Thermal Engineering Basic and Applied
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Lecture – 06
Combined First and Second Laws Flow and Non Flow Processes

I welcome you all to the session of thermal engineering and today we shall discuss about the first and second law, to be precise the combined first and second laws applied to different non-flow and flow processes. In the last class, we have discussed about the mathematical formulation of the combined first and second laws, we also could derive the expressions which is obtained by making use of second law and the property relations. And we also have discussed about one particular process that is reversible constant volume process.

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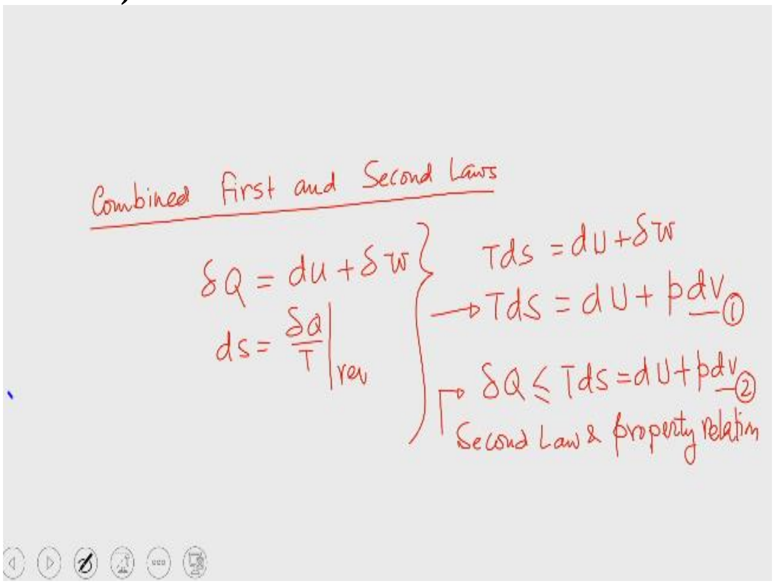

Combined First and Second Laws

$$\delta Q = du + \delta w \quad \quad Tds = dU + \delta w$$

$$ds = \frac{\delta Q}{T}\bigg|_{rev} \quad \rightarrow Tds = dU + pdV \quad ①$$

$$\rightarrow \delta Q \leq Tds = dU + pdV \quad ②$$

Second Law & property relation

So, just for brief recapitulation, we can write the combined first and second laws. So, basically we are trying to again just write the mathematical formulation of the combined first and second laws essentially for a system and that system is a control mass system and assuming that the processes occurring within the system are the reversible processes.

$$\text{First Law} \rightarrow \ \delta Q = dU + \delta W$$

$$\text{Second Law} \rightarrow \ ds = \left(\frac{\delta Q}{T}\right)_{rev}$$

In fact so long we are using this equality sign it is valid for the reversible processes. So, if we try to combine these 2 laws, we will be getting

$$Tds = dU + \delta W$$

And if the system contains of substance and if the substance is a simple compressible pure substance, then the work done can be written in the form of pdV.

$$Tds = dU + pdV - - - - - (1)$$

So, you know that this equation could be written taking one important assumption that is we have ignored the changes in kinetic and potential energies. So, basically if the system is changing its state from state 1 to state 2, the changes in kinetic and potential energies are ignored and pertaining to that case, combined first and second law takes this form. Ideally, it should have been greater equal sign in the equation. So, this inequality sign is valid if the process is reversible process.

Now, if we use the just second law and property relation that means

$$\delta Q \leq Tds = dU + pdV - - - - - (2)$$

So, this is basically obtained by making use of second law and property relations. So, this is first Tds equation I have used. We can recall that if we do not use this inequality sign, the first equation and the second equation are similar. So, these 2 equations are similar provided if we remove this inequality sign from the second equation. We also have discussed in the last class about the process being reversible constant volume process.

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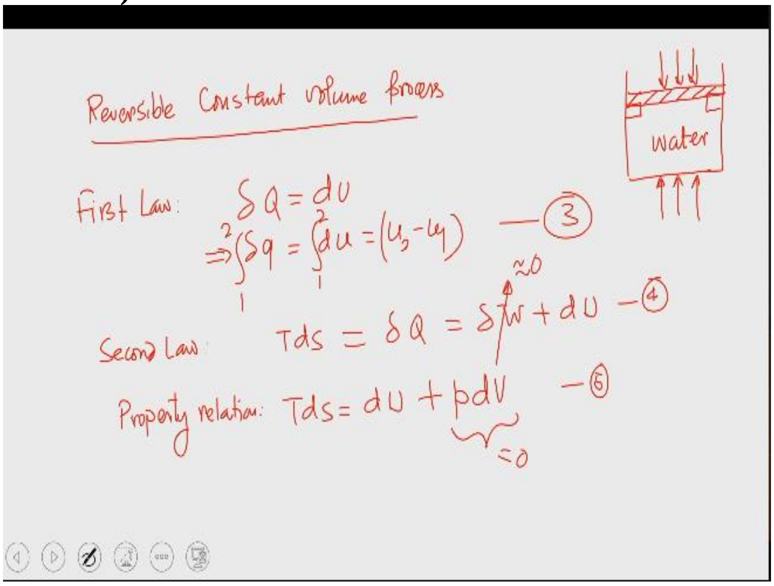

Reversible Constant volume process

First Law: $\delta Q = dU$

$$\Rightarrow \int_1^2 \delta q = \int_1^2 du = (u_2 - u_1) \quad — ③$$

Second Law: $Tds = \delta Q = \overset{\approx 0}{\delta W} + dU$ — ④

Property relation: $Tds = dU + \underbrace{pdV}_{=0}$ — ⑤

So, if the process is a reversible constant volume process, just for the recapitulations we can write

$$\text{First Law} \rightarrow \delta Q = dU$$

$$\text{In specific form; } \delta q = du$$

If we try to integrate this equation from process 1-2 because this is exact differential, so we can write

$$\int_1^2 \delta q = \int_1^2 du = (u_2 - u_1) - - - - - (3)$$

So, the amount of heat exchange because of the change of state from state 1 to state 2 performed by this system is nothing but the change in internal energies. So, basically constant volume process the work done is 0 and what about second law?

$$\text{Second law} \rightarrow Tds = \delta Q = \delta W + dU$$

$$\Rightarrow Tds = \delta Q = dU - - - - - (4)$$

So, basically we do not consider this inequality sign here. Just if we use the first law maybe $\delta W = 0$. For this particular case and if we write the property relation

$$\text{Property Relation} \rightarrow \; Tds = dU + pdV$$

$$\Rightarrow Tds = dU - - - - - (5)$$

As this is a constant volume process, so $pdV = 0$. So, apparently, we can see that equation 3 equation 4 and equation 5 are 3 different equations, but, if we look carefully then these 3 equations are not 3 different equations rather these are 2 equations, because equation 4 and 5 are identical. So, it is very important, I have again discussed this particular process today.

So, long as the process is reversible, the property relation is not an additional equation to describe this particular process that means, the combined first and second law for a reversible process is exactly equal to the property relation. So, the property relation that we can see from equation 5, is obtained by combining first and second laws specific to the case of a reversible process. So, it is not an additional equation. It would be an additional equation if the process is not reversible. So, you should keep that in mind.

So again I am telling so long as the process is reversible, equation 5 that is the property relation is not an additional equation. So this is just the derived equation obtained by combining first and second law. Remember that the combination of first and second law specific to the case of a reversible process.

You have studied typical example of this constant volume process in thermodynamics. If you have a container and this container is having these 2 stops and on the top of there is the piston, so piston is at rest on the stops initially and this container is having one pure substance say water. If we keep on supplying heat from the bottom of the container, piston will not start moving towards top until and unless the internal pressure overcomes the atmospheric pressure plus the weight of the piston. So, basically you know that atmospheric pressure is acting, so, force due to that atmospheric pressure plus the weight should be balanced by the internal pressure. If we further supply heat then the internal pressure increases further and the piston will start moving upward. So, basically until that moment, this is a constant volume process because the volume of water is remaining constant. Until and unless piston is moving towards the top, the volume of the pure substance that is water will remain constant so, that is a constant volume process. So, today again I just wanted to recap this.

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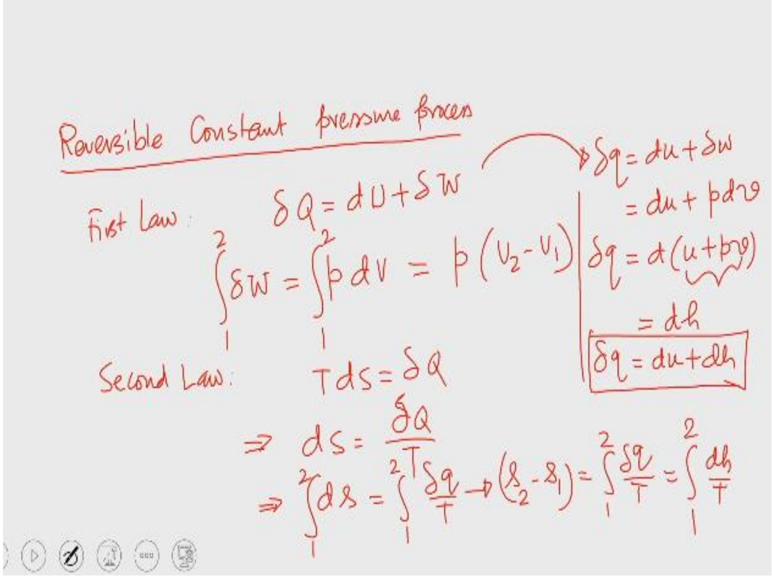

Reversible Constant pressure process

First Law: $\delta Q = dU + \delta W$

$$\int_1^2 \delta W = \int_1^2 p\,dV = p(V_2 - V_1)$$

$$\delta q = du + \delta w$$
$$= du + p\,dv$$
$$\delta q = d(\underbrace{u + pv})$$
$$= dh$$
$$\boxed{\delta q = du + dh}$$

Second Law: $T\,ds = \delta Q$

$$\Rightarrow ds = \frac{\delta Q}{T}$$

$$\Rightarrow \int_1^2 ds = \int_1^2 \frac{\delta q}{T} \rightarrow (s_2 - s_1) = \int_1^2 \frac{\delta q}{T} = \int_1^2 \frac{dh}{T}$$

So, next we will be discussing about reversible constant pressure process. Our objective is to frame the mathematical equation of the combined first and second laws along with the property relation. Why you are doing so? As we have discussed in the last class that our objective is to find out the efficiency of a system in which there are different processes.

So, there could be several processes, maybe one processes reversible constant pressure process, so first of all we need to identify what are the properties we know at the initial and final states and which property we are really looking for. So, basically if such a process is there in the system that is reversible constant pressure process, then what would be the first law, second law combined first & second law and the property relation.

$$\text{First Law for constant pressure process} \rightarrow \ \delta Q = dU + \delta W$$

So, here the work done is very important. Pressure is constant, again you are assuming that the system is containing a substance which is simple compressible pure substance. So, the changes in pressure volume temperature are considered. Other effects arising out of the electrical, magnetic forces are not considered.

$$\text{So, basically here } \delta W = pdV$$

So you know that p is constant. So, basically we try to integrate it to obtain the work done. So, we really do not know whether the change in pressure & volume following the path. So, basically a system is changing its state from 1 to 2 following a particular path. If we really do not know because δW is the path function, so, it is like this. So, basically we need to know the relationship of pressure and volume, how it changes following that particular path?

$$\int_1^2 \delta W = \int_1^2 pdV$$

Since p is constant, as in constant pressure process, pressure does not change, so you can take it out.

$$\int_1^2 \delta W = \int_1^2 pdV = p(V_2 - V_1)$$

So, this is first law. What about second law?

$$\text{Second Law for reversible process} \rightarrow Tds = \delta Q$$

Now, this is very important that as we are not using inequality sign, the process is reversible process and what we can do? So, basically you can write that

$$dS = \frac{\delta Q}{T}$$

$$\text{In specific form} \Rightarrow ds = \frac{\delta q}{T}$$

$$\int_1^2 ds = \int_1^2 \frac{\delta q}{T} \Rightarrow (s_2 - s_1) = \int_1^2 \frac{\delta q}{T}$$

Now, I have something to say here, this equation for first law can be written in specific form,

$$\delta q = du + \delta W$$

$$\Rightarrow \delta q = du + pdv$$

Since pressure is constant very simple that we can write

$$\delta q = d(u + pv)$$

So, what is this? You have studied in thermodynamics that this is again one derived property that is enthalpy, h.

$$\delta q = dh$$

So, the first law takes a form like this

$$\delta q = du + dh$$

So this is the first law for this particular process. Try to remember it, we shall be using these expressions, frequently when we will be discussing about several thermal systems. So, if this is the first law of thermodynamics for a reversible constant pressure process so, you can write one step further that is

$$(s_2 - s_1) = \int_1^2 \frac{\delta h}{T}$$

So this is basically first and second law. Now, it is very important that I would like to discuss all these just from the graphical representation along with on practical example. So, what will be the practical example? So if we go back to the previous example and say you are having water in a container. And now you are supplying heat. Time will come when internal pressure will overcome the pressure due to atmospheric pressure plus weight of the piston and piston will slowly move up and the process at that time is known as constant pressure process. So, try to understand there will be a moment when piston will start moving upward, until that moment processes constant volume process. When piston is moving towards the top following this force balance that is the internal pressure is greater than the atmospheric pressure which is acting on the top of the piston plus weight of the piston. And if we continue supplying heat to the system, maybe piston will slowly move up and maybe you are allowing the supply of heat that will be continued until when piston is moving up, and the volume of water may be converted to steam depending on the temperature.

So, the volume of the substance will keep on increasing. So, it is no longer a constant volume process rather it is the constant pressure process. Because the process is executed in presence of the atmospheric pressure, so upon receiving heat, this volume of the substance is getting increased, you can see the piston is moving up, but it is moving up against the atmospheric pressure, so this is a constant pressure process. So, this is a constant pressure process and I am telling that supply of heat is continued until the volume becomes double.

So, this is an example of reversible constant pressure process. Why you are telling reversible, because movement of piston is very very slow and occurs quasi statically. So, you know that the work focuses on the system boundary, is pdv type of work. So, that movement of piston is very slow I mean quasi static. So, the deviation from equilibrium is almost nil. In that case, we can express the process by a reversible constant pressure process and for which we have derived the expression.

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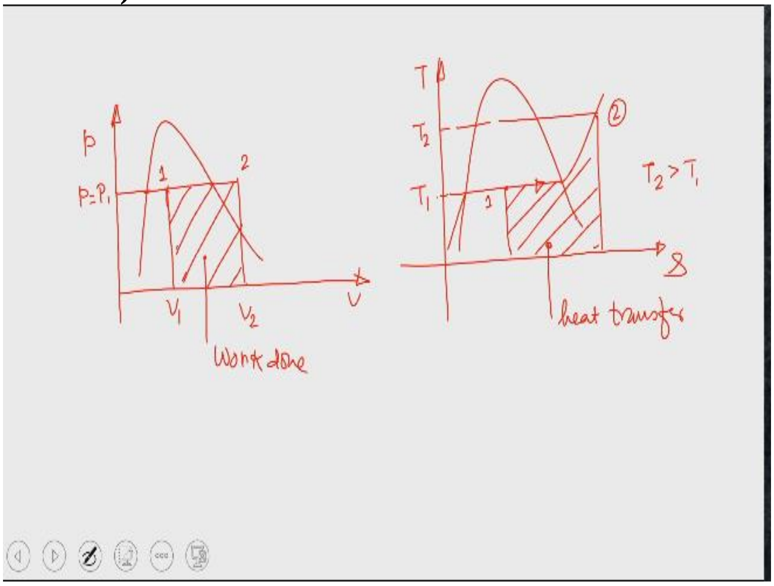

So, let us now try to map the processes in thermodynamic planes. So, let's start with P-V diagram. So, in our constant pressure process, so, this $p = p_1$. So initially water temperature is somehow here. So, when piston is about to lift from the top, this stops, that time some amount of water has converted into steam and this is two phase mixture and we can represent that particular point as state point 1 and the corresponding volume V_1. So what I said that heating is continued until volume becomes double of the initial value. So, basically process will continue till volume reaches $2V_1$ and that point is named state 2. So, what I was discussing is that heating is continued until volume is doubled.

$$V_2 = 2V_1$$

So area under the process line is work done. So, that is work done during the process.

So you have studied in thermodynamics that the area under this process line in P-V plane will give you the work done during the process. Similarly, if we can map the process in T-s plane, and then area under the process line will give us the quantification of the heat which is added to the system.

Again I am coming back to the previous slide upon receiving heat, substance phase will change. Now, to have an estimate about the heat which is being added to the system for this particular case that until volume of the substance is doubled, we can map the process in T-s plane. So you know that pressure is remaining constant so, constant pressure line but temperature changes. So, definitely the temperature has to be changed, volume is also getting changed, pressure is remaining constant. So at state point 1 temperature is T_1. So, as long as the process line is within this vapour dome, pressure and temperature are correlated. So, basically if pressure is remaining constant, temperature also remain constant. So, here the heating is continued until the temperature becomes T_2. So $T_2 > T_1$. So, T_2 is at point 2. So, area under the process line is heat transfer. So, this is amount of heat which is added to the system.

So, we have discussed about constant volume process and the constant pressure process and all these processes are reversible. Mind it in reality, it is very difficult to have or achieve a process to be reversible. So, all processes are irreversible process. But why we are doing so? Essentially you are trying to discuss about reversible process towards the quantification of the heat which is being added to the system and work which is done by the system.

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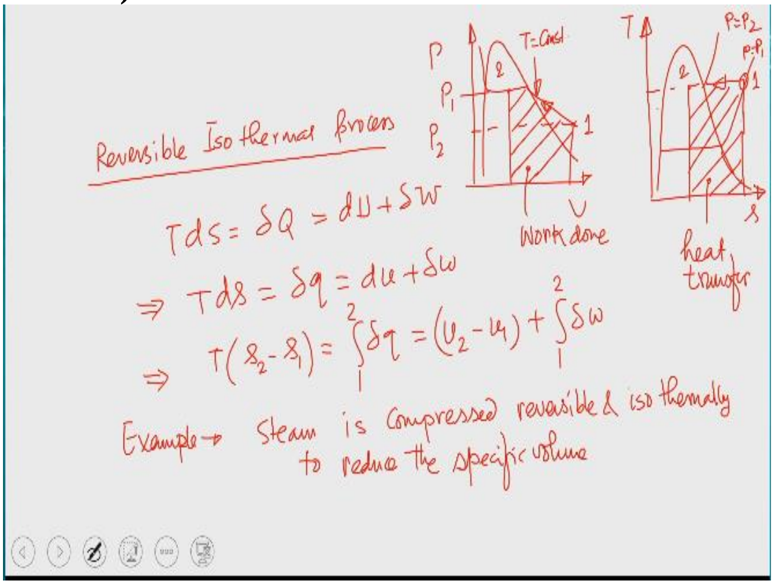

Reversible Isothermal Process

$Tds = \delta Q = dU + \delta W$

$\Rightarrow Tds = \delta q = du + \delta w$

$\Rightarrow T(s_2 - s_1) = \int_1^2 \delta q = (u_2 - u_1) + \int_1^2 \delta w$

Example → Steam is compressed reversible & isothermally to reduce the specific volume

So, next will be discussing about reversible isothermal process. So, the combined first and second law we need to write for the reversible isothermal process. You can understand that for reversible isothermal process, temperatures remain constant.

$$TdS = \delta Q = dU + \delta W$$

Now, temperature is remaining constant because process is reversible isothermal process.

Specific form → $Tds = \delta q = du + \delta W/w$

So, in this process the system is changing its state from 1 to 2. So, you can integrate it

$$T(s_2 - s_1) = \int_1^2 \delta q = (u_2 - u_1) + \int_1^2 \delta W/w$$

So, again we need to map the processes in T-V and P-V 28 35 plane. So, again we can take the same example that we compress the steam reversible and isothermally. So for example, steam is again is compressed reversible and isothermally. If we compress the steam reversible and isothermal to a specific volume, so, what is the meaning of this particular process would like to compress or reduce the specific volume.

So, if you would like to reduce this specific volume, we need to have this particular process that is reversible isothermal process. I mean, we are compressing steam in the reversible adiabatically. So, can we represent these 2 processes in TV and PV plane? So, X-axis is V and Y-axis is p. So isothermally means you know the constant temperature line. So, you know that it is compressed, so definitely pressure will reduce. So, if the pressure is reducing say we are having p_1 at state 1 and it is reduced up to this particular point p_2. So, now this is the work done as shown in the slide. So at point 1 is $T = T_1$. Temperature is constant. So, process is isothermal process, but we are compressing. If we compress it so this is the work done as shown in diagram.

So, this is very important that if you would like to compress, pressure will increase. So, suppose initial point is 1 & final point is 2 and the process is along the constant temperature line. So, this is the process 1 -2 so the area under the process line is the work done. So, basically to increase the pressure you have to compress it. Pressure will increase and our objective is to reduce this specific volume. You can see that the volume is getting reduced from 1 to 2.

So, objective is steam is compressed reversible and isothermally to reduce the specific volume. So, work done needed for this particular process is nothing but the area under this process line. If you would like to have the corresponding T-s diagram, so you can understand temperature is remaining constant, so, say this is a constant pressure line & this is another constant pressure line. So, objective is to increase the pressure or reduce the specific volume, but temperature is remaining constant. So, there is a constant pressure line and temperature is remaining constant.

So, at state 1 $p = p_1$ and at 2 it is$p = p_2$. I can this is s. So, area under the process line is the heat transfer. So, try to understand this is point 1 and this is point 2. It is at constant temperature because point 1 and point 2 lie on the same temperature line constant. It is isothermal process.

So you can reduce this specific volume. When pressure is increasing from $p_1\ to\ p_2$. So, this $p = p_1$ and $p = p_2$ are the constant pressure lines. While steam is compressed reversibly isothermally temperature remaining constant & specific volume drops. So, this is the amount of heat transfer.

So, what we can see from this that if we can identify the process, we can map that process in p-V and T-s plane, from there just by knowing the process line, we can quantify the work being done by the system or heat is which is added to the system.

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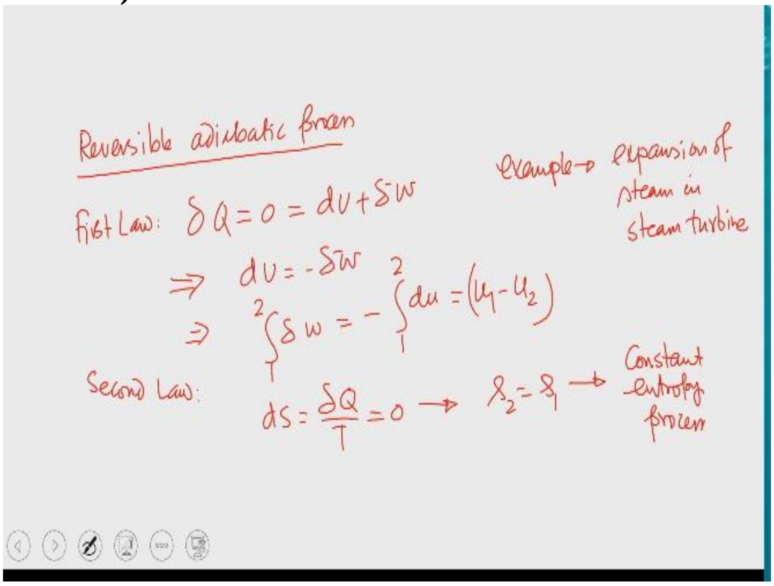

Reversible adiabatic process

First Law: $\delta Q = 0 = dU + \delta W$

$\Rightarrow dU = -\delta W$

$\Rightarrow \int_1^2 \delta w = -\int_1^2 du = (u_1 - u_2)$

Second Law: $ds = \frac{\delta Q}{T} = 0 \rightarrow s_2 = s_1 \rightarrow$ Constant entropy process

example → expansion of steam in steam turbine

Next one is reversible adiabatic process. You can understand the name is implying that the process is reversible adiabatic process. So, you have seen the expansion of steam in the turbine. So, example is expansion of steam in steam turbine. Just for the sake of completeness let’s see what is done using a turbine?

In turbine, the steam is allowed to flow through the turbine. Steam is produced in boiler and that steam is taken to the turbine definitely not directly but steam is allowed to pass through flow nozzles and then only taken to turbine. Now, when steam is passing through the turbine, it does work on the rotating part of the turbine wheel that is runner. So, we considered that while steam is passing through the turbine, the process would be reversible and adiabatic.

So, basically at the inlet to the turbine, steam is having high enthalpy and that enthalpy will drop during its course of flow through the turbine. And it is because of this enthalpy drop we will be getting work output. Now, if we allow that during the flow of steam through the turbine, heat will be transferred from the system to the surroundings, maybe the work output from the turbine will be reduced. If the work output from the turbine is getting reduced, it will definitely have impact on the overall efficiency of the cycle or plant. So, this is an example of reversible adiabatic process. So, if the reversible adiabatic process is there then

$$\text{First Law} \rightarrow \ \delta Q = 0 = dU + \delta W$$

$$\Rightarrow \delta U = -\delta W$$

$$\Rightarrow \int_1^2 \delta w = -\int_1^2 \delta u = (u_1 - u_2)$$

So try to understand that work that will be done by the steam on the rotating part of the turbine is nothing but the change in internal energy $(u_1 - u_2)$. Now from the second law we write that

$$\text{Second Law} \rightarrow \ dS = \frac{\delta Q}{T} = 0$$

$$\Rightarrow s_2 = s_1$$

So, this is very important. You know that frequently you have studied that reversible adiabatic processes isentropic process. So, the entropy at the initial state and entropy at the final state of the process is remaining same that is $s_2 = s_1$. So, this is constant entropy process. So we can map this particular process in p-V and T-s plane.

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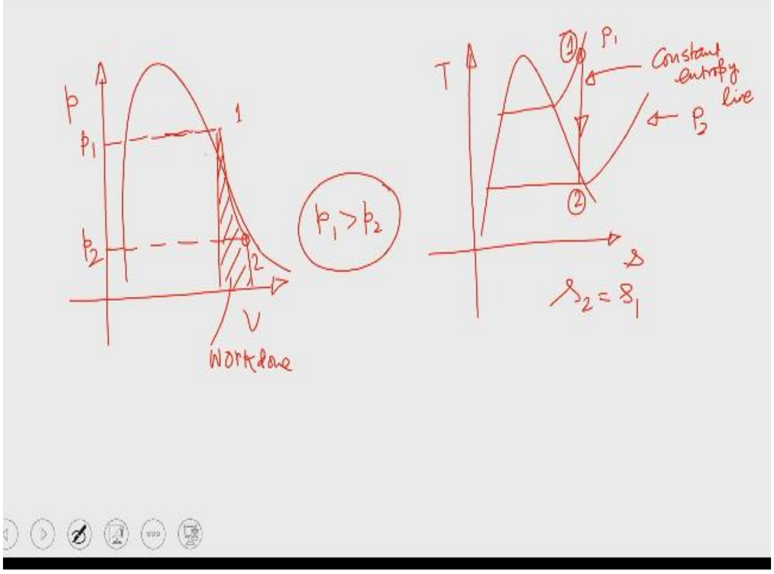

You know that if we try to draw it p-V plane then what will be the process? So, there is two state points 1 & 2 as shown in the diagram in slide. So the pressure at point 2 is p_2 and there is the saturated vapour line drawn in the diagram. You know this is the process 1 - 2. So, this is in p-V plane. So, you can understand what would be work done.

And similarly, we can draw the process in the T-s plane. So, basically we could establish that the entropy is remaining constant that is isentropic process. So, you know that process changes from p_1 to p_2. So, say there is p_2 and another constant pressure line is p_1. So, maybe this is the process 1-2. So it is isentropic line, because $s_2 = s_1$ and this is constant entropy line. So, what is heat transfer? So, area under the process line in this particular case is 0. So, there is no heat transfer. So, basically you can write

$$\delta Q = 0$$

So, this is basically what reversible adiabatic processes is. So, we have discussed about 4 different processes that is reversible constant volume process, reversible constant pressure process, reversible isothermal process and reversible adiabatic process, we have taken 4 different examples to illustrate these 4 different processes.

So, now what we will be doing? Till now you know that in all these processes we have discussed about considering the combined first and second laws and also the property relation. So today I will discuss about one important thing that is work done, which is very important. So, we have seen that you know either work is done by the system; so, basically energy is transferred from the system by work or energy is added to the system by heat. If the processes are flow processes and if we try to find out energy addition to the system by heat or energy which is taken away from the system by work then we can write first law of thermodynamics across the control volume

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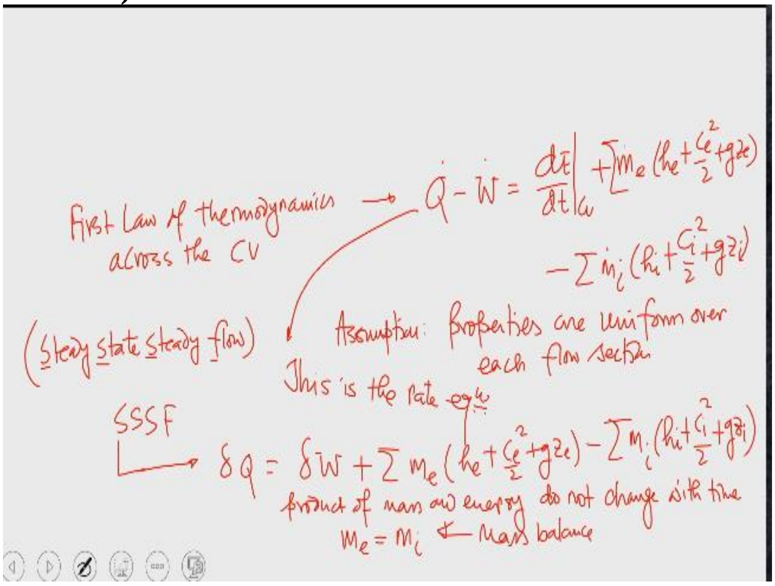

First Law of thermodynamics across the CV $\rightarrow$ $\dot{Q} - \dot{W} = \left.\frac{dE}{dt}\right|_{cv} + \sum \dot{m}_e \left(h_e + \frac{c_e^2}{2} + gz_e\right) - \sum \dot{m}_i \left(h_i + \frac{c_i^2}{2} + gz_i\right)$

(Steady state steady flow)

Assumption: Properties are uniform over each flow section

This is the rate eq^n

SSSF $\rightarrow$ $\delta q = \delta w + \sum m_e \left(h_e + \frac{c_e^2}{2} + gz_e\right) - \sum m_i \left(h_i + \frac{c_i^2}{2} + gz_i\right)$

Product of mass and energy do not change with time

$m_e = m_i$ $\leftarrow$ Mass balance

First law of thermodynamics all across the CV →

$$\dot{Q} - \dot{W} = \left(\frac{dE}{dt}\right)_{CV} + \sum \dot{m}_e \left(h_e + \frac{c_e^2}{2} + gz_e\right) - \sum \dot{m}_i \left(h_i + \frac{c_i^2}{2} + gz_i\right)$$

So, this equation is obtained under one important assumptions that is the properties are uniform over each flow sections. And it is because of this assumption we could take out this $h_e + \frac{c_e^2}{2} + gz_e$ outside the integral when it is obtained from the Renault transport theorem. So, this is the rate equation. We also can write not in the rate form. So, why I am writing we will be discussing that if we apply the steady state steady flow processes,

So, for the steady state steady flow processes or SSSF and if you do not write this in the rate form that is if we integrate it over time over the cycle then we can write

$$\delta Q = \delta W + \sum m_e \left(h_e + \frac{c_e^2}{2} + gz_e\right) - \sum m_i \left(h_i + \frac{c_i^2}{2} + gz_i\right)$$

Why? Because for the steady state steady flow processes this $\frac{dE}{dt}$ = 0. Here, the state is steady and also there is you know steady flow. So, property does not change with time. So, density does not change with time. So, basically you know that we could write this equation only for the case that the product of mass and energy do not change with time. So, this is the steady state steady flow processes and we could write it that the product of mass and energy do not change with time.

So, this is the steady state, steady flow energy balance and we can also write mass balance that is

$$m_e = m_i$$

I told one thing that energy balance is not a balance in an isolated manner rather energy balance has to be coupled of the mass balance and that is why you could write this.

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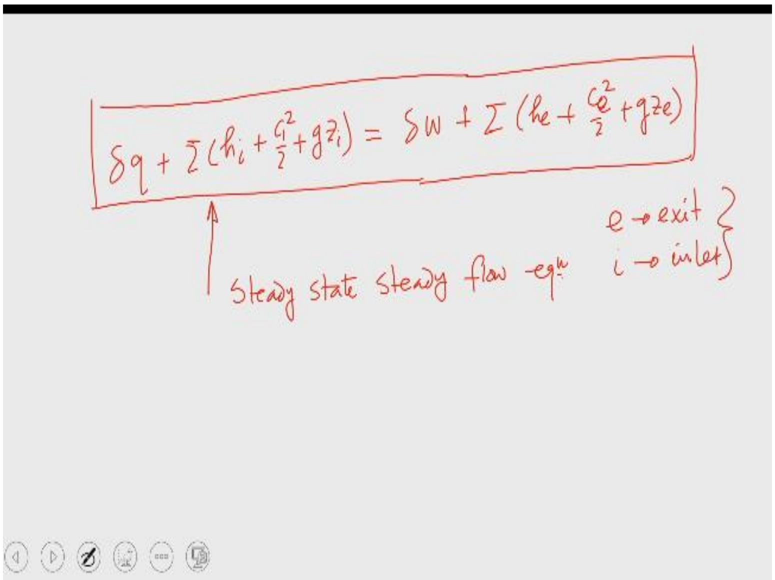

$$\boxed{\delta q + \Sigma\left(h_i + \frac{c_i^2}{2} + g z_i\right) = \delta w + \Sigma\left(h_e + \frac{c_e^2}{2} + g z_e\right)}$$

Steady state steady flow eq^{n}

$\left.\begin{array}{l} e \to \text{exit} \\ i \to \text{inlet} \end{array}\right\}$

You know that we also can write this equation in other form that is

$$\delta q + \sum\left(h_i + \frac{c_i^2}{2} + g z_i\right) = \delta w + \sum\left(h_e + \frac{c_e^2}{2} + g z_e\right)$$

So, this is the important equation. So, we will be using this equation frequently when we shall try to find out the heat and work interaction of a process occurring in a particular device or particular system.

So, this is the steady state steady flow equation. So, why I am writing; because if you would like to apply the first law or also the combined first and second law applied to the flow processes, so this is the equation we shall be using frequently. You know that I have taken summation, keeping in mind that there might be multiple exits and multiple inlets. So, here e stands for exit & i for inlet. So, this is very important equation we shall be using. Since we will be using frequently so, I was thinking to derive this equation not the full derivation, but from the derivation that we have done in one of the previous classes I have recalled that and I have written in this form. So, now, we can identify if a particular system we considered and we know that the process occurring inside the system is heat interacting process or work interacting process.

So, by identifying the particular process, we can easily calculate the terms. Suppose the process is not a heat interacting process, so, this δq term will be equal to 0. So, in that case we can easily quantify the work done by the system by the process is nothing but this change in this. Maybe we have to take another one important assumption is that the changes in kinetic and potential energies are negligibly small and then simply the work done by the process is nothing but the change in enthalpy.

So, this particular equation will be very much useful, when we shall be trying to find out the energy interaction in a process, whether it is by heat or work when there is a flow. So, by using this equation and by considering second law of thermodynamics, we shall try to find out work done in a reversible adiabatic and work done in a reversible isothermal processes.

So, work done in a reversible adiabatic and reversible isothermal processes is also important. We shall try to derive an important equation and we shall see that the work done by reversible isothermal process is equal to the work done in a reversible adiabatic process. This particular exercise we shall, discussion the next class. With this I stop here today. Thank you