POWER PLANT SYSTEM ENGINEERING

Lec 2: Thermodynamics Concepts (Part II)

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course- Power Plant System Engineering, Module 1- Review of Basic Thermodynamics. So, in the first lecture we have given the fundamental concepts of thermodynamics; system, surrounding, the first law, steady flow devices and so on. Now, in this lecture we will continue our discussion further, we will also move on to some other fundamental topics, which are going to be used in our subsequent modules. So, in this lecture we will touch upon the topics that is the second law of thermodynamics and it also talk about Carnot cycle that gives the concept of heat engine.

Then second law of thermodynamics also introduces another thermodynamic property that is entropy and this entropy has a definite relationship with respect to irreversible nature of a system. So, to quantify the irreversibility, we will define the topics that is entropy and what will again happen if the process is reversible, what will happen to this entropy. So, this concept will be discussed here and again coming back to the application sides, we will touch upon some fundamental aspects of pure substance that is properties of pure substance. This is mainly required because in our subsequent module we will be talking about steam power systems, where we will be frequently using water as a working fluid in a steam power systems and its continuous changes of its phase from liquid to superheated regions.

So, to address those concepts, we will briefly discuss some introduction topics of pure substances. Then in the last segment, we will also talk about some other aspects of second law that is exergy which is nothing but the work potential of any form of energy and to quantify exergy we also need to define an efficiency called as second law efficiency. So, these are the gross outline of this lecture. Now, let us move on to our main topic that is second law of thermodynamics. So, prior to this we have introduced the first law which is nothing but the conservation of energy and with thermodynamic viewpoint, we say that energy is available either in the form of work or heat, but then issue is that which has higher quality.

So, that is not clear in the first law, but first law of thermodynamics rightly do all kinds of energy auditing like energy can be converted to in any other form, but it does not talk about which is of higher quality and which is of lower quality. So, for that it introduces the concepts of energy transfer either in work mode or heat mode, but again it was found that when energy conversion takes place from work to heat, we can have a complete conversion of energy from work form to heat, but reverse was not supposed to be true. So, that means heat can be considered as a low grade energy and work can be considered as a high grade energy. But this kind of statement does not appear in the first law of thermodynamics. So, for that we introduce the topic of second law; that means when the heat is to be converted to work and complete work conversion is not possible then where is the rest amount of work that is going? Some cases it is unavailable energy and in some cases if at all, work it has to be converted how much what is the upper limit of this conversion. So, all kinds of answers that we are going to get in the second law.

So, there are two concepts here in the second law; first thing is that we are going to introduce Carnot cycle which gives the concept of heat engines. That means modality of harnessing or extracting work potential from heat or work from the heat source and second aspect that we are going to talk about is a thermodynamic property, entropy to quantify the unaccounted energy: where it goes. This is also defined through a term what we call is irreversibility. And another additional topic that we are going to be concerned about is, exergy. So, in the first law we talked about energy available in various forms. So, mainly it can be either kinetic energy or potential energy or chemical energy or heat energy, but work potential of each form of energy is different.

Work potential means, what is its maximum amount of work that can be extracted from these forms of energy. So, that is termed through a term called exergy. Now when we define this exergy we have to bring the system and surrounding together. Then only we can say that what the work potential is. So, these are some of the topics that we are going to touch upon in this lecture. Now, coming back to the second law of thermodynamics, which is unanimously accepted by two fundamental statements; one is Kelvin Planck statement & the other one is Clausius statement.

These statements are appear almost same in all the fundamental books. So, I will read these statements and in fact these are the negative statements of second law. And of course, there are two statements basically, one is Kelvin Planck statement other is Clausius statement and both are in negative form, but violation of one statement also violates the other. So, when you say Kelvin Planck statement, it talks about a cycle which operates in a heat engine. It says that it is impossible to construct a device, which will operate in a cycle and produce no effect other than the raising of a weight and exchange heat with a single reservoir.

That means, when we propose a heat engine and it takes energy as input from the heat source and without rejecting it to any kind of sink, work cannot be extracted. So, there are some terms; when you say operate in a cycle, it means it has to operate in a continuous manner. So, it is not like instantaneous rather it is continuously operating. And when you say raising of weight which means it is doing work because by definition, we say work is viewed that in some form we can raise this weight. Then we can think of exchange of heat in a single reservoir which means that only heat is added there is no heat rejections. So, this is possible only in the first law with 100% thermal efficiency, but this is not true with respect to the second law.

The second statement i.e., Clausius statement says that it is impossible to construct a device that operate in a cycle and produces no effect other than the transfer of heat from cooler to hotter body. That means, without giving any work input to a device, we cannot transfer heat from a low temperature reservoir. This concept is mainly meant for refrigerator. So, both these particular figure show that, violation of one statement will also lead to the violation of other.

The next topic that we are going to introduce for the heat engine is the Carnot cycle. The Carnot cycle was essentially proposed for the second law and it only tells that the modality or method or mechanism in which, work can be extracted from a heat source.

So, this particular figure shows that we have a high temperature reservoir source which available at temperature T_H and a low temperature reservoir which is available at temperature T_L . Our main objective is to take this heat from the high temperature reservoir and produce work. For that we need to have a cyclic device that is called as heat engine. This heat engine operates with a working fluid that continuously takes heat from the high temperature source; reservoir and it also continuously rejects heat to the sink. So, through this process we can do the energy auditing or first law analysis which will give you the net work output. So, this is exactly what we do in all kinds of devices like power plants, IC engines.

So, this cyclic manner of operation means that in order to extract work from a heat source we must operate a cyclic device. So, this is the general statement for a heat engine, but when you put with respect to the efficiency view point, the Carnot cycle also says that what will be the maximum efficiency for this heat engine. So, to do that analysis, a hypothetical cycle, the Carnot cycle was proposed if you want to operate that cyclic device. So, that cyclic device should operate in 4 processes which are shown in this p-v & T-s diagrams.

The first one is reversible adiabatic compressions. In compression process, we are giving work in, meaning there is a work input in this compression. So, this is an adiabatic process from 1-2. Correspondingly since it is a reversible adiabatic, the entropy remains constant. So, it is a vertical line shown in the T-s diagram. Then second one is reversible isothermal heat addition process. So, isothermal heat addition process is from 2-3, where heat is getting added which you say Q_A.

The third one is reversible adiabatic expansion. So, it is expansion, means it is a power producing device that means W_{out}. So, essentially this is $W_{net}= W_{out} - W_{in}$ as proposed in the Carnot cycle. So, this is the net work that the cyclic device is going to produce.

And the last one is the reversible adiabatic heat rejection. So, cycle will be completed only when the state of the system goes from 4-1.

So, to complete the cycle some heat must be rejected that is Q_R. Now, without this heat rejection, which comes from the high temperature source that is T_H and heat is getting rejected to the low temperature sink which is maintained at T_L and through this process we are getting W_{net} work output. So, this is how the cyclic device should operate and for that reason, we can subsequently say that

Heat added, $Q_A = T_H(S_3 - S_2)$

Heat rejected, $Q_R = T_L(S_1 - S_4)$

Processes1-2 &3-4 are isentropic: $S_2 = S_1$& $S_3 = S_4$

So, ultimately it leads to calculating the net work output and what is the thermal efficiency of this heat engines. And with respect to Carnot cycle we have, $\frac{Q_A}{T_H} = \frac{Q_R}{T_L}$. This ratio holds good and based on that we can have this cyclic efficiency that can be defined.

Network & thermalefficiency,

$\Delta W_{net} = Q_A - Q_R$;

$$\eta_{th} = \frac{\Delta W_{net}}{Q_A}$$

Thermal efficiency of Carnot cycle, $\eta_c = \frac{T_H - T_L}{T_L}$

So, this talks about a concept that, if an engine has to operate between a high temperature source at T_H and low temperature sink at T_L, then above equation provides the maximum possible efficiency. Now, one more important point to be noted here is that

$T_H = T_2 = T_3$ and $T_L = T_1 = T_4$.

This is the assumption that Carnot cycle makes and that assumption is only true, when the processes are reversible in nature.

Then moving further, we are now going to define another term which is entropy and that comes by virtue of the fact that complete conversion of heat to work is not possible then where this heat goes. So, we introduce some situation where we cannot have complete conversion. So, we need to define some kind of irreversible nature of the process and that is called a degree of irreversibility and that can be either external to the cyclic device or within the internal components of the cyclic device. So, this irreversibility can be classified as external or internal.

The external irreversibility occurs for main reason of heat transfer because whenever there is a temperature difference then only heat transfer is possible and due to this heat transfer, heat irreversibility is introduced and the friction in the machines is also irreversible in nature. The internal irreversibility occurs during the mixing process, throttling process because cyclic device requires some kind of valves, regulators, for which we need to have thermodynamic parameters that needs to be specified. So, that is going to change.

So, with respect to thermodynamic viewpoint main sources of irreversibility are friction, heat transfer, throttling and mixing. So, this is a particular case of diesel cycle and since it is a cyclic device we are going to say that in this we can put the location of the state points that normally defines a thermodynamic process and a working fluid can be part of the cycle which continuously takes heat and also rejects it, side by side it produces work output. This particular cycle is a diesel cycle which is a fundamental air standard cycle for a diesel engine. Then moving further to quantify the requirement of nature of irreversibility or degree of irreversibility we are now going to define the term entropy which is very common and have been used frequently, but the main significance of this term entropy is that, this is something analogous to a non-flow reversible work because when you say reversible work with respect to first law we can say

Non-flow reversible work, $\Delta W = \int_1^2 pdV$. That means, when you say rising mass.

Now, when you define the term heat which is the main culprit or main parameter that is going to be addressed in the second law. Now, in the similar fashion or similar analogous manner how do you define the reversible heat? So, for that reason we introduce a diagram called as temperature entropy (T-s) diagram that will also tell us that

Non-flow reversible heat, $\Delta Q = \int_{1}^{2} TdS$

So, in other way we can say that area under p-V diagram represents non flow reversible work and area under the T-s diagram represents non flow reversible heat.

And for Reversible adiabatic (isentropic) process, $\int_1^2 TdS = 0$ as ΔQ=0

$\Rightarrow dS = 0$ or $S =$ constant

So, that means entropy remains constant. So, a reversible adiabatic process happens to be an isentropic process.

Then moving further there are some other philosophical thought of entropy process since it quantifies the irreversibility which means that, higher the increase in the entropy the greater will be irreversibility. For example, in a reversible adiabatic turbine, the maximum work is produced whereas, when you say irreversibility in turbine, the work gets reduced. And in case of a compressor, it consumes least work when the processes are reversible adiabatic, but when there is an irreversibility, the work input will be more. So, this is how the irreversibility parameter gets quantified through the term entropy. Another significant point, I need to emphasize is that entropy is a measure of unavailable energy. That means this energy cannot be possible for reutilization which means entropy is disorderness of the system.

Of course, there is the law of entropy which says that entropy of universe continuously increasing and one point of time entropy will reach at its maximum. Now, when we say entropy reach at maximum, all the matters will have same temperature. So, when all the matters have same temperature it is not possible for any extraction. This is a hypothetical situation, all availability will be lost, all sources of energy will be lost and that point human life will cease to halt. This is a philosophical thought process of entropy, but that is not part of our discussions.

Our main focus of discussion is that entropy is a measure of irreversibility while we are looking at work extractions from a heat source. So, this is another example that we commonly come across; expansion of a gas, compression of a gas. So, when you say expansion of a gas, gas goes from high pressure to low pressure. So, the thermodynamic process that goes with respect to second law, fundamentally we call is an isentropic process that is 1-$2_s$and when you say compression it is the reverse case to the former that means process goes from 1-2_s as opposed to the expansion. Now, if the process is non-isentropic, we define the terms called as isentropic efficiency for work producing device and work consuming device as follows

Isentropic efficiency for turbine, $\eta_T = \dfrac{h_1 - h_2}{h_1 - h_{2s}} = \dfrac{T_1 - T_2}{T_1 - T_{2s}}$

Isentropic efficiency for compressor, $\eta_C = \dfrac{h_{2s} - h_1}{h_2 - h_1} = \dfrac{T_{2s} - T_1}{T_2 - T_1}$

So, accordingly they are defined in terms of actual enthalpy change for a reversible gas. So as defined by first law enthalpy for ideal gas i.e, $h = c_p T$, the enthalpy term can be reduced to temperature form. So, this is about the turbines and compressors.

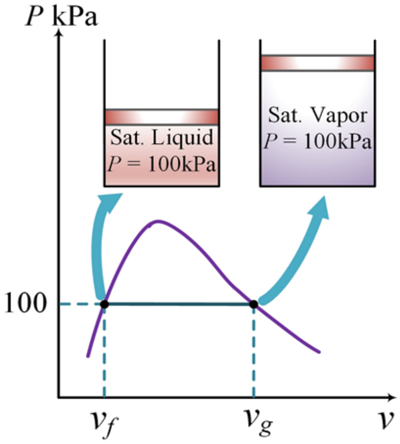
But when you talk about pumps, normally pump handles incompressible liquids and change in the temperature is quite insignificant for that reasons the pump process or pump work is defined by the following equation

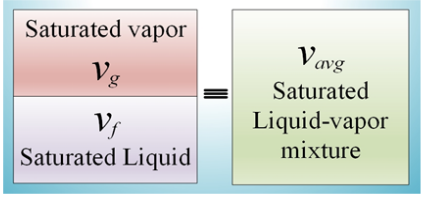
Actual pump (handles liquid) work, $W_p = \frac{V(p_1 - p_2)}{\eta_p}$, where we introduce the pump efficiency η_p.

Now, another topic that we are going to touch upon is the pure substance. So, pure substance is a very vital analysis. For all substances we are going to represent them in thermodynamic coordinates like, pressure-volume, temperature-entropy, pressure-temperature, different diagrams that can be drawn with thermodynamic viewpoints. And substances that are treated mainly as pure substance are water, nitrogen, helium, carbon dioxide etc. So, for all the gases or whatever substance that we say is a pure substance, there are some characteristics parameters or behavior that do exist; either they are available in data form or in equation form or in graphical form. So, this is what we call as a properties of pure substance.

Now, ideally speaking when you say pure substance, there are three phase; solid, liquid and gas. When the substance changes its phase, it can go from solid to liquid phase, liquid to gas phase of course, gas to solid, solid to gas; that means in multiple number of ways substance can change its phase. When there is a change in phase that means, when we are going from liquid domain to gas domain it passes through a phase change process and during this phase change process whatever heat, either consumed or liberated/ extracted or comes out is known as latent heat. So, accordingly we define latent heat of freezing, latent heat of fusion and of course, we can also think of latent heat of vaporization. So, these terms are associated with substance when it undergoes a change of phase. Another point that is that during a phase change process, pressure and temperature are dependent property that means, either one of the parameter is sufficient to define the state, because during the phase change, when there is a pressure change that corresponds to change in saturation temperature, how? We are going to look upon it.

So, the first thing we look at, while dealing with the properties of pure substance is dryness fraction or quality. When you think a two phase system that means, a liquid plus vapor in a container, we can divide it into two parts; one is saturated vapor and the other is saturated liquid and they can be represented in pressure-volume diagrams through this process. Now in this pressure volume diagrams we can see, there is a dome and within the dome we have liquid plus vapor and a line can be drawn through the peak point of dome which is called as critical point. So, left hand side of that line we call this as a saturated liquid and right hand side of this critical point, we call this as a saturated vapor . If you have a mixture of these two and at a given temperature or pressure we can fix its state as saturated liquid or saturated vapor, each one will have its own specific volume. And any other parameter which is given within the dome is called a liquid vapor mixture, to define the states we require a term called as dryness fraction or quality and that is defined as ‘x’ which is nothing, but the ratio of mass of vapor to the total mass.



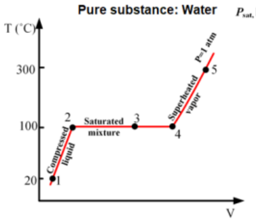


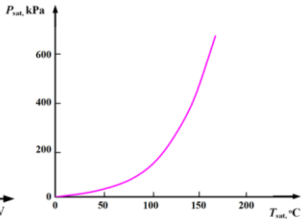
$$x=\frac{m_v}{m_t}=\frac{m_v}{m_l+m_v};\ v_{av}=v_f+x\,v_{fg}=v_f+x\left(v_g-v_f\right)$$

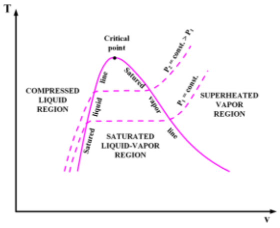
$$u_{av}=u_f+x\,u_{fg}=u_f+x\left(u_g-u_f\right);\ h_{av}=h_f+x\,h_{fg}=h_f+x\left(h_g-h_f\right)$$

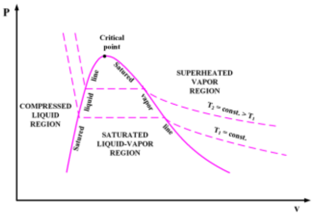
So, accordingly this equation can be framed and once you know this dryness fraction, the properties associated with that location at that state can be found like its average internal energy, enthalpy within this liquid vapor region.

Then we have this saturated ratio curve that means if you look at this figure, i.e, the temperature volume diagram, a pure substance, let us say water, is at initial state 1 and that initial state which is at 20℃ and if you keep adding heat, which means the temperature is continuously increasing to point 2.







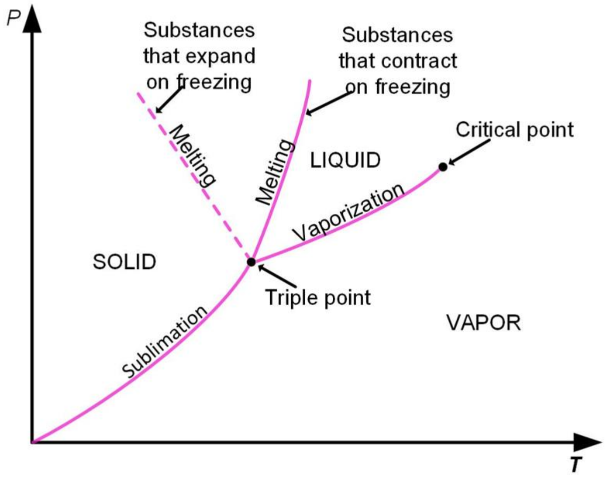


So, when you are increasing temperature through this process there is a temperature change. So, whatever heat that gets added we call this as a sensible heat. Then from 2 to 3 already it is at 100℃ so, it is going to change its phase. So, point 2 is the saturated liquid state.

So, when further heat is added the point 2 moves to point 4 that is saturated vapor state and further heat addition will go to state 5 which is called as a superheated region. So, any other point which is 3 that is nothing, but liquid plus vapor regions and beyond point 5 we will say superheated regions. And this curve is drawn at one particular pressure. So, in similar way we can draw infinite number of curves and locus of the curve goes in this manner. And we call this as a dome and that dome consists of a peak point which is the critical point. The higher you go towards the critical point, we do not have two distinct points for saturated liquid and vapor. They try to merge together at a point which is called as critical point.

Now, this is also plot for pressure and volume. Other point is that, for each pressure there is a saturation temperature. So, a curve that can be plotted corresponding to saturated pressure and saturated temperature and that goes in this manner. So, higher is the saturation temperature higher will be the saturation pressure. So, for water the critical points are defined as 22.09 MPa, 374.14°C, 0.003155 m3/kg.

Then moving further we are also going to introduce the term which is called as phase diagrams. So, phase means solid/ liquid/ gas that are three different phases, but ideally speaking solid can change its state to liquid and liquid to vapor. So, this is the normal process that we go. So, solid if you want to go to vapor it has to melt then after melting it will vaporize. So, it will go to vapor region. Now the solid also can go to vapor directly through the process called as sublimation process.



So, this particular diagram talks about pressure, temperature which is normally known as phase diagram. So, phase diagram talks about a point, that means at a certain pressure and temperature we can say it is possible to transfer from solid to vapor region. So, for that region you have to go through the sublimation curve. Now, if you go for further higher temperature that means, we will go out of that means, we will bypass this triple point and we will have to take the other routes that is solid to liquid to vapor.

So, that way through this process we define a point called, where all the lines that are associated with whatever thermodynamic processes like melting, vaporization and sublimation merge to, is called as a triple point. So, in a phase diagram triple point is very unique point and we have a critical point which is defined on this vaporization curve. Now, melting curves has two lines one is given by the solid line other is the dotted line. There are some substances that expand during freezing and some substances that contract during freezing. So, that's the way melting lines are defined in this manner.

So, this is all about to talk about different points that we have during a phase change process. So, in this phase diagrams we define the term that is triple point. One important point that I need to emphasize here, there are some numbers associated with this triple point for some substances like

Water: (273.16 K, 0.61 kPa)

Nitrogen: (63.18 K, 12.6 kPa)

Oxygen: (54.36 K, 0.152 kPa)
Carbon dioxide: (216.55 K, 517 kPa)
Acetylene: (192.4 K, 120 kPa)
Atmospheric condition (298 K, 101.325 kPa)

Now, comparing this we will find that with respect to this atmospheric conditions water has very low value of triple point parameters, whereas, carbon dioxide have close to almost 5 times atmospheric pressures and it has also temperature in the range of 216.55 K. So, through this number it is possible to predict that for some substances it is possible we can go from solid to vapor line through this sublimation curve. One such example is the carbon dioxide. So, normally this is used for artificial rain and we call it them as a dry ice.

Then moving further some other terms that we are going to use that is compressed liquid and this compressed liquid is also called sub-cooled liquid. So, that is defined not on the dome, rather in a temperature entropy diagram, temperature specific volume diagram, we have a point that is critical point and this is saturated liquid & saturated vapor region and before this saturated liquid, the characteristic locations are called as compressed liquid region or sub-cooled liquid regions. And beyond this saturated vapor curve we call this as a superheated regions. And to summarize everything it is consolidated in two parameters, two diagrams we have steam tables which is drawn for water which you have we have already come across in our previous thermodynamics course.

So, how do you view the steam tables? So, we have given all kinds of theoretical backgrounds. So, in a steam table there are saturated water temperature table, saturated water pressure table. That means if you know temperature, you can get back pressure or if you know pressure you can get back temperatures. So, these two are interrelated property and for each case all the parameter like specific volume, internal energy, enthalpy and entropy can be specified.

Now when you move on to superheated regions we require two parameters to specify this thermodynamic states. One is pressure and other one is temperature. On top of that we can have specific volume, enthalpy and also entropy, so all these can be specified. So, these are the extracts that are taken from the book Moran and Shapiro just for visualization purpose. Another graphical representation of these water properties is done through a Mollier diagram. So, Mollier diagram is nothing but an enthalpy-entropy diagrams and in fact it is very vital to find the operating points for a steam power system.

The next segment that we are going to introduce is the exergy and second law efficiency. So, exergy is the term that is used that is derived from the second law is that for any source of energy if you want to quantify the work potential for that energy then we call this as exergy. So, energy is available in the kinetic form, it can be potential energy form, it can be from heat source and corresponding work potential we can define. So, this particular expression says that if you have kinetic energy or potential energy, the exergy is

$$x_{KE} = KE = \frac{V^2}{2}; x_{PE} = PE = gh;$$

Now, for heat it is not possible. So, to find the work potential we have to introduce the Carnot cycle concept in of heat engines.

$$X_{heat} = \int \left(1 - \frac{T_0}{T}\right) \delta Q = \left(1 - \frac{T_0}{T}\right) Q$$

So, remember here, T_0 stands for temperature of the environment or dead state. So, that means exergy is defined by keeping consideration of environment into picture. And of course if there is a mass flow we can define this exergy of mass as

$X_{mass} = m\psi$; $\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$; ψ is nothing but the specific exergy.

So, in other words in a flow system, exergy can be defined by considering any arbitrary system and surrounding into picture. So, we can define them as this, ψ. So, based on this, we can refer many books to find out what non-flow exergy is and what flow exergy is. So, derivations are already there in the books.

Non-flow exergy and Flow exergy

Closed system(non-flow exergy)

$$X = (U - U_0) + p_0(\cancel{V} - \cancel{V}_0) - T_0(S - S_0) + \frac{1}{2}mV^2 + mgz$$

$$\phi = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + \frac{1}{2}V^2 + gz$$

$$= (e - e_0) + p_0(v - v_0) - T_0(s - s_0)$$

$$\Delta X = X_2 - X_1 = m(\phi_2 - \phi_1)$$

$$\Delta X = (U_2 - U_1) + p_0(\cancel{V}_2 - \cancel{V}_1) - T_0(S_1 - S_1) + \frac{1}{2}m(V_2^2 - V_1^2) + mg(z_2 - z_1)$$

$$\Delta\phi = \phi_2 - \phi_1 = (u_2 - u_1) + p_0(v_2 - v_1) - T_0(s_2 - s_1) + \frac{1}{2}(V_2^2 - V_1^2) + g(z_2 - z_1)$$

$$\Delta\phi = \phi_2 - \phi_1 = (e_2 - e_1) + p_0(v_2 - v_1) - T_0(s_2 - s_1)$$

Open system (flow exergy)

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{1}{2}V^2 + gz$$

$$\Delta\psi = \psi_2 - \psi_1 = (h_2 - h_1) - T_0(s_2 - s_1) + \tfrac{1}{2}(V_2^2 - V_1^2) + g(z_2 - z_1)$$

However I just need to emphasize the end expressions that we are going to use for our exergy calculations. So, for a closed systems like we have a fixed mass systems; there is no mass interactions. So, entire system is defined through the exergy in terms of internal energy of arbitrary state and this internal energy for the environment or dead state. So, correspondingly we can find the change in the exergy for a closed system, ΔX. In a similar logic we can find the flow exergy for an open system. For that reasons we define this $\Delta\phi$ and $\Delta\psi$. So, $\Delta\phi$ stands for specific exergy terms associated with a closed system and that is defined through this internal energy change, $(u_2 - u_1)$, then specific volume change

$p_0(v_2 - v_1)$, entropy change $T_0(s_2 - s_1)$, kinetic energy change $\frac{1}{2}(V_2^2 - V_1^2)$, potential energy change $g(z_2 - z_1)$.

Similarly, for flow exergy, $\Delta\psi$, it is defined through enthalpy change $(h_2 - h_1)$, entropy change $T_0(s_2 - s_1)$, kinetic energy change $\frac{1}{2}(V_2^2 - V_1^2)$, potential energy change $g(z_2 - z_1)$. So, only difference between these two is that here internal energy is replaced with enthalpy for open system. Now, associated with this exergy, we have this exergy principle which says that exergy of an isolated systems always decreases. So, entropy always increases whereas exergy always decreases. And in a limiting case, in a reversible process it remains constant. And based on that for an actual process, we can say that exergy never increases it always decreases and when we say that exergy always decreases means it is destroyed.

$X_2 - X_1 = -T_0 S_{gen} \geq 0; \Delta X_{isolated} = (X_2 - X_1)_{isolated} \leq 0$

$X_{destroyed} = T_0 S_{gen} \geq 0;$ Reversible process: $X_{destroyed} = 0$

Irreversible process: $X_{destroyed} > 0;$ Impossible process: $X_{destroyed} < 0$

So, this is similar law of entropy is it also called as law of exergy. Law of entropy talks about increase in the entropy principle, law of exergy talks about destruction of exergy. And to give a physical meaning to this, if this total energy available with us and that is mainly with respect to work, heat, kinetic energy, potential energy, flow energy, so, all these things are available, but for each one there is exergy, but out of this total energy the work potential if you actually count we will call this as exergy. Anything which does not have the work potential we call this as unavailable energy.

So, this is nothing but whatever energy is going as waste and that is not possible to recover by any means. So, that is called as irreversibility. So, for accountability of exergy we will talk about irreversible nature of a process or cycle. Now, to quantify this term what we define is called as second law efficiency. So, we all know the first law efficiency which is derived from the Carnot cycle.

Heat engine(work producing device):

$$\eta_{II} = \frac{\eta}{\eta_{rev}} \; \& \; \eta_{II} = \frac{W_u}{W_{rev}}$$

Refrigerators and Heat pumps (work consuming device):

$$\eta_{II} = \frac{COP}{COP_{rev}} \& \eta_{II} = \frac{W_{rev}}{W_u}$$

Now, for that Carnot cycle we have this efficiency, η and for the second law efficiency we are defining the same expression, but in a different way that is the ratio of actual efficiency to the maximum possible efficiency for same operating conditions. So, maximum possible efficiency is possible when the system is completely reversible and we also take into account the system and its associated surrounding into pictures to find the maximum possible reversible efficiency and that is you take this ratio and we call this as a second law efficiency, η_{II} and that term can be further found out in terms of exergy that is, second law efficiency is defined by

$$\eta_{II} = \frac{X_{re\,\mathrm{cov}\,ered}}{X_{\mathrm{sup}\,plied}} = 1 - \frac{X_{destroyed}}{X_{\mathrm{sup}\,plied}}$$

So, this is all about the overall concepts of thermodynamic viewpoint for the basic understanding. Now this knowledge will be the benchmark for our analysis in the subsequent modules. So, in the subsequent modules, we are going to discuss about steam cycle, gas turbine cycles and renewable systems.

So, although this module is just a repetition, but the concepts are very vital for our analysis in the subsequent modules. Now whatever we discuss so far in this lecture, let me put out some numerical problems which will be helpful for understanding this thermodynamics concepts.

Q1. A heat source at 537°C loses 1.5 kJ of heat to sink. Determine the heat transfer process which is more irreversible: (a) sink at 200°C; (b) sink at 450°C.

So, the first problem talks about the entropy and that is the benchmark point for the second law analysis. It tells that there is a heat source which is available at 537 ℃ and it loses 1.5 kJ of heat to a sink, sink means low temperature location and there are two ways this sink is maintained.

Case 1) the sink is at 200℃ & Case 2) the sink is at 450℃.

Our job is to find out which is more irreversible. Now, to find the more irreversible process then we must find what are the entropy changes are associated in both the situations. Then only we can define this irreversible nature and accordingly, we will say that whether a particular heat transfer process is more irreversible or not.

So thermodynamically we say there is a source which is at 537℃ and so I can say that

T_H= 537℃ = 810 K

Case 1) the heat source rejects 1.5 kJ of heat to sink and this sink is at 200℃.

Case 2) the same source with above temperature rejects 1.5 kJ of heat to sink at 450℃.

So here I can say, T_{L1}= 200 ℃ = 473 K and T_{L2}= 450 ℃ = 723 K

So in both the cases our main intention is to find out what is entropy change.

Case 1) $(\Delta S)_1 = \frac{-Q}{T_H} + \frac{Q}{T_{L1}}$;

Because when heat is rejected from the source, entropy drops & when heat is added to the sink, entropy is gained.

$(\Delta S)_1 = \frac{-1500}{810} + \frac{1500}{473}$ =1.32 kJ/K

Case 2) $(\Delta S)_2 = \frac{-Q}{T_H} + \frac{Q}{T_{L2}} = \frac{-1500}{810} + \frac{1500}{723}$ = 0.22 kJ/K

So it is seen here that, $(\Delta S)_1$ > $(\Delta S)_2$;

⇒ heat transfer for case 1 is more irreversible.

So this is how we need to quantify the irreversible nature through entropy analysis.

Q2. A piston-cylinder device contains 0.04 kg of steam at 1 MPa and 300°C. Steam expands to final state of 0.2 MPa and 150°C. by doing work. Heat losses to the surroundings is 1.5 kJ. Determine, (a) the exergy of the steam at the initial and final state; (b) exergy change of the steam; (c) exergy destroyed; (c) second law efficiency.

The second problem that we are going to discuss is about same irreversible nature, but through an analysis called as exergy analysis. So in the second problem we have a closed system like you have a piston cylinder device. That piston cylinder device initially contains a gas and in this case it is steam. So you say that is state-1 (initial state) and that state-1 steam is at pressure, $p_1 = 1$MPa and temperature, $T_1 = 300$ ℃

So we say this is steam and it expands to a final state that means this piston when it expands into final state we reach the state-2 and the state-2 is at
Pressure, $p_2 = 0.2$MPa and temperature, $T_2 = 150$ ℃.

So this is again in the superheated steam and these data we need to find out from the steam table. So this problem will also give how to refer steam table, second thing it gives the concept of exergy and second law. So to solve the problem first thing that we require is to get the property data using the steam table.

So for state-1; $p_1 = 1$Mpa , $T_1 = 300$℃.

We can refer superheated steam table. So superheated steam table will give you

Internal energy, U_1 = 2793.2 kJ/kg
Specific volume, v_1 = 0.2579 m^3/kg
Entropy, s_1 = 7.1229 kJ/kg.K

And for state-2; $p_2 = 0.2\text{MPa}$, T_2 = 150°C.

Internal energy, U_2 = 2576.9 kJ/kg
Specific volume, v_2 = 0.9596 m^3/kg
Entropy, s_2 = 7.2795 kJ/kg.K

Additionally we have to take the dead state. So dead state is outside this piston cylinder device. So this dead state is defined by pressure p_0 & temperature T_0 and at this dead state conditions we have to find the water properties or that is at environment

p_0 = 100 kPa; T_0 = 300 K

& again we have, U_0 =104.88 kJ/kg; s_0 =0.3674 kJ/kg.K; v_0 = 0.001 m^3/kg

So the first thing that we are going to find is exergy.

a) Exergy at initial state; (since it is a closed system)

$$X = m[(u - u_0) - T_0(s - s_0) + p_0(v - v_0)]$$

$So, X_1 = m[(u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0)]$ & we have the mass of steam, m= 0.04 kg

$\Rightarrow X_1 = 0.04[(2793.2 - 104.88) - 300(7.1229\text{-}0.3674) + 100(0.2579\text{-}0.001)]$

$\Rightarrow X_1$ = 27.5 kJ

Similarly for state 2, Exergy at final state;

$X_2 = m[(u_2 - u_0) - T_0(s_2 - s_0) + p_0(v_2 - v_0)]$ = 19.8 kJ.

b) Exergy change ΔX = $X_1 - X_2$ = 7.7 kJ

c) Exergy destroyed, $X_{destroyed}$ = ΔX - W_u

Now to calculate W_u we have to use this equation-for a closed system, $W_u = Q - \Delta U$

$\Rightarrow W_u = (-1.5) - m(U_2 - U_1)$; $Q = -1.5$, Because heat is rejected.

$\Rightarrow W_u = (-1.5) - 0.04(2576.9\text{-}2793.2) = 7.15$ kJ

Now W_u is known, so we can say, $X_{destroyed} = 7.7 - 7.15 = 0.55$ kJ

d) Last one is second law efficiency

Second law efficiency we write by basic definition, $\eta_{II} = \frac{W_u}{X_1 - X_2}$

$\Rightarrow \eta_{II} = \frac{7.15}{7.7} = 0.928 = 92.8\%$

So it means that this particular problem gives an indications that for this stream, there is quite a significant amount of work potential which is not possible to extract. That means still we have ability to get maximum work out of this, but however the system does not allow to get it extracted. So that means you will have very high destruction in this particular closed systems. So this is the indication that how you are going to calculate exergy and how it is linked to the irreversible nature of a thermodynamic process. So with this I conclude. Thank you.