end of 160 sec. Calculate the following:
    a. The value of the reaction rate constant in s^{-1}.
    b. The time for destruction of 80 % of B.

From the first order chemical reaction, B → Products and Eq. 1.98 a, thus: $\ln [B] / [B_0] = - k_B t$

where $[B_0]$ is the intial concentration of the reactant at t = 0, while [B] is the concentration at time t.

Let x represent the concentration of B which has reacted, then at time t the remaining concentration of B is given by; $[B] = [B_0] - x$

Substituting in the above equation, we have; $k_B = (1/t) \ln [B_0] / ([B_0] - x)$

Considering $[B_0] = 100$ %, then; $k_B = (1/160) \ln (100 / (100-40)) = 0.00319$ s^{-1}

The time for 80 % distruction of B; $t = (1 / k_B) \ln (100 / (100-80)) = 505$ sec.

5-B Consider the measurement of turbulent flame speeds. An air-fuel mixture passes through a 40x40 mm flow channel with a flame anchored at the channel exit along the top and bottom walls. Quartz sidewalls contain the flame beyond the exit, while the top and bottom are open to the laboratory. For a mean flow velocity of 68 m/s, the resulting wedge-shaped flame has an included angle of 13.5 ° estimated from time-exposure photographs. Estimate the turbulent burning velocity at this condition. The properties of the unburned mixture are T = 293 K. P = 1 atm. and MW = 29 kg/kmol.

Solution: the turbulent burning velocity can be determined from

$$S_t = \frac{\dot{m}}{\bar{A}\rho_u}$$

The reactants flowrate is $\dot{m} = A_{duct} v_{duct} \rho_u = 1.206 * 0.04^2 * 68 = 0.131 \, kg/s$
where the reactants density is estimated using the ideal-gas law.
From the flame geometry (wedge), we estimate the apparent flame area. $\bar{A}$, first by finding the length of the flame sheet. L:
$$\frac{h/2}{L} = \sin\left(\frac{13.5}{2}\right) \text{ or } L = \frac{h/2}{\sin 6.75} = 0.17 \, m$$

Then $\bar{A} = 2 * width * length = 2 * 0.04 * 0.17 = 0.0136 \ m^2$

The turbulent burning velocity is:

$$S_t = \frac{\dot{m}}{\bar{A}\rho_u} = \frac{0.131}{0.0136} = 8 \ m/s$$

5) A- Acetylene (C_2H_2) gas and x times theoretical air (x > 1) at room temperature and 500 kPa are burned at constant pressure in an adiabatic steady flow process. The flame temperature is 2600 K, and the combustion products are assumed to consist of N_2, O_2, CO_2, H_2O, CO, and NO. Determine the value of x.

Combustion:

$$C_2H_2 + 2.5x\,O_2 + 9.4x\,N_2 \rightarrow 2\,CO_2 + H_2O + 2.5(x-1)O_2 + 9.4x\,N_2$$
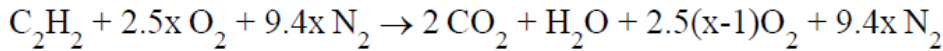
Eq. products 2600 K, 500 kPa: N_2, O_2, CO_2, H_2O, CO & NO

2 Reactions:

$$1) \quad 2\,CO_2 \Leftrightarrow 2\,CO + O_2 \qquad 2) \quad N_2 + O_2 \Leftrightarrow 2\,NO$$
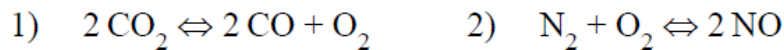
change -2a   +2a   +a   change -b   -b   +2b

Equil. Comp.: $n_{N2} = 9.4x - b$, $n_{H2O} = 1$, $n_{CO} = 2a$, $n_{NO} = 2b$

$n_{O2} = 2.5x - 2.5 + a - b$, $n_{CO2} = 2 - 2a$, $n_{TOT} = 11.9x + 0.5 + a$

At 2600 K, from A.11: $K_1 = 3.721 \times 10^{-3}$, $K_2 = 4.913 \times 10^{-3}$

EQ1:
$$\frac{K_1}{(P/P^o)} = \frac{3.721 \times 10^{-3}}{5} = \left(\frac{a}{1-a}\right)^2 \left(\frac{2.5x - 2.5 + a - b}{11.9x + 0.5 + a}\right)$$

EQ2:
$$K_2 = 4.913 \times 10^{-3} = \frac{(2b)^2}{(9.4 - b)(2.5x - 2.5 + a - b)}$$

Also, from the 1st law: $H_P - H_R = 0$ where

$H_R = 1(+226\ 731) + 0 + 0 = +226\ 731 \ kJ$

$H_P = (9.4x - b)(0 + 77\ 963) + (2.5x - 2.5 + a - b)(0 + 82\ 225)$

$\quad + (2 - 2a)(-393\ 522 + 128\ 074) + 1(-241\ 826 + 104\ 520)$

$\quad + 2a(-110\ 527 + 78\ 679) + 2b(90\ 291 + 80\ 034)$

Substituting,

EQ3: $988\ 415x + 549\ 425a + 180\ 462b - 1\ 100\ 496 = 0$

which results in a set of 3 equations in the 3 unknowns x, a, b. Assume x = 1.07   Then

EQ1: $7.442 \times 10^{-2} = \left(\frac{a}{1-a}\right)^2 \left(\frac{0.175 + a - b}{13.233 + a}\right)$

EQ2: $1.2283 \times 10^{-3} = \frac{b^2}{(10.058 - b)(0.175 + a + b)}$

Solving,   a = 0.1595, b = 0.0585   Then checking in EQ3,

$\quad 988\ 415 \times 1.07 + 549\ 425 \times 0.1595 + 180\ 462 \times 0.0585 - 1\ 100\ 496 \approx 0$

Therefore, x = **1.07**

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