Advanced Thermodynamics and Combustion
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Lecture - 33
Tutorial 1

Dear learners, greetings from IIT, Guwahati. We are in the MOOC's course, Advanced Thermodynamics and Combustion till this point of time we have completed all the lectures for this course. Now, in another subsequent lectures I will be explaining some learning components or some important points that we have learnt so far from this course. At the same time, we will try to solve some numerical problems, which will be useful for building the concept of this course.

And also it will add towards the benefit of the final examinations. So, if I divide this course in two parts; one is thermodynamics parts, which is being advanced version, other component for this course is combustions. So, in today's lectures I will be focusing on mainly the learning modules from the topic advanced thermodynamics. So, let us understand that what are the topics what we have learnt so far in this course.

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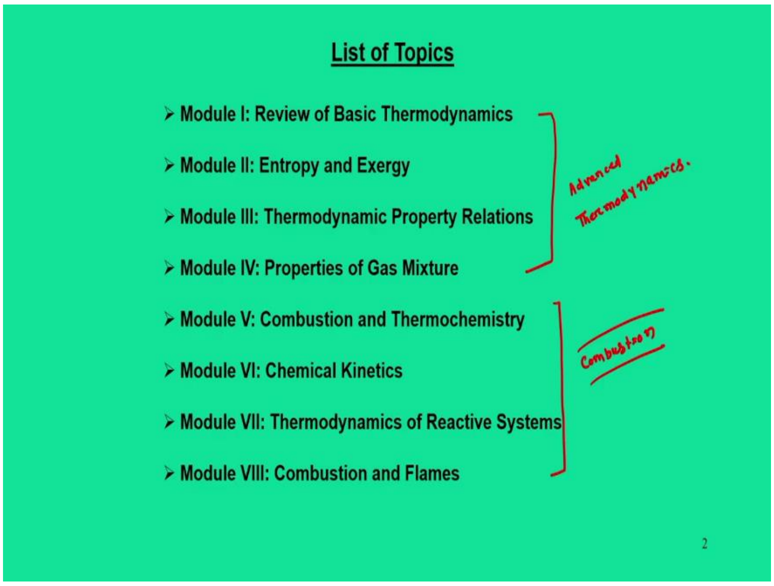

So, in the Ist module, we had discussed the review of basic thermodynamics. IInd module was focused mainly on entropy and exergy. IIIrd module was based on thermodynamic property relations. And in fact, this particular model is highly mathematical in nature, because it requires the knowledge of partial differential equations to derive the thermodynamic equations.

In the IVth module we have properties of gas mixture. So, these four parts basically constitutes mainly the advanced thermodynamics part. Why I say advanced thermodynamics parts? Because, we have seen this course already at UG level and the approach in which the concept of the course was completely different.

Here we mainly focus on advanced topic that is mainly related towards the research purpose at the same time analysis of other important components mainly in the areas of entropy and exergy, which finds a great deal of applications with respect to IC engines.

Then there are certain situations, which requires the knowledge of different gas models. So, mainly till this point of time, we have focused on ideal gas models. So, the concept of different real gas models was also introduced. This is the additional components, which was added in this course. And the second part of this course that is from module Vth to module VIII that is mainly dealt with the combustion.

Combustion is one of the important fundamental topics, which is used in our day-to-day life, but unfortunately the basic course of combustions is normally absent in most of the syllabus. So, with this view point in this particular course, we have added the basics of combustions and mainly which is inclined for the thermodynamic parts of the combustions.

So, we start with combustion and thermo chemistry then during this combustion reactions we study its chemical kinetics. Then in the next module, we studied the thermodynamics of reactive systems, because the combustion is nothing but the fuel and air, when they burn it gives rise to combustion products.

So, if this reaction takes place in which direction the reaction should proceed, what is the thermodynamic relations for which the reaction should proceed, which is mainly dealt with the knowledge of entropy calculations. So, this is all about the thermodynamic parts.

And the last module that is module VIII, we discussed about the combustion and flames. In fact, this is one of the practical applications, where we dealt with different types of combustions. So, we have laminar flame propagation, we have diffusion flame, we have droplet burning, we have droplet evaporation all these concepts were taught in the last module.

So, this is all about the overview of this course. In fact, this overview I have already given in the beginning of the course and at the end of this course I am just trying to the collate all the information and try to see what are the different learning components in each module.

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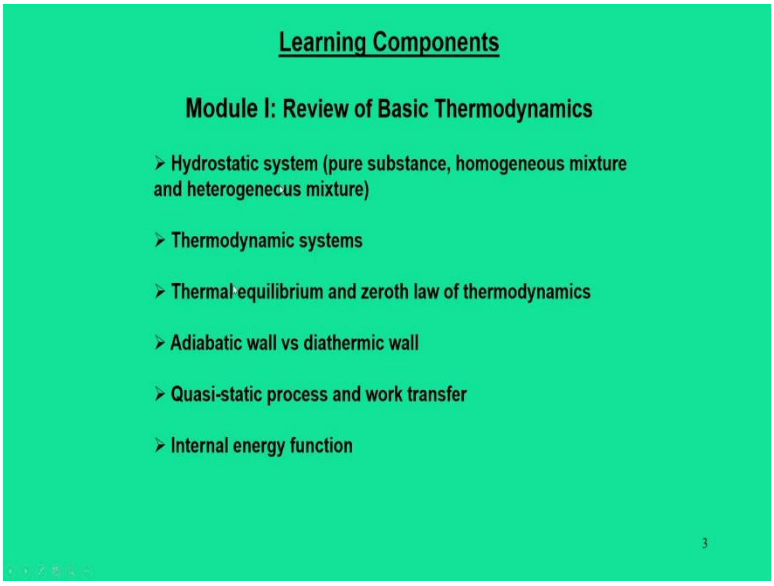

Now, to segregate module wise, when you talk about the review of basic thermodynamics there, we learnt about hydrostatic systems mainly it is a compressible system and where we also studied the pure substance, homogeneous mixtures, heterogeneous mixtures.

Then, moving to the thermodynamic systems, where we all know system surroundings, environment, universe all this concept was taught. At the same time, we also know the closed systems, open system then we have property of the systems all these things are discussed. Then, moving towards the laws of thermodynamics, the first law that we are introduced is the zeroth law of thermodynamics.

And in fact, it talks about the concept of thermal equilibriums. Then, we introduced two types of wall, although it is a wall, but physically it is not an wall it is like a word that is used in the thermodynamic viewpoint that talks about how the information of work and heat is being propagated in a medium.

So, if you say adiabatic wall the complete closure of heat transfer is ensured; that means, no information of energy due to heat cannot be propagated. But, if you say diathermic wall complete information of work and heat can be possible through a diathermic wall. So, this is nothing but the conceptual viewpoint. Then, we introduced the quasi-static process work transfer then, we introduced internal energy function.

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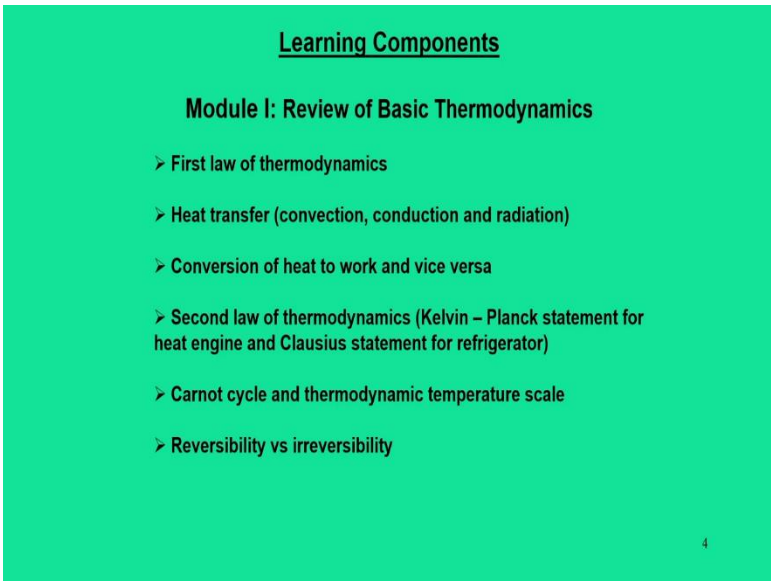

Now, while talking about internal energy functions, we also come across the first law of thermodynamics. So, the first law of thermodynamics nothing but the equalization of work transfer with internal energy function with additional heat transfer. But, the question is that, why that heat transfer has to come?

So, basically, during an energy interaction process, if the total energy transfer due to work and due to heat if they are not equal then, it is closely related with the internal energy functions or I mean the total energy transfer due to work and heat, they are equalized through this internal energy functions, this is nothing but the first law of thermodynamics.

Now, talking about heat transfers, the energy transfer due to heat if it has to happen then it has to be done through temperature difference. Now, with the view point of work and energy transfer I would like to emphasize that most of the work transfer we say it during a quasi-static process, it is regarded as integral of PdV.

Now, if the work transfer is not possible and if it has to be any other energy transfer due to work if it is not possible then, it can be regarded as heat transfer. And heat transfer mainly occurs due to the temperature difference. So, looking at the mode of heat transfer or transfer of energy through heat, we have modes like convection, conduction and radiations.

So, these are the different modes of heat transfer those accounts for the energy balance while formulating the first law of thermodynamics. Then, we move to the complete conversion of heat to work and vice versa. Now, while talking about the first law of thermodynamics, we emphasize that heat and work although they have different mode of energy transfer, but there is no difference in terms of quantifications. For example, unit of heat and work they are same.

So, in other words, first law does not differentiate the energy as heat or work. So, thereafter the second law of thermodynamics comes into pictures, which talks about the spontaneous process of energy transfer. Now, in a spontaneous process is possible only when a system can follow in a certain direction.

So, directionality of a system is introduced through the second law of thermodynamics. So, here two points that needs to be emphasized, first thing it emphasizes that work is a high-grade energy for which complete conversion of work to any other mode is possible. And heat is a low-grade energy in which complete conversion of heat is not possible.

Now, if we want to find the convert heat to work mode; that means, from low grade energy you have to convert to high grade energy then, we must reject some of the heat to the surroundings. And thereby we can transfer only certain quantities or certain percentage of this heat into work.

And this process will be ensured through a Carnot cycle, which is a hypothetical theoretical cycle. Then, based on that some workable models for second law of thermodynamics comes into picture, which talks about concept of heat engines and refrigerators; so, heat engines are like work producing devices whereas, refrigerators and air conditioning systems they are work consuming devices.

Now, based on this concept the Kelvin-Planck statement and Clausius statement was formulated. Another important aspect of the second law that it introduces the thermodynamic temperature scales. Normally, prior to the second law, when the temperature was measured it was measured either in a degree centigrade or degree Celsius or degree Fahrenheit.

And this temperature measurement was mainly based on the fact that there is a working fluid, which comes into picture based on the limiting situation of this working fluid temperature was quantified. But, while talking about second law of thermodynamics it introduces a new temperature scale, which is called kelvin scale and this kelvin scale is independent of the working fluid of the substance while measuring the temperature.

Now, because of this reason the kelvin scale is regarded as the most appropriate and universal scale in SI system. The next important aspect of this second law is the concept of reversible and irreversible process. So, second law emphasizes the fact the need of a spontaneous process; that means, a system can undergo in a particular directions reverse direction is not possible.

So, if a system can undergo in both the directions; that means, the path or traces that it makes while going from state point one to state point two if it follows this exactly same path, then we call this as a reversible process. And we say reversibility is the very fundamental word to define this its characteristics. But, if the process is not irreversible then, we call regard it as a irreversibility.

There are many sources of irreversibility, externally irreversibility, internal irreversibility then chemical irreversibility, which we have emphasized in our discussions. And in each of these cases, we have given some examples like heat transfer from a reservoir another can be work done during a free expansion process or free expansion process is another situations, where we quantify the heat transfer as well as work transfer.

And based on this, we find the nature of irreversibility that affects during the spontaneity of a given process.

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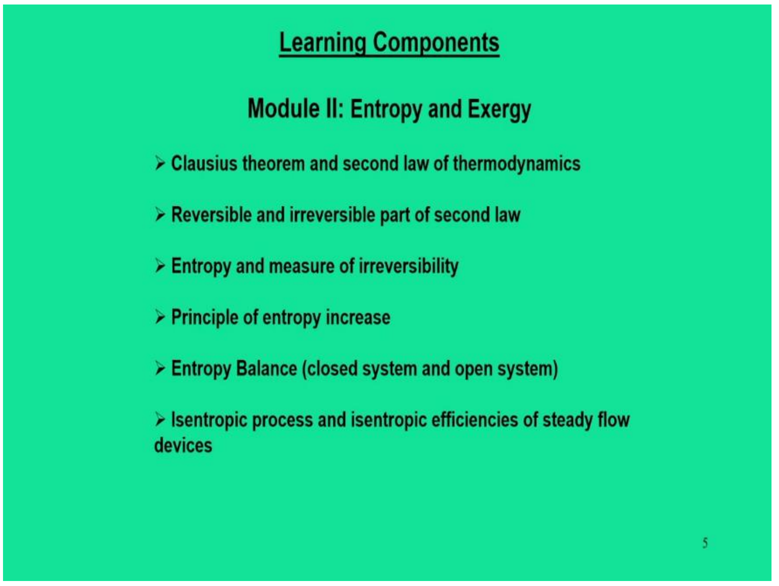

Then, in the next module, which is very important topics as far as this module is concerned. And in fact, almost this lecture was for two weeks and almost we have covered all the important aspects of entropy and exergy. The concept of entropy was introduced as a part of second law and this concept was continued for two important situations one is for reversible part, other is for irreversible part.

Now, to give a mathematical indications for this property, we started with Clausius theorem with Clausius inequality equations, there we consider the reversible part of the Clausius equality. And after doing so, we define the term entropy then while looking at the irreversibility part, we framed the equation which is called as a entropy generations.

And this entropy generation we say, it is a measure of irreversibility in a medium. Then, it is followed by entropy balance; that means, for a closed system and open systems we frame the equations for entropy balance. Then, we introduce the concept of principle of entropy increase. In fact, it talks about that entropy of universe always increases.

Now, to give a thermodynamic view point or estimate for practical applications, we define the process, which is commonly known as isentropic process then, introduce the terms like isentropic efficiencies for different steady flow components. In fact, part of this analysis was also covered at the UG level there we have turbines, compressors, nozzles, heat exchangers, we can apply these equations.

Now, with this entropy formulations, we can correlate the information of heat through the second law. The other important part of module II is exergy.

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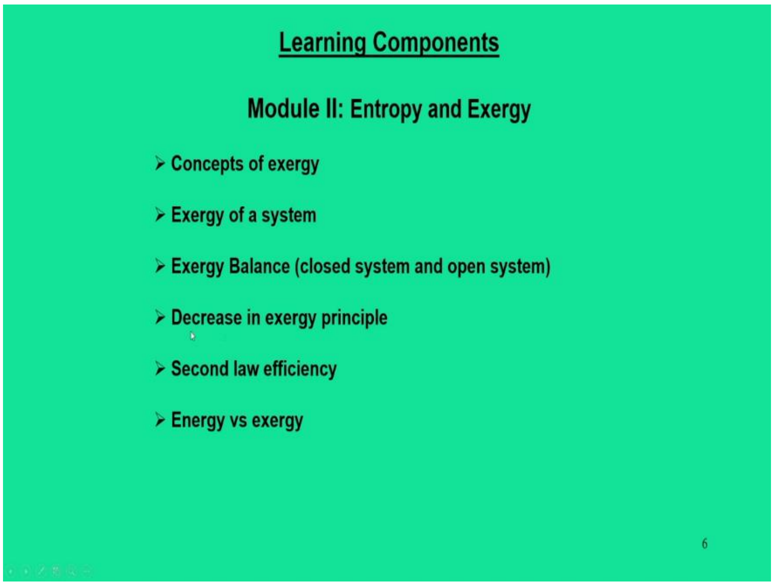

Exergy is nothing but the maximum work that can be extracted from a given systems. Now, in our all our previous discussions, when you dealt with work or heat transfer, we never bring surrounding into picture. Now, whether a system in reality gives the best of its performance or not to account for this fact, we define the term exergy.

And exergy is nothing but the maximum work that can be recovered through a work producing device or minimum work that can be consumed for a work consuming device while taking into consideration about the state of the environment.

So, for that the exergy of all kinds of heat modes of heat transfer can be quantified. Exergy of work transfer can be found out, exergy of kinetic energy, potential energy, corresponding exergy term can be evaluated, exergy of heat transfer can also be evaluated. So, based on this, we define the exergy of the system. Then, the similar analogy was made for exergy balance.

So, likewise we made the analysis of entropy balance we also analyze the exergy balance for the closed system as well as open systems. Now, while looking at this exergy one important thing is that while we deal with energy and exergy, exergy always decreases, but energy is always conserved.

So, this is the very fundamental difference between energy and energy, but energy can be considered as work mode or heat mode, but exergy is always interpreted as a work mode. Because, it is the maximum work that can be extracted from a given systems while considering surroundings into account.

So, in a similar analogy of increase in the entropy principles, we also have the reverse expression that is decrease in the exergy principles and this will add to another term, which is called as a second law efficiency. Because, in the first law during Carnot efficiency it talks about the efficiency of engines and in which we say that the work that is recoverable from heat.

But, while talking about second law, the work that will be recovered from a given systems while taking into consideration of the surroundings, which is at a dead state. So, second law efficiency was defined.

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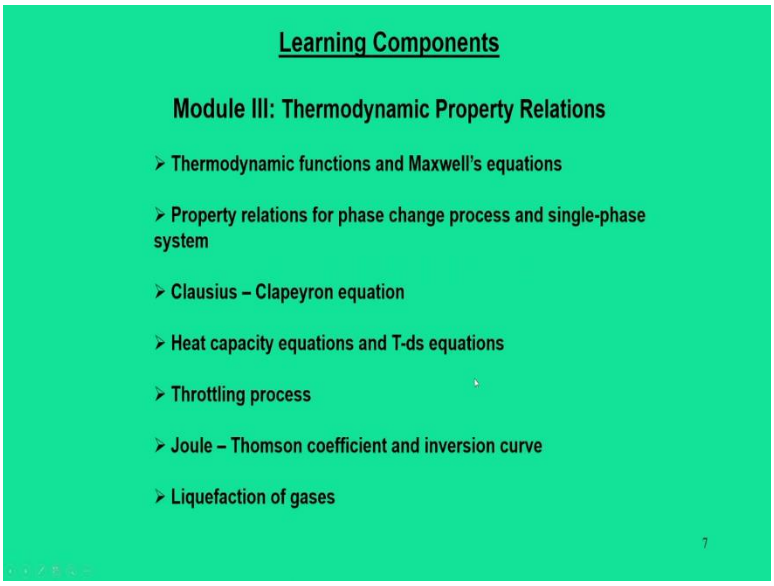

Then, the IIId module, which is the thermodynamic property relations. So, prior to this we have talked about the pure substance and its basically speaking that, when you deal with the thermodynamic property relations here, we are trying to interpret the all the thermodynamic behavior or properties and try to find out the correlation among the properties.

Because, normally thermodynamic systems are interpreted as a compressible medium, where temperatures, specific volume, entropy, density enthalpy, internal energy all these properties are defined. Then, what is relations among these properties? To find this this, particular module was designed and where we define thermodynamic functions and in particular we derived this Maxwells equations.

There are 4 Maxwell equations and through these 4 maxwell equations, we derived about 16 thermodynamic relations. And these relations are mathematical in nature, but they can be used as and when they are being recalled for a given practical applications. Now, while using these equations, we have applied this property relations mainly for two situations for a phase change process and for a single-phase systems accordingly equations also were derived.

One more important application for a phase change process is Clausius-Clapeyron equations. And in fact, it is a very widely used equations during a phase change process. And this equation helps us in designing the property diagrams of pure substance. Then moving further, we derived the heat capacity equations involving cp cv relations. And these are actually general relations and subsequently these relations were simplified for an ideal gas.

Then we have T-ds equations that we all know there are two fundamental T-ds equations that is based on first law and second law analysis. One of the practical applications of these thermodynamic property relations is towards the liquefaction of gases. Normally, when we liquefy the gases there are certain situations, we require the gases has to be stored in a liquefaction conditions.

For example, when the space shuttle goes to the higher altitudes it carries the fuel as well as oxidizers and this fuel is typically is nothing but hydrogen and oxidizers also is nothing but the oxygen. And while taking them in a gaseous mode we require a very large size because, energy density for the gases is less.

So, you require a large volume. So, for those reasons those fuels and oxidizers like hydrogen and oxygen they have to be liquefied and stored. And the concept of liquefying the gases into liquids deals with the process which is known as throttling. During throttling process normally, we decrease this pressure at the same time we have to see whether temperature increase or decrease. So, this quantification was done through a parameter, which is known as Joules-Thomson coefficient. So, in fact, it gives a graphical representations of pressure temperature curve for given substance, which is known as the inversion curve.

And this inversion curves are the basics for liquefaction of the gases. And during these liquefactions, we can get the highest yield when the Joule-Thomson coefficient value is zero; that means, we have to follow the inversion curve for maximum yield during a liquefaction process.

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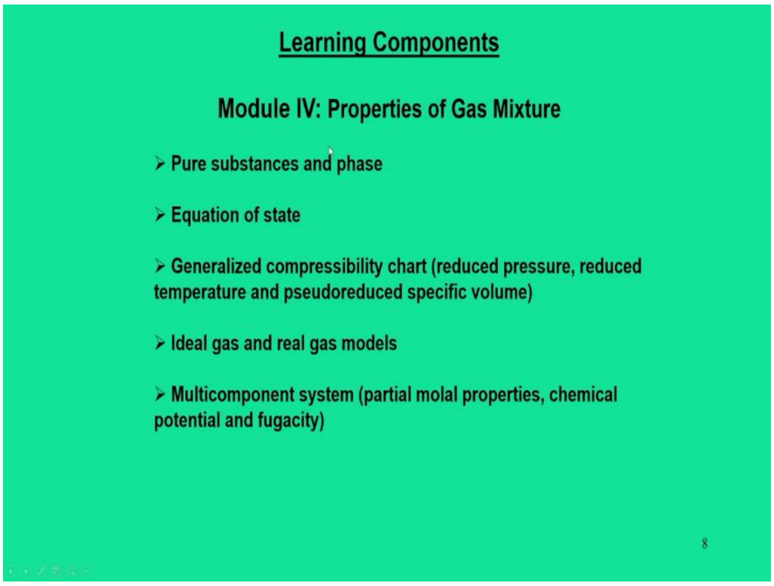

Then, in the model IV, we move to properties of gas mixtures; that means, whatever equations that we are derived from the thermodynamic property relations that was carried forward to define for various applications. So, while talking about the gas mixtures, we can have ideal gas, we can have a real gas. So, one way to interpret this ideal and real gas is to find the equation of state.

So, initially this equation of state was represented through virial equation of states that involves the expansion relations among pressure volume and temperatures. But, later point of time we found the various real gas models that involves the Van der Waal gas models then, Redlich- Kwong equation model which are highly used for variety applications.

But, apart from this, we have ideal gas equation model, which gives a simple pressure volume and temperature relations through the gas constant or universal gas constant.

Before you do that to quantify this real gas models in a graphical manner or to simplify this, generalized compressibility chart was introduced.

So, where we found the parameters like reduced pressure, reduced temperature, pseudo specific volume all these parameters were defined in a non dimensional form, where all the pure substances they are brought into a common platform, which gives the generalized compressibility chart and it is nothing but the plot between the compressibility factor versus reduced pressure at various reduced temperatures.

So, this will help us in finding the compressibility factor for any kind of real gas. And this will give a indication that how far we deviate from this ideal gas model? Now, to analyze all these gas mixtures, we define this called as a multi component systems and this multi component system in general is that a gas it can have a multiple number of gases or system may be at different phase liquid or gas phase or it may be mixture or it may be a solution.

So, various possible combinations are can be done. But more details analysis is inclined for the chemical thermodynamics parts, but; however, in this course, we have given some basic concepts for a multi component systems by introducing the properties like partial molal properties, chemical potential, fugacity, all these things were covered in this course.

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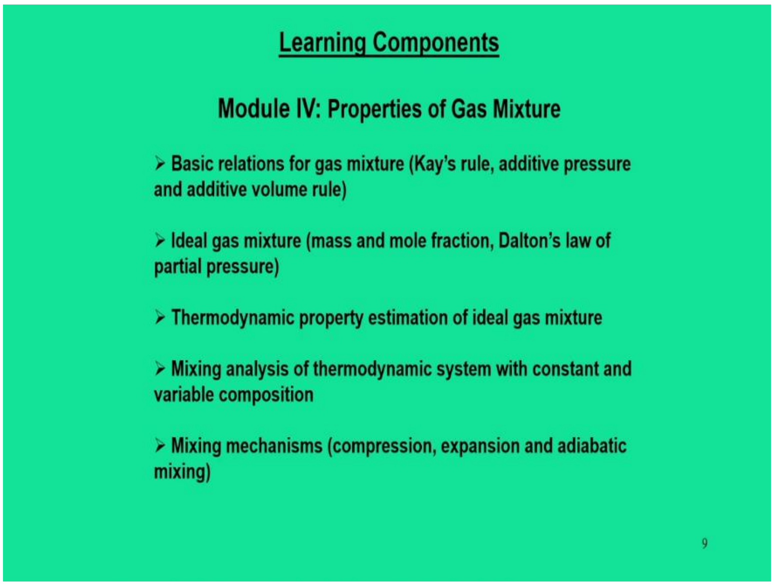

In addition to that for a multi component systems, we define the rules of gas mixture that is Kay rules, additive pressure and additive volume rules. And this gas mixtures model can be simplified if we assume this gas to be an ideal gas. So, by considering mole and mass fractions, we can find out the expressions for Dalton's law of partial pressure.

And in fact, in reality this the approach or the assumption of ideal gas mixtures has a tremendous advantage in simplifying the mathematical equations or expressions. Then, for this ideal gas mixture we also find out the how we can find the global thermodynamic property estimation for a mixture.

So, a mixture may have multiple number of components, but when all these components are mixed together how they behave? If they behave as if they were in ideal gas then, what would have been its combined internal energy, combined specific heat, combined enthalpy that has to be calculated through the individual share of each of these gases.

Then, moving further for application side the mixing analysis can also be interpreted with respect to constant compositions or variable compositions means, the composition of the mixture was known initially, when it is done, other situation is that two gases they come from two separate entities and they mix together.

So, there we call this as a mixture of variable compositions. Now, this mixing process can be analyzed for a compression process, expansion process, adiabatic mixings, these are the things that we discussed in the module IV.

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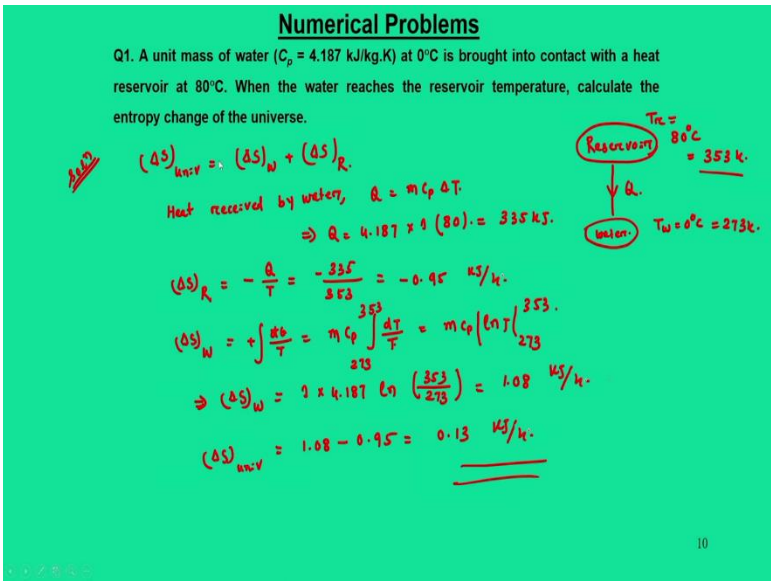

So, in the next section I will be discussing about the other modules, but till this point of time up to module IV, whatever contents we have covered if I try to consolidate through some numerical approach or problem solving approach how I should do.

So, in this backdrop you can think of some question bank or some solutions or some problems that needs to be solved during the examinations. And in the benefit of learners, I am trying to explain some favorable problems that can be attempted during the examinations.

So, the first problem talks about the entropy because this comes from the topic entropy, it is a very simple problem that, when the unit mass of water for which specific heat is given at 0 degree Centigrade is brought to contact with a heat reservoir at 80 degree Centigrades then, we need to find out the what is the change of the entropy of the universe.

To solve these problems, we have to recall this entropy equations first. But, before you do that if I draw this thermal diagram. Now, this reservoir this reservoir is at 80 degree Centigrade. So, I say $T_r = 80C = 353K$. Now, it is in contact with water.

So; this water is at 0 degree Centigrade that is 273 kelvin. So, obviously, heat will flow from reservoir to water. Now, during this process, we have surroundings. So, we can calculate this entropy change for the universe.

$$\Delta s_{univ} = \Delta s_W + \Delta s_R$$

So, heat received by water, we can calculate this $Q = mC_p\Delta\text{T} = 1 \times 4.187 \times 80 = 335\ kJ$. Now, let us calculate, what is Δs_R, because reservoir is at uniform temperatures. So, its heat is losing.

$$\Delta s_R = -\frac{Q}{T} = -\frac{335}{353} = -0.95\ kJ/K$$

$$\Delta s_W = \int \frac{dQ}{T} = mC_p \int_{273}^{353} dT/T = mC_p |\ln T|_{273}^{353} = 1.08\ kJ/K$$

So, entropy change of the universe, which is always increasing would be 1.08 - 0.95 this is 0.13 kilo joule per kelvin. So, this is the answer that was being asked calculate the entropy change of the universe.

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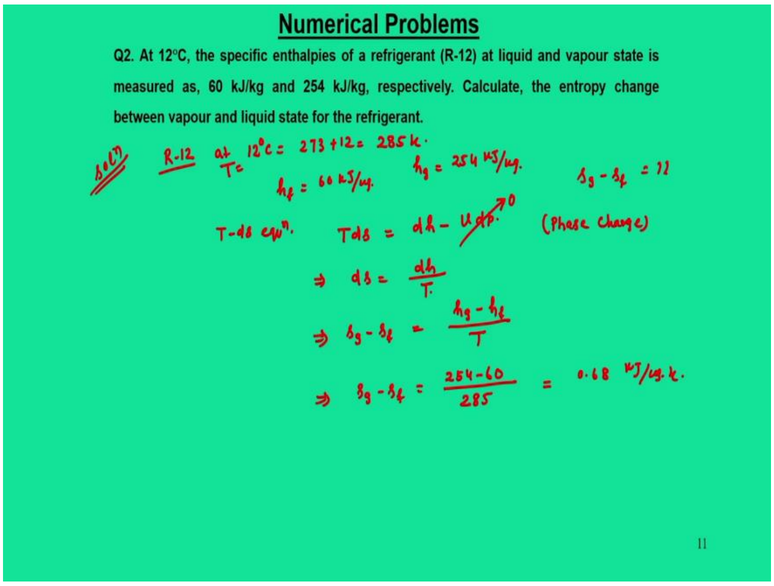

The next problem is we are talking about specific enthalpies of refrigerant at liquid and vapour state is measured. So, data is given that for refrigerant R12 at 12 degree Centigrade or we can say, it is 285K. So, temperature is 285 K. The refrigerant has two values of enthalpy; that means, h_f liquid phase is 60 kilo joule per kg and h_g would be 254 kilo joule per kg. And we require to find out entropy change that is $s_g - s_f$.

Now, to find this, you have to recall the equations that were derived from the thermodynamic property relations. One such equation is the T-ds equation, it says, $Tds = dh - vdp$. Now, in a phase change process $dp = 0$, there is no change in the pressure or we can say in its a constant temperature process.

So, this will give you that $ds = \frac{dh}{T}$. Now, if they can be interpreted in a finite number, we can write $s_g - s_f = \frac{h_g - h_f}{T} = 0.68\ kJ/kgK$. So, this is how in fact the refrigerant data tables were prepared.

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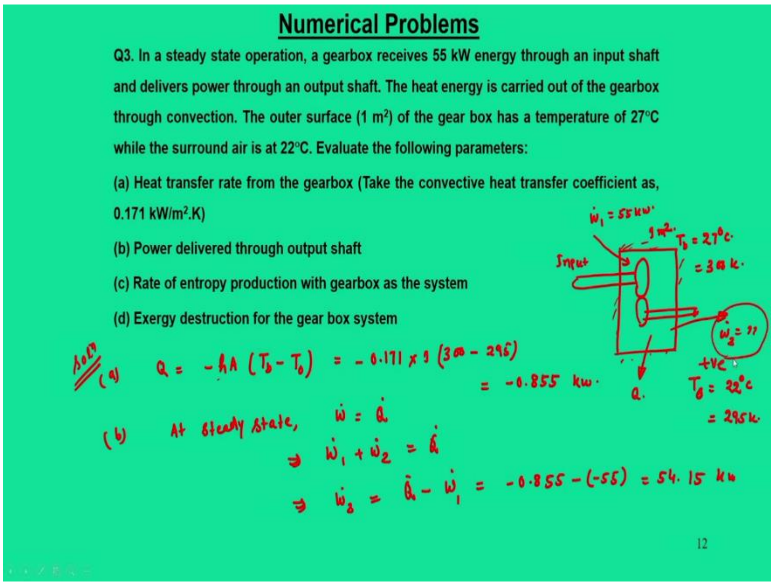

The next problem is about a gear box, what it says is that in a steady state operations a gearbox receives 55 kilowatt energy through an input shaft and delivers the power through an output shaft. Heat energy is carried out of this gear box through the convections. Outer surface area for the gear box is given as 1 meter square and it has a temperature of 27 degree Centigrades while surrounding air is 22 degree Centigrades.

So, we have to evaluate the heat transfer from the gear box. So, we can draw a schematic diagram for this gear box, that we have two shafts that connects the gear box system one is input shaft that receives the energy, second one is output shaft that delivers this energy. So, basically energy that is being received is W_1 is 55 kilowatt and we required to find out what is W_2.

And through this process, what it says that, it has surface area as 1 meter square and boundary temperature T_b is 27 C = 300K, while the surrounding temperature is 22 C = 295 K. So, this is the problem and we need to find out the heat transfer from this gear box. Since there is a temperature difference so; obviously, there will be heat transfer, q will be coming out.

So, we can find out the solution the first thing that this q will be through convections.

$$Q = -hA(T_b - T_0) = -0.171 \times 1(300 - 295) = -0.855\ kW$$

Now, we need to find out what is the power delivered through output shaft. So, to do that we need to find out at steady state; how I can write the energy balance equations.

$$\dot{W} = \dot{Q};\ \dot{W}_1 + \dot{W}_2 = \dot{Q}\ ;\quad \dot{W}_2 = -0.855 - (-55) = 54.15\ kW$$

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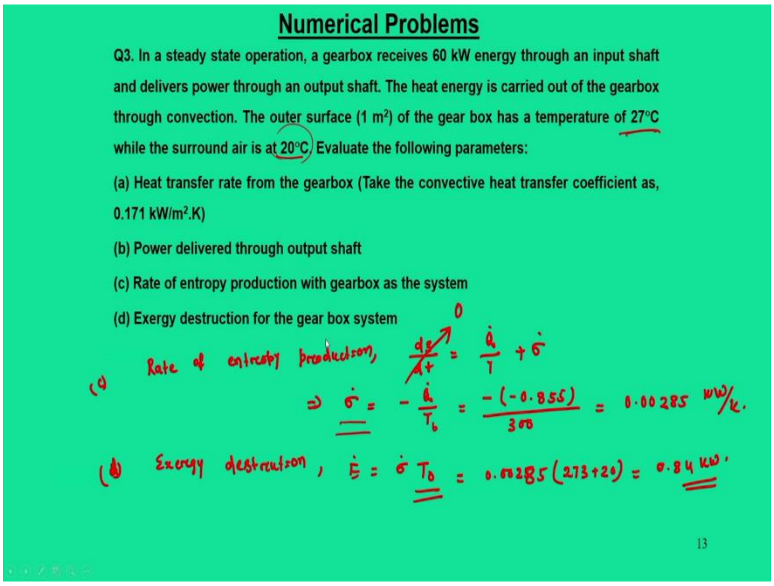

The next part is we need to calculate the entropy productions. So, for this entropy production if I write the expression for rate of entropy production then, we can recall for a closed system energy balance. $\frac{ds}{dt} = \frac{\dot{Q}}{T} + \dot{\sigma}$

So, this number $\frac{ds}{dt}$ is 0 as steady state, then we can calculate $-\frac{\dot{Q}}{T} = \dot{\sigma}$. So, here we can there are two temperatures one is surrounding temperatures, other is the boundary temperatures; two ways to look at. Since, the boundary temperature of the gear box is 27 degree Centigrades. So, this T is nothing but your Tb. $\dot{\sigma} = -\frac{-0.855}{300} = 0.00285\ kW/K$

Now, once we know this entropy productions the; we can easily find out the term exergy destruction. This exergy destruction rate we can say, it is $\dot{E} = \dot{\sigma} T_0$. Now, here T_0 is nothing but your surrounding temperatures. So, by putting this number, we can approximate get is 0.84 kilowatt. So, this is the exergy destruction for the gear box.

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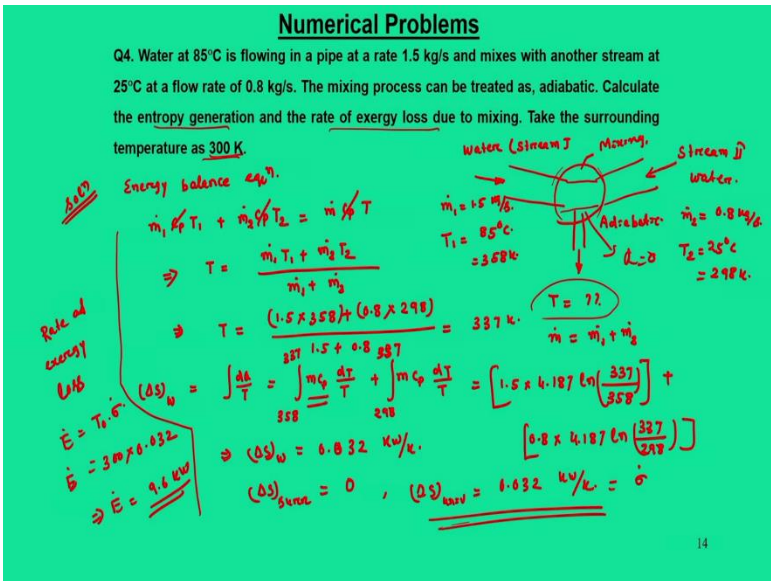

Next problem is about a mixing process, we have water at 85 degree Centigrades is flowing in a pipe. So, we say water and it is stream 1. And it is mixing with another stream of water. And the conditions is given that they are being mixed and taken out as another stream. So, this is a mixing arrangement and this mixing process is considered as adiabatic.

Now, what conditions we know that for stream $\dot{m}_1 = 1.5\frac{kg}{s}$; $\dot{m}_2 = 0.8\frac{kg}{s}; T_1 = 85C = 358K, T_2 = 25C = 298K$. And this we have the stream 3, this temperature is not known we also can find out what is the common total mass that is $\dot{m}_1 + \dot{m}_2$. So, this is the problem.

So, we say mixing is adiabatic. That is the first thing. We are going to find out, what is the entropy generation and exergy loss, one thing that we need to find out what is this uniform temperature or final equilibrium temperatures. So, we can say the energy balance equation for this mixing system can be done by considering these equations as $\dot{m}_1 C_p T_1 + \dot{m}_2 C_p T_2 = \dot{m} C_p T$.

So, Cp gets cancelled from both sides. So, this will give you the final temperature $T = \frac{\dot{m}_1 T_1 + \dot{m}_2 T_2}{\dot{m}_1 + \dot{m}_2}$. So, now, we have this numbers. So, we can get is T as 337 K.

So, here this entropy generation has two parts, one is Δs_W.

$$\Delta s_W = \int \frac{dQ}{T} = \int_{358}^{337} mC_p dT/T + \int_{298}^{337} mC_p dT/T$$
$$= 1.5 \times 4.187|\ln T|_{358}^{337} + 0.8 \times 4.187|\ln T|_{298}^{337} = 0.032\ kW/K$$

Now, Δs_{surr} is equal to 0, because the mixing process is adiabatic there is no net transfers from this mixing process being an adiabatic.

So, total entropy generations $\Delta s_{univ} = \dot{\sigma} = 0.032\ kW/K$. Now, once I know this entropy generations then, we can find out rate of exergy loss that is $\dot{E} = \dot{\sigma} T_0$. So, T_0 is given as 300 K. So, this means $\dot{E}$ is about is equal to 9.6 kilowatt.

So, this is all about this problem mainly entropy and exergy expressions. So, with this I conclude, in the next lecture I will be try to cover the second part of this tutorial session, which involves on the combustions.

Thank you for your attention.