

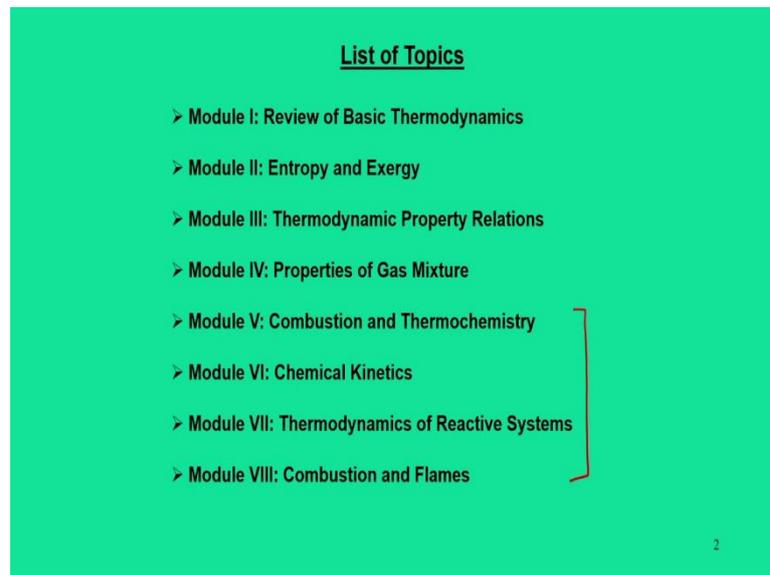
Advanced Thermodynamics and Combustion
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Lecture - 34
Tutorial 2

Dear learners, greetings from IIT, Guwahati, we are in the MOOC's course Advanced Thermodynamics and Combustions. Till this point of time, we have completed the entire modules and in the last lectures I was discussing about the learning components of this course. In fact, you can consider this as a tutorial session, where we are trying to learn some of the important concepts about this course.

Side by side we are also exploring to many new exploring many numerical problems and its solutions which can be considered as the question bank for the final exam.

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Now, let me start we covered up to the Module IV, where we talked about mainly on advanced thermodynamics parts involving basic concepts, entropy and exergy, thermodynamic property relations and gas mixtures. Today, we are going to summarize what we have discussed in the topic combustion.

So, for this course module Vth to module VIII covers the concept of combustion. While talking about the combustion, the first thing that we do is that we try to find out the

thermodynamic angle towards this combustion analysis. In fact, a combustion process can be considered as a multi-component system as we explored in the module IV.

So, in this multi-component systems which consist of many numbers of gases, these gases can be considered as a mixture, but in similar philosophy we can say combustion is nothing but the mixture of fuel and oxidizer in the beginning now after the fuel ignites the entire reactants and the oxidizers they vanish and when they vanish, we get the combustion products.

So, in totality we can say it has the components, which was initially in a mixing phase, but and they vanish and combustion products are formed. So, by doing so, one simplest approximation that can be made is that if at all we want to get an estimate of the reaction temperatures or maximum temperature during these combustions, then you have to bring the concept of thermodynamics.

So, one such topic or one such parameters was discussed about the adiabatic flame temperatures. Now, while discussing about these combustion and thermodynamics link, we find out the thermodynamics of reacting systems that involves the calculations of enthalpy, entropy, internal energy all these parameters.

And side by side we also try to explore the various combustion parameters related to thermodynamics. Now, this is dealt in the module Vth where we talk about thermo chemistry. Then moving further, we discuss about the reaction kinetics or chemical kinetics. In fact, combustion is nothing but a chemical reaction and during this chemical reaction under stoichiometric kind of situations, we see the reactants and finally, we see the products.

But formation of this products, there may be many kind of reactions that has participated and though some of the components has been formed and during this reaction process they also vanishes. But if you look at the exact replication of this combustion process, we will find that there are some reactions, which are treated as a global reaction some reactions that are treated as a individual reactions.

And reaction has to proceed in a particular direction. In fact, in the combustion process reaction is always a exothermic because, heat comes out. So, while maintaining the directionality of these reactions, we also see that whether this system goes in the

maximization of entropy or not. And equilibrium situation is reached when entropy is maximum during this reaction phase.

Then we also dealt with the thermodynamics of reactive systems, which means that a reactor is nothing but a combustion environment which can be viewed as a open system, where the reactants under or fuel and oxidizer they come as 2 inlets and the products that goes out is called as the combustion products. So, there are two-inlet one-exit.

So, if you view this as a reactor then there are different models associated with. So, this module 7 deals with the thermodynamics of reactive systems. And the last part talks about the combustion and flames which in general happens in various applications some of the applications include SI engines combustion, CI engine combustions gas turbine combustions.

And the in order to find out the methodology of combustion process, we dealt with the fact that about the combustion and flames, where we discussed about laminar flames and laminar pre-mixed flames, laminar diffusion flames then we dealt with droplet evaporations, droplet burning all these concepts.

Now, during this process also we find out that the flame is another kind of a very small region in this combustion medium, which actually differentiates the un-burnt products and burned products, means instantly when this combustion happens we say that it is viewed as two distinct zones of burned products and unburned products. So, the flame differentiates between these two zones.

So, when the flame propagates in a combustion medium it tries to burn out the reactants and side by side the concentration of products also goes off. So, this is about the pre-mixed flame when it propagates in the combustion medium. There are also diffusion flames, which means that we do not view this as exactly as a flame, but the ignition takes place at multiple locations in the combustion medium.

And each may be viewed as a discrete flame that propagate in the medium. And this is how the entire combustion products are formed are the flame propagates into the entire medium. Apart from that there is a concept called droplet evaporation normally in many situations' fuels are introduced as a droplet and these droplets has certain lifetime and when they enters into the combustion medium or domain it sees a very high temperatures.

Because, already high temperature is reached during the compression process, now when it sees the high temperature it suddenly evaporates; that means, the droplets are formed and side by side they evaporate and while evaporating they burn as well; that means, when they burn nowhere they will be called as a fuel droplets rather they burned into combustion products. So, this is dealt with the droplet formation and burning.

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Learning Components

Module V: Combustion and Thermochemistry

- Combustion fundamentals (fuels, oxidizers, products of combustion, stoichiometry, lean/rich mixture, equivalence ratio, enthalpy of formation, enthalpy of combustion, heating value)
- Energy balance for combustion models (closed/open system)
- Adiabatic flame temperature
- Equilibrium products of combustion (water-gas shift reaction)
- Effective energy utilization techniques from flue gases (recuperation/regeneration and exhaust gas recirculation)

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So, to give more elaborate and to each modules. So, while talking about combustion on thermochemistry we dealt with the combustion fundamentals, fuels, oxidizer, products of combustions, stoichiometry, lean and rich mixtures, equivalence ratio, enthalpy of formations, enthalpy of combustions, heating value.

Why I am discussing all these things because these are the critical parameters that will be very beneficials and while refreshing this course you must understand this parameter. So, that you can do well in the examination, we also dealt with the energy balance of combustion models. So, we dealt with the closed systems, open systems.

Then we define the parameter called as adiabatic flame temperatures and in fact, this adiabatic flame temperature can be achieved through constant pressure process or constant volume process. Now, while dealing with these combustions we also defined the chemical equilibrium and the equilibrium products of combustions, now normally stoichiometric is the ideal case where maximum heat is released during this during the combustion process.

But in reality, either the reaction process occurs in a lean regime or rich regime. So, for that when we have a lean combustion, we can say that there is enough oxidizers. So, oxygen will be in the products, but when we are going for a rich combustion, we will find that the components like unburned products like carbon monoxides are presents.

So, in those cases to kill these carbon components we need to recirculate the gas. So, normally that way we can say effective energy utilization of flue gases. So, we recirculate this gas and; that means, the flue gases that comes out again is recirculated during the combustions. So, thereby we introduce the concept called as water shift reactions to find out what are the different equilibrium products of combustions.

And while rich combustions the other components of interest that are formed like a NO NOX emissions, NO₂ all these things are formed. So, effective way of looking at energy utilization of flue gas is the incorporating the exhaust gas recirculation or regeneration.

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Learning Components

Module VI: Chemical Kinetics

- Fundamentals of chemical reaction (global and elementary reaction, rate coefficient and equilibrium constant)
- Reaction mechanisms (uni-molecular reactions, chain and branch reactions, chemical time scale)
- Hydrogen – oxygen reaction system (pressure –temperature diagram for explosion behavior)
- Carbon monoxide oxidation
- Oxides of nitrogen formation (Thermal/Zeldovich mechanism, Fenimore/prompt mechanism, N₂O intermediate mechanism)

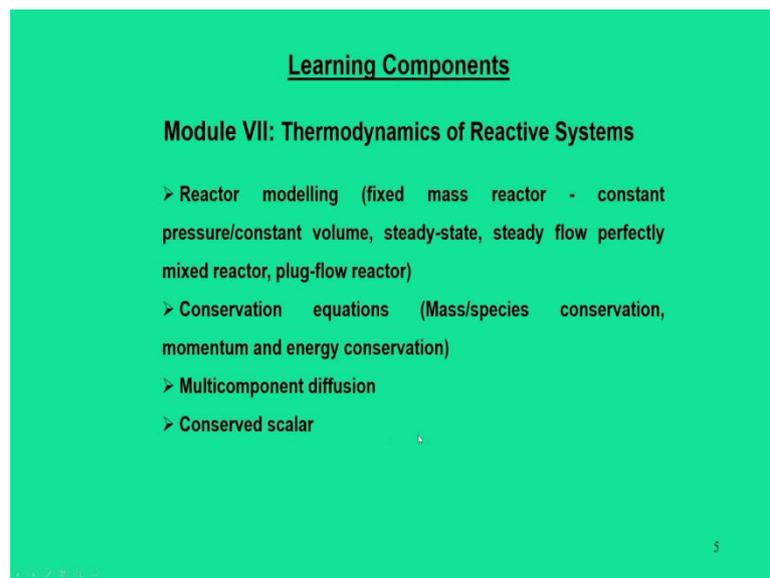
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While talking about the chemical kinetics, we dealt with the fundamentals of chemical reactions where we defined global and elementary reactions, rate coefficients, equilibrium constants. Then we dealt with reaction mechanisms that involves unimolecular reactions, chain and branch reactions in some situations the chain and branch reactions prevails; that means, we can have a multiple number of reactions or similar reactions.

So, thereby it is very difficult to stop then some reactions are unimolecular reactions, in some reactions also the some of the products are formed and immediately they vanishes. While dealing with we gave some examples of hydrogen oxygen reaction systems through its pressure temperature diagrams and where we discussed about the explosion behavior of the hydrogen.

Then during the combustion process we find out that what is the mechanism through which carbon monoxide oxidation takes place. Of course, similar mechanisms we also defined for which oxides of nitrogens are formed. So, such mechanisms are detailed here for. So, when we have very high temperatures the Thermal or Zeldovich mechanism is more relevant and when we have lean mixtures the other reactions like Fenimore and prompt mechanism or N_2O intermediate mechanisms are important.

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Learning Components

Module VII: Thermodynamics of Reactive Systems

- Reactor modelling (fixed mass reactor - constant pressure/constant volume, steady-state, steady flow perfectly mixed reactor, plug-flow reactor)
- Conservation equations (Mass/species conservation, momentum and energy conservation)
- Multicomponent diffusion
- Conserved scalar

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Then in the module VII that is thermodynamics of reactive systems we introduced the reactor modelling. So, reactor modelling can be a fixed mass type or it can be a steady state steady flow perfectly mixed type. So, in a fixed mass reactor type we can have a constant pressure or constant volume. In addition to that we have reaction modelling through plug flow reactors, where axial propagation of species is restricted.

Then we dealt with detailed conservation equations involving mass and species conservations, momentum and energy conservations, then you introduce the concept of multi component diffusions and conserved scalar.

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Learning Components

Module VIII: Combustion and Flames

- Laminar premixed flame (physical features, flame propagation, flame speed correlations, quenching, flammable limits, ignition, flashback, blow off, flame liftoff and flame stabilization)
- Laminar diffusion flame (jet flame characteristics, spreading rate, spreading angle, conserved scalar – mixture fraction)
- Droplet evaporation through mass and heat transfer (D^2 law, droplet life time, droplet burning)
- Combustion phenomena in engines (SI, CI and GT engines)
- Pollutant emissions and quantifications

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And in the last modules that is combustion and flames, we have discussed in elaborate manner about laminar pre-mixed flame where we talked about its physical features of the flame, flame propagations, flame speed correlations. The quantities like how to define the quenching, flammability limits, ignition, blow off, flame lift off and flame stabilizations.

Normally, when a laminar flame is considered ideally it should be stabilized in such a way that flame should not propagate back to this main fuel source otherwise it will create an explosion. To do this flame stabilizations all this quenching and flammability limits has to be taken into account.

Now, while talking about laminar diffusion flames, we say that the fuel diffuses in air. So, thereby we say that when the fuel comes out it comes out as a jet. So, that way we model this laminar diffusion flame through jet flame characteristics.

Thereby we introduced parameters like what is the spreading rate, what is the spreading angle, then there is a factor called as mixture fraction, which is a very important parameters which is nothing but a conserved scalar; during this diffusion process we have to find is there any trace of fuel particles at the end product of the combustion process or not.

Then we moved on to other important concepts like droplet evaporations through mass and heat transfers. So, there we define D^2 law droplet lifetime, droplet burning. And

towards the end we saw that how this the methodology of flames pre-mixed and diffusion flames, they are utilized in the engine combustions that is in spark ignition engines, compression ignition engines and gas turbine engines.

And the last segment of this discussion was pollutant emissions and quantifications. So, this is another source, where we already stated that during this combustion process there is reaction mechanisms in which carbon monoxides are formed or soot particles are formed or we can have the NOX formations.

So, to quantify these at the end products, what are the remedies that you are going to take. So, to quantify them we defined some characteristics parameters through which the pollutants emissions are quantified one such parameter is emission index of different pollutants. So, this is all about the overall picture of this course.

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Numerical Problems

Q1. The combustion takes place between isooctane (C_8H_{18}) and air in an engine. The molecular weight of isooctane and air, are 114 and 28, respectively. Calculate, (a) the air-fuel ratio for a stoichiometric combustion; (b) the air-fuel ratio for a 110% theoretical air; (c) the equivalence ratio.

Handwritten notes:

Q1
 Stoichiometric reaction,
 $C_8H_{18} + 12.5(O_2 + 3.76 N_2) \rightarrow 8CO_2 + 9H_2O + 12.5(3.76 N_2)$

$C_8H_{18} + (a)O_2 \rightarrow xCO_2 + yH_2O + z(N_2)$

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So, in the last tutorial sessions we discussed about some numerical problems up to module 4. Now, in this tutorial sessions we will try to find out some of the question banks which are related in the areas of combustions. So, we are going to solve them one by one and you can treat them as a question bank for the final exams. So, the first problem is based on stoichiometry.

So, the problem statement is that the combustion takes place between isooctane that is C_8H_{18} and air in an engine. The molecular weights of isooctane and air are given, we need

to find out the air fuel ratio for a stoichiometric combustions and the air fuel ratio for 100 percent theoretical air means it is rich in air. So, rich in air means lean fuel and then we have to find the equivalence ratio.

So, to solve such kind of problems first thing what you are going to write is the stoichiometric reaction. So, in this case we need to find out how this reaction should look like for isooctane and air. If I write isooctane and air reactions in stoichiometric case. So, $C_8H_{18} + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 12.5(3.76N_2)$

So, these reactions we can make based on our generalized reactions based on the fact that we can treat this fuel as C x H y and correspondingly when it is added to air, it gives CO₂ plus H₂O plus N₂ with some stoichiometric coefficient c, d, e respectively. So, this was given as an example in our earlier discussions. So, by taking that concepts we write this stoichiometric reaction.

So, for the time being let us not revisit those things. So, first we write this stoichiometric reactions of isooctane then for this stoichiometric reactions, we can see that in both sides the atoms are balanced atoms I mean carbon, hydrogen, oxygen and nitrogen.

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Numerical Problems

Q1. The combustion takes place between isooctane (C₈H₁₈) and air in an engine. The molecular weight of isooctane and air, are 114 and 28, respectively. Calculate, (a) the air-fuel ratio for a stoichiometric combustion; (b) the air-fuel ratio for a 110% theoretical air; (c) the equivalence ratio.

Soln

Stoichiometric reaction,
 $C_8H_{18} + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 12.5(3.76N_2)$

(a) $\frac{A}{F}$ ratio, $\frac{A}{F} = \frac{12.5 + 12.5 \times 3.76}{1} = 59.5 \frac{\text{kmol air}}{\text{kmol fuel}}$

$\frac{A}{F} = 59.5 \times \frac{28}{114} = 14.6$

(b) $C_8H_{18} + (12.5)(1.1)(O_2 + 3.76N_2) \rightarrow b CO_2 + c H_2O + d N_2 + e O_2$

Balancing of atoms: $b = 8$ $c = 9$ $d = 51.7$ $e = 1.25$

$\frac{A}{F} = \frac{(12.5)(1.1) + (12.5)(1.1)(3.76)}{1} = 65.45 \frac{\text{kmol air}}{\text{kmol fuel}}$

$\frac{A}{F} = 65.45 \times \frac{28}{114} = 16$

(c) $\phi = \frac{(\frac{A}{F})_{\text{act}}}{(\frac{A}{F})_a} = \frac{14.6}{16} = 0.9$

Then the first thing that is asked is what is air fuel ratio? So, air fuel ratio can be calculate as A/F we can see if it is 1 mole, it is 12.5 mole. So, we can say that $AF = \frac{12.5 + 12.5 \times 3.76}{1} =$

59.5 kmol air/kmol fuel. Now, if you make them in terms of ratio then we have to bring molecular weight into pictures. So, we can write this is $\frac{A}{F} = 59.5 \times \frac{28}{118} = 14.6$.

The second part of the solutions that we need to find the air fuel ratio for 110 percent of theoretical air. So, when you deal with the stoichiometric reactions then we have to bring this reactions with 110 percent of theoretical layer. So, this reaction now becomes $C_8H_{18} + 12.5 \times 1.1(O_2 + 3.76N_2) \rightarrow bCO_2 + bH_2O + dN_2 + eO_2$. why I am writing O_2 ? Since it is a lean combustion. So, oxygen will be in the products, then you do the balancing of atoms.

So, it says then we will find out $b = 8; c = 9; d = 51.7; e = 1.25$. Then this air fuel ratio now becomes $AF = \frac{12.5 \times 1.1 + 12.5 \times 1.1 \times 3.76}{1} = 65.45 \text{ kmol air/kmol fuel}$

Then A by F in terms of ratio will be $\frac{A}{F} = 65.45 \times \frac{28}{118} = 16$. So, we have air fuel ratio for 100 percent theoretical air is 16, stoichiometric air is 14. So, equivalence ratio

$$\phi = \frac{\left(\frac{A}{F}\right)_{stoich}}{\left(\frac{A}{F}\right)} = \frac{14.6}{16} = 0.9$$

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Numerical Problems

Q2. A mixture of 0.2 kg of carbon dioxide (molecular weight 44) and 0.3 kg of nitrogen (molecular weight 28) is compressed from initial state (1 bar, 310 K) to a pressure of 3 bar in a polytropic process with index of compression as 1.25. Take the universal gas constant as, 8.314 kJ/kmol. K Calculate, (a) the apparent molecular weight of mixture; (b) the final temperature; (c) compression work.

Soln

$CO_2: (0.2 \text{ kg}), (MW) = 44$] Total mass = $m = 0.5 \text{ kg}$
 $N_2: (0.3 \text{ kg}), MW = 28$

$\eta_{CO_2} = \frac{m_{CO_2}}{(MW)_{CO_2}} = \frac{0.2}{44} = 0.0045 \text{ kmol}$. $\eta_{N_2} = \frac{m_{N_2}}{(MW)_{N_2}} = \frac{0.3}{28} = 0.0107 \text{ kmol}$

(a) $(MW)_{mix} = \frac{m}{\eta_{CO_2} + \eta_{N_2}} = \frac{0.5}{(0.0045 + 0.0107)} = 32.9$

(b) Polytropic Compression, $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$. $\gamma = 1.25$
 $P_1 = 1 \text{ bar}$. $P_2 = 3 \text{ bar}$.
 $T_1 = 310 \text{ K}$.
 $\Rightarrow T_2 = (3)^{\frac{0.25}{1.25}} \times 310 = 386 \text{ K}$.

(c) $w = \int PdV = \frac{m R T}{1-\gamma} = \frac{m \left(\frac{R}{MW}\right) DT}{1-\gamma} = \frac{0.5 \left(\frac{8.314}{32.9}\right) (386 - 310)}{1 - 1.25}$
 $\Rightarrow w = -38.5 \text{ kJ}$

The next problem is something like its a mixture of CO_2 and nitrogen and they are compressed in a medium from its initial state 1 bar, 300 kelvin to 3 bar pressure through a

polytropic compression process of with index of compression as 1.25. So, we need to find out the apparent molecular weight of mixture, final temperature and compression work.

So, this is a kind of a problem which is a mixture at the same time this mixture typically is not reacting, but what we need to find out this apparent molecular weight. So, while dealing with our combustion course we try to find out the correlation between molecular weight, mole fractions and mass fractions. So, with that concept the problem needs to be solved.

$$CO_2: 0.2 \text{ kg}, MW = 44; \quad N_2: 0.3 \text{ kg}, MW = 28; \quad \text{Total mass } m = 0.5 \text{ kg}$$

But we do not know what is the total number of moles.

$$n_{CO_2} = \frac{m_{CO_2}}{(MW)_{CO_2}} = \frac{0.2}{44} = 0.0045 \text{ kmol}; \quad n_{N_2} = \frac{m_{N_2}}{(MW)_{N_2}} = \frac{0.3}{28} = 0.0107 \text{ kmol}$$

So, we require apparent molecular weight. So, the first answer we can write that apparent molecular weight as

$$(MW)_{mix} = \frac{m}{n_{CO_2} + n_{N_2}} = \frac{0.5}{0.0045 + 0.0107} = 32.9$$

Now, this mixture is compressed. Now when it is compressed from this initial state to final states and the process is a polytropic compressions. So, for polytropic compression we can write the expressions as

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \quad (\because n = 1.25)$$

$$T_2 = 310 \times \left(\frac{3}{1}\right)^{\frac{0.25}{1.25}} = 386 \text{ K}$$

So, final temperature is known as we got as 386 K. So, compression work. So, compression work w can be written as integral of $p dv$ and this expression can be written as $\frac{mR\Delta T}{1-n}$. So, by assuming this mixture to be an ideal gas, but here R is not known. So, because it is a characteristics gas constants. So, it has to be replaced with \bar{R}/M .

$$W = \frac{m(\bar{R}/M)\Delta T}{1-n} = \frac{0.5 \left(\frac{8314}{329}\right) (386 - 310)}{1 - 1.25} = -38.5 \text{ kJ}$$

This minus signs is there because it is a compression work. And this minus sign arises because you have used 1 minus 1.25.

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Numerical Problems

Q3. A multi-component system consists of a mixture containing hydrogen (H₂), oxygen (O₂) and nitrogen (N₂) with mole fractions of 0.14, 0.18 and 0.63, respectively. The binary diffusivities between species are; $D_{H_2-O_2} = 2.5 \text{ cm}^2/\text{s}$; $D_{H_2-N_2} = 2.4 \text{ cm}^2/\text{s}$; $D_{N_2-O_2} = 0.7 \text{ cm}^2/\text{s}$. Calculate the effective binary diffusion coefficient for species H₂, O₂ and N₂.

Effective binary diffusion coefficient in a mixture,

$$D_{i-m} = \frac{1 - X_i}{\sum_{j=1}^n \frac{X_j}{D_{ij}}}$$

Solution

$$D_{H_2-m} = \frac{1 - X_{H_2}}{\frac{X_{O_2}}{D_{H_2-O_2}} + \frac{X_{N_2}}{D_{H_2-N_2}}} = \frac{1 - 0.14}{\left(\frac{0.18}{2.5}\right) + \left(\frac{0.63}{2.4}\right)} = 2.57 \text{ cm}^2/\text{s}$$

$$D_{O_2-m} = \frac{1 - X_{O_2}}{\frac{X_{H_2}}{D_{O_2-H_2}} + \frac{X_{N_2}}{D_{O_2-N_2}}} = \frac{1 - 0.18}{\left(\frac{0.63}{0.7}\right) + \left(\frac{0.14}{2.5}\right)} = 0.86 \text{ cm}^2/\text{s}$$

$$D_{N_2-m} = \frac{1 - X_{N_2}}{\frac{X_{H_2}}{D_{N_2-H_2}} + \frac{X_{O_2}}{D_{N_2-O_2}}} = \frac{1 - 0.63}{\left(\frac{0.14}{2.4}\right) + \frac{0.18}{2.5}} = 1.17 \text{ cm}^2/\text{s}$$

The third problem is going to introduced with a concept of binary diffusion coefficients. So, in a multi-component systems which is a mixture of hydrogen, oxygen and nitrogen. So, each of them has their own mole fractions. And binary diffusion among them is also given we need to find out the effective binary coefficients for the species in the mixtures.

So, we can recall the expression for effective binary diffusion coefficient in a mixture how do you write them in terms of i j. So, i stands for any species, m stands for mixtures.

$$D_{im} = \frac{1 - X_i}{\sum_{j=1}^n \frac{X_j}{D_{ij}}}$$

And if you say want to find the hydrogen. So, the j would be for nitrogen and oxygen. So, this is the general expressions.

$$D_{H_2,m} = \frac{1 - X_{H_2}}{\frac{X_{O_2}}{D_{H_2O_2}} + \frac{X_{N_2}}{D_{H_2N_2}}} = \frac{1 - 0.14}{\frac{0.18}{2.5} + \frac{0.63}{2.4}} = 2.57 \text{ cm}^2/\text{s}$$

$$D_{O_2,m} = \frac{1 - X_{O_2}}{\frac{X_{H_2}}{D_{O_2H_2}} + \frac{X_{N_2}}{D_{O_2N_2}}} = \frac{1 - 0.18}{\frac{0.63}{0.7} + \frac{0.14}{2.5}} = 2.86 \text{ cm}^2/\text{s}$$

$$D_{N_2,m} = \frac{1 - X_{N_2}}{\frac{X_{H_2}}{D_{N_2H_2}} + \frac{X_{O_2}}{D_{N_2O_2}}} = \frac{1 - 0.63}{\frac{0.14}{2.4} + \frac{0.18}{2.4}} = 1.17 \text{ cm}^2/\text{s}$$

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Numerical Problems

Q4. A spherical fuel droplet with its initial diameter of 0.1 mm evaporates in a combustion medium by assuming D^2 law. If the evaporation constant is $5.8 \times 10^{-7} \text{ m}^2/\text{s}$, calculate the life time of fuel droplet.

Handwritten solution:

Soln
 $D^2 = K \cdot t$
 Droplet
 Life time, $t_d = \frac{D_0^2}{K}$
 $t_d = \frac{(0.1 \times 10^{-3})^2}{5.8 \times 10^{-7}}$
 $\Rightarrow t_d = 0.01724 \text{ s} \approx \underline{\underline{17.24 \text{ ms}}}$

$K = 5.8 \times 10^{-7} \frac{\text{m}^2}{\text{s}}$  $D = 0.1 \text{ mm}$

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So, next problem is on droplet evaporation or simply it follows this D square law. So, initially there is a spherical droplet whose diameter is 0.1 mm and it evaporates for which the evaporation constant is given. So, by D square law we find out droplet lifetime is defined as $t_d = D_0^2/K$ where K is evaporation constant that is 5.8×10^{-7} meter square per second and D is given.

$$t_d = \frac{D_0^2}{K} = \frac{(0.1 \times 10^{-3})^2}{5.8 \times 10^{-7}} = 0.01724 \text{ s}$$

So, after simplifying we say t_d is approximately 17.24 milliseconds, which says that during a droplet evaporation process the lifetime of the droplets is hardly about 17 milliseconds or close to 20 milliseconds.

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Numerical Problems

Q5. A premixed laminar flame is stabilized in a one-dimensional gas flow where the vertical velocity (v_u) of unburnt mixture varies linearly with horizontal distance (x) as per the following data: $x = 0$; $v_u = 0.5$ m/s and $x = 0.02$ m; $v_u = 0.9$ m/s. If the flame speed is 0.4 m/s, then find the local angle that the flame sheet makes with vertical plane at $x = 0.01$ m.

Soln

$x = 0$ $v_u = 0.5$ m/s.
 $x = 0.02$ m, $v_u = 0.9$ m/s.

Linear

$$v_u = (v_u)_{x=0} + \left[\frac{(v_u)_{x=0.02} - (v_u)_{x=0}}{0.02} \right] x$$

$$v_u = 0.5 + \left(\frac{0.9 - 0.5}{0.02} \right) x = 0.5 + 20x$$

Laminar flame speed, $S_L = v_u \sin \alpha$ $\Rightarrow \sin \alpha = \frac{S_L}{v_u} = \frac{0.4}{0.7}$
 $\Rightarrow \alpha = \sin^{-1} \left(\frac{0.4}{0.7} \right)$
 $\Rightarrow \alpha \approx \underline{\underline{34.85^\circ}}$

$S_L = 0.4$ m/s
 $x = 0.01$ m
 $v_u = 0.5 + (20 \times 0.01)$
 $\Rightarrow v_u = 0.7$ m/s.

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So, this next problem is about pre-mixed laminar flame. So, the statement says that a premixed laminar flame is stabilized in an one-dimensional glass flow, the vertical velocity v_u of the unburnt mixture varies linearly with distance. So, as per the following data. So, data that is given $x = 0$, $v_u = 0.5$ m/s; $x = 0.02$ m, $v_u = 0.9$ m/s.

So, this is linear that is given. Then we can find out the equation for this vertical velocity component

$$v_u = (v_u)_{x=0} + \frac{(v_u)_{x=0.02} - (v_u)_{x=0}}{0.02} x = 0.5 + \left(\frac{0.9 - 0.5}{0.02} \right) x = 0.5 + 20x$$

So, vertical velocity of unburned mixture varies linearly with x with this equation and what we need to find out local angle that flame sheet makes.

So, we can recall that laminar flame speed $S_L = v_u \sin \alpha$. So, from this we required this local angle α .

$$\sin \alpha = \frac{S_L}{(v_u)_{x=0.01}} = \frac{0.4}{0.5 + 20 \times 0.01}; \alpha = 34.85^\circ$$

So, the local angle that makes flame sheet with the vertical flame is 34.85 degree.

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Numerical Problems

Q6. It is desired to calculate the laminar flame speed for a spark ignition engine operating with gasoline mixture with the following experimental correlation. The engine operating pressure and temperature conditions are, 15 atm and 585 K, respectively. Take the reference pressure and temperature as 1 atm and 298 K. Calculate the laminar speed.

$$S_L = 20 \left(\frac{T}{T_{ref}} \right)^{2.2} \left(\frac{P}{P_{ref}} \right)^{-0.2} ; S_L \text{ in cm/s}$$

Handwritten solution:

Soln

$$S_L = 20 \left(\frac{585}{298} \right)^{2.2} \left(\frac{15}{1} \right)^{-0.2}$$

$p = 15 \text{ atm}$
 $T = 585 \text{ K}$

$$\Rightarrow S_L = \underline{\underline{0.5 \text{ m/s}}}$$

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The next problem is on a laminar speed correlation for an experimentally verified data and or you can say this experimental correlation of laminar flame speed is related to pressure and temperature of the medium and with respect to that of reference pressure and temperatures.

So, we have these conditions of pressure and temperature is given. So, p is given as 15 atmosphere, T is given as 585 K, then it is very easy that we need to find at this pressure and temperature conditions what is this laminar flame speed. Reference condition is 1 atmosphere and 298 K.

$$S_L = 20 \left(\frac{585}{298} \right)^{2.2} \left(\frac{1.5}{1} \right)^{-0.2} = 0.5 \text{ m/s}$$

So, after simplifying we need to find the laminar flame speed through an experimental observation of that condition pressure and temperature as 0.5 meter per second.

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Numerical Problems

Q7. In an engine test with isooctane (C_8H_{18}) fuel, the following exhaust products are measured. CO_2 : 12.5%; CO : 0.1%; O_2 : 2%; NO : 76 ppm; C_6H_{14} (hexane equivalent): 250 ppm. All concentrations are by volume on dry basis. Calculate, the emission index (gram/kg of fuel) of unburned hydrocarbons expressed equivalent to hexane.

Quantification of pollutants

$$(EI)_{C_6H_{14}} = \left(\frac{X_{C_6H_{14}}}{X_{CO} + X_{CO_2}} \right) \left(\frac{x (MW)_{C_6H_{14}}}{(MW)_{C_8H_{18}}} \right)$$

$$(EI)_{C_6H_{14}} = \left[\frac{(250 \times 10^{-6})}{0.001 + 0.125} \right] \left(\frac{8 \times 86}{114} \right)$$

$$(EI)_{C_6H_{14}} = 0.01197 \text{ ug/ug of fuel.}$$

$$(EI)_{C_6H_{14}} = 12 \text{ gm/ug of fuel}$$

Quantification of pollutants

$$(MW)_{C_6H_{14}} = (6 \times 12) + 1 \times 14 = 86 \text{ ug/kmol.}$$

$$(MW)_{C_8H_{18}} = (8 \times 12) + 18 \times 1 = 114 \text{ ug/kmol.}$$

$$X_{CO} = 0.1\% = 0.001$$

$$X_{CO_2} = 12.5\% = 0.125$$

$$X_{C_6H_{14}} = \frac{250 \times 10^{-6}}{1}$$

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And the last problem that we are looking at the problem with respect to quantification of pollutants, which says in an engine test which is engine is running with isooctane as a fuel, this fuel when it releases the combustion products it releases CO_2 as 12.5 percent, CO as 0.1 percent, O_2 as 2 percent, NO as 76 ppm.

And soot particles or carbon particles normally represented in hexane equivalent. So, in this hexane equivalent means we can say that number of carbon particles is 6. So, that is given as 250 ppm. And all of them are dry volume basis. Now, we need to find out emission index of unburned hydrocarbons expressed equivalent to hexane.

So, basically this is another way of quantifications for unburned hydrocarbons. So, by definition if you want to find out this emission index, we write its definition emission index of we can say unburned hydrocarbons equivalent to hexane.

$$EI_{C_6H_{14}} = \left[\frac{X_{C_6H_{14}}}{X_{CO} + X_{CO_2}} \right] \left[\frac{x(MW)_{C_6H_{14}}}{(MW)_{C_8H_{18}}} \right]$$

$$(MW)_{C_6H_{14}} = 6 \times 12 + 1 \times 14 = 86 \text{ kg/kmol}$$

$$(MW)_{C_8H_{18}} = 8 \times 12 + 1 \times 18 = 114 \text{ kg/kmol}; \quad x = 8$$

$$X_{CO} = 0.1\% = 0.001; \quad X_{CO_2} = 0.125; \quad X_{C_6H_{14}} = 250 \times 10^{-6}$$

So, after simplifying it, we write $EI_{C_6H_{14}} = 0.01197 \text{ kg/kgfuel}$. And a better approach for this quantification is writing in terms of grams. So, it will be about 12 grams of C_6H_{14} per kg of fuel, which means that emission index is 12 grams of unburned hydrocarbons equivalent to hexane with respect to unit kg of fuel that is C_8H_{18} isooctane.

So, with this I conclude this syllabus and I conclude this tutorial sessions. I hope you have we all have enjoyed this course, subsequently down the line we will have another live session class, where learners are requested to frame their questionnaires, which can be clarified.

And towards the end of this course, we will have final exams and the learners are requested to do all kinds of problems that has been derived during the lecture sessions as well as the tutorial sessions. And you can take them as a benchmark of question banks, which will be definitely useful for the final exams.

Thank you and best wishes for your future. With this let us close this course.

Thank you for your attention.