Thermal Engineering: Basic and Applied

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Lecture - 05

Combined First and Second Laws Applied to Processes

We shall start our discussion today on this course on thermal engineering and the topic that we shall discuss today is the combined first and second laws applied to processes. In this course, we shall be discussing about a few systems in particular thermal systems, we shall discuss that to complete the cycle, whether it is a thermodynamic cycle or mechanical cycle essentially, in that particular system, there will be a few processes.

So, if we need to understand the performance of the system itself, then we also need to carefully study about the processes, those are there in the system rather the processes which will eventually complete the cycle and we can determine the cycle efficiency. If we need to do so, we need to know the first and second laws. We have discussed about these 2 laws. So, today we shall see that if we combine these 2 laws and apply to the processes perhaps, we shall be in a position to map those processes in different thermodynamic planes essentially to estimate different properties at the end of the process, there after we can calculate the energy transfer either into the system by heat or energy transfer from the system by work.

So, we have already discussed about first and second laws. Because in this course, we are not permitted to have a detailed discussion on this particular 2 laws because those are there in basic thermodynamics course, but we have discussed about that and in fact, we can really recall whatever we have learned from our undergraduate course and from our previous lectures, now, we are in a position to frame the combine first and second laws. In fact, we are in a position to frame a mathematical formulation for the combination of first and second laws.

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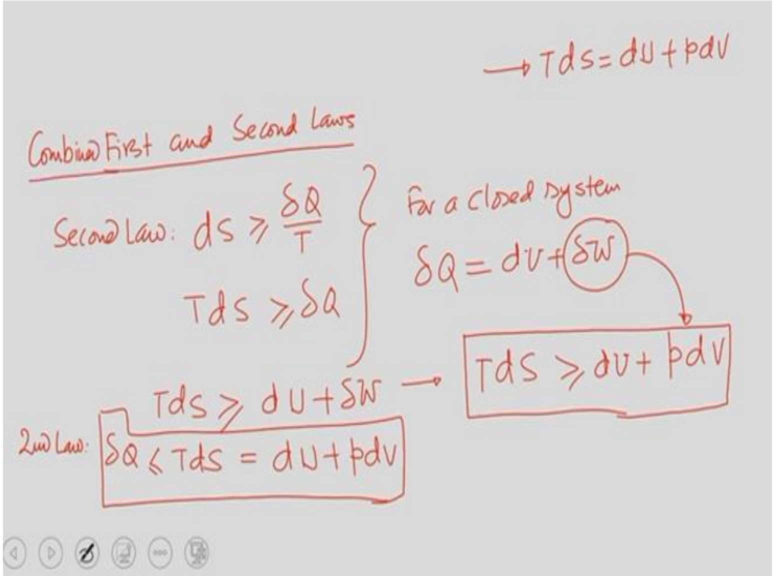

$\rightarrow Tds = dU + pdV$

Combine First and Second Laws

Second Law: $ds \geq \frac{\delta Q}{T}$

$Tds \geq \delta Q$

For a closed system

$\delta Q = dU + \boxed{\delta W}$

$Tds \geq dU + \delta W \rightarrow \boxed{Tds \geq dU + pdV}$

2nd Law: $\boxed{\delta Q \leq Tds = dU + pdV}$

So, if we try to combine these 2 laws, then first you should know whether we are going to combine these 2 laws for a closed system or open system. As I was talking earlier, if we are interested in the performance of the system, be it a mechanical system or a thermal system, first we need to know the processes, which will eventually constitute the cycle. And by knowing the processes they are corrected, whether the processes are reversible process or irreversible process, whether the process is a constant volume process or a constant pressure process, we can map those processes in different thermodynamic planes.

And then we can calculate the unknown properties and eventually we can calculate the energy. Essentially, you know that if we are in a process in quantifying the efficiency, so, at the cost of the input energy, what the output energy is. I mean we are looking at the transfer by the system at the cost of the input energy or at the cost of work input to the system, what is the net energy that we are getting.

So, first and second law, we have seen. We also have discussed about the most classical inequality that is deployed in thermodynamics that is the Clausius inequality. So, one of the most important classical inequalities to be precise deployed in thermodynamics that is the Clausius inequality. So, we can write that

$$ds \geq \frac{\delta Q}{T}$$

So, this we have studied earlier, the equality sign is valid for the reversible process, whereas, this inequality sign is applicable for the processes which are irreversible in nature. So, now, we can write

$$Tds \geq \delta Q$$

So, this we can write from the second law. If we now use first law then we can write,

$$\text{For a closed system; } \delta Q = dU + \delta W$$

We have ignored the changes in kinetic and potential energy. We considered this equation is the first law of thermodynamics for the closed system. Now

$$Tds \geq dU + \delta W$$

So, we are doing so, because if we really do not know it, we would not be able to map several processes in thermodynamic planes. So, this is the combined first and second law for the closed system. This equation can also be written differently by using second law and property relation.

If the closed system contains a simple compressible pure substance that is a substance in which the changes in pressure, volume and temperature are considered rather the work done due to mechanical, electrical and magnetic effects are not considered. So, basically, in a simple compressible pure substance, only the changes in PVT are considered the effects stemming from the applied or induced electrical and magnetic interactions are not considered. So, if that is the case then

$$Tds \geq dU + pdV$$

If we would like to write the work done by this quantity pdV, it is not necessary that the system has to be a closed system. Even when the system is open system, means there maybe flow into the system, but the displacement of the system boundary is quasi static. If the work done focuses on the system boundary and the boundary moves quasi statically that means, the deviation from equilibrium is almost negligible. In that case, we still can write $\delta W = pdV$. So, the above equation is again the combined first and second law but written in different form. As I was telling that we can write this equation by simply using second law and the property relation, how? We can write that

$$\text{Second Law; } \delta Q \leq Tds$$

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

$$\Rightarrow \delta Q \leq Tds = dU + pdV$$

So, this is what we got from the second law and property relation.

So, what I told you in the last class that

$$Tds = dU + pdV$$

This equation is valid for any processes, but, we should be careful in applying this equation for any processes, why? Because if you would like to apply this equation for any processes, then the equation has to be integrated over a reversible path and the results of integration can be applied to any processes. So, that is very important point we should remember.

So, this equation is valid for any general processes. But if we try to apply this equation for any general processes, we know that if it is a reversible process, this is fine, but if you would like to apply it even for the reversible process that we have discussed in the last class. So, basically this equation is valid for any processes, only thing we should be careful that it should be integrated over a reversible path and the results of integration can be applied.

So, this is first you know combined first and second laws for the closed system.

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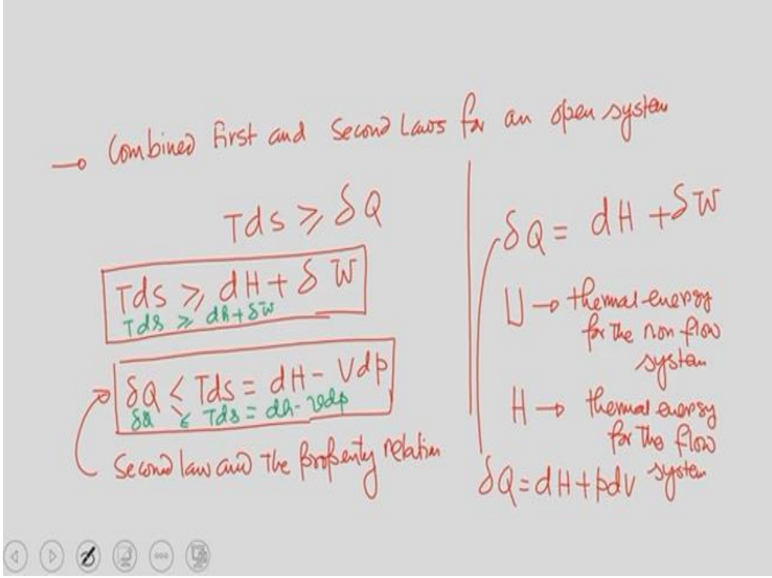

→ Combined first and Second Laws for an open system

$Tds \geq \delta Q$

$\boxed{Tds \geq dH + \delta W}$

$Tds \geq dh + \delta w$

$\boxed{\delta Q \leq Tds = dH - Vdp}$

$\delta q \leq Tds = dh - vdp$

Second law and the property relation

$\delta Q = dH + \delta W$

U → thermal energy for the non flow system

H → thermal energy for the flow system

$\delta Q = dH + pdV$

Now let us write combined first and second laws for an open system. So, this is very important. You know, in a similar way we can write that

$$Tds \geq \delta Q$$

In the previous case, we have used first law applied to the control mass system when we have replaced δQ by $dU + pdV$. So, the expression for δQ will come from first law for the open system. I also have discussed about this particular aspect that this U is the thermal energy for the non-flow system that is the internal energy not specific. This H is the thermal energy for the flow system. So, when the system is open, there is a flow. The thermal energy is not the internal energy rather the thermal energy is internal energy plus some energy which is required to maintain the flow in the presence of pressure.

$$\delta Q = dH + \delta W$$

So, this is the first law. Instead of using U we are writing in the form H that is enthalpy. So, again if the movement of the system boundary follows a quasi-equilibrium process, then still we can write this expression

$$\delta Q = dH + pdV$$

$$\text{Now}, Tds \geq dH + \delta W$$

So, this is the combined first and second law applied to the process executed by an open system. Similarly, again

$$\delta Q \leq Tds$$

$$\text{Property relation} \rightarrow Tds = dH - Vdp$$

$$\Rightarrow \delta Q \leq Tds = dH - Vdp$$

So, this is what we know from the property relation. So, this is obtained by making use of second law and property relation that is second Tds equation; $Tds = dH - Vdp$. So, these are very important to understand.

Now, if you look carefully whether the combined first and second law is for the open system or closed system then we are essentially obtaining some properties like internal energy, enthalpy which cannot be measured directly. We can measure volume, pressure directly. So, volume, pressure, temperature, these are also thermodynamic properties and these can be measured these properties can be measured directly. But if we look at these equations dU and dH, these properties cannot be measured directly. What we can do is that we can still write these equations in specific form.

$$Tds \geq dh + \delta W$$

$$\delta Q \leq Tds = dh - vdp$$

If we go to the previous slide, still we can write

$$Tds \geq du + pdv$$

$$\delta Q \leq Tds = du + pdv$$

So, these are written in the specific forms. So, now, what I was talking about that, we have at least identified that by making use of the combined first and second law or by making use of second law and property relations, we can at least describe several processes and we also can calculate the properties which cannot be measured directly. So, now, we shall be discussing today that there are several processes in our system, when a system is running following cyclic processes. So, if we try to measure the performance efficiency of the system, at least we need to identify several processes, those constitute together to form a cyclic process. So, before I go to discuss about a few specific cases, we could frame some mathematical formulation by making use of the combined first and second laws also, by making use of second law and the property relations. We shall be using these mathematical formulations essentially to calculate the properties at the end of several processes.

Knowing these properties, numerical value of these properties, we shall be able to calculate the total energy whether it is added to the system by heat or it is coming out from the system by work. And of course, if we can do so, we can easily calculate the efficiency. But, I would like to discuss a few important issues. So, slowly we are moving towards the different systems those are there in this course content. First of all, we will start our discussion with power cycle. So, now, whether it is a power cycle or any other cycles, maybe the cycle is a thermodynamic cycle or the cycle is not a thermodynamic cycle, but it is still a mechanical cycle so, what we need to do? So, basically before going to apply the combined first and second law, the most important points someone should remember is to identify the processes. So, here I am discussing that whether someone is interested in calculating efficiency towards predicting the performance essentially you need to go through certain procedures of calculating different thermodynamic properties. So, I would like to discuss a few important points, those points should help us to proceed systematically essentially to perform those processes, but, the bottom line is, we need to apply combined first and second law. Before applying this, combined first and second laws we should now see.

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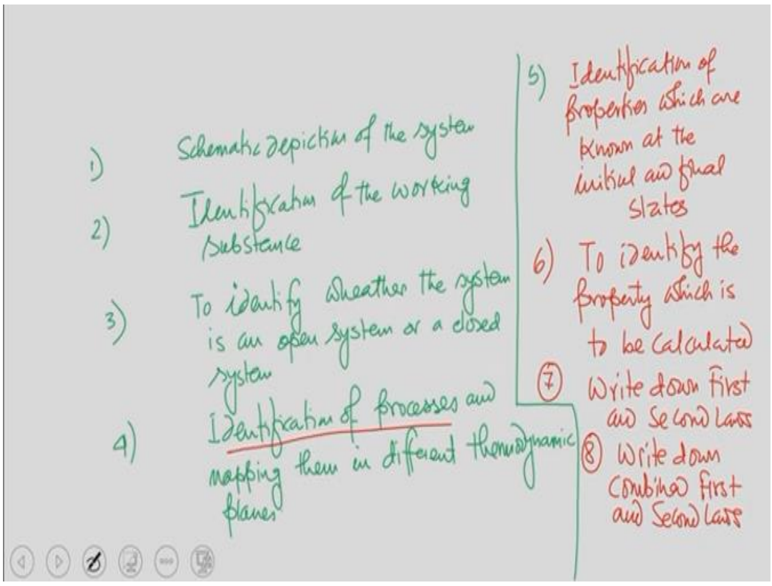

1) Schematic depiction of the system
2) Identification of the working substance
3) To identify whether the system is an open system or a closed system
4) Identification of processes and mapping them in different thermodynamic planes
5) Identification of properties which are known at the initial and final states
6) To identify the property which is to be calculated
⑦ Write down First and Second Laws
⑧ Write down Combined First and Second Laws

As I was talking about in the system, if the system is running through a cyclic process, so there will be a few processes which will constitute together to form the cyclic process. So, first of all we need to do is

1) Schematic depiction of the system. So, this is very important. So, if we can schematically identify the system perhaps it will help us to identify several processes.

When I am talking about thermal power plant, if we can at least visualize, it is difficult to identify or it is very difficult to trace all the components present in the thermal power plant and those components are directly or indirectly associated with the performance of the plant. But at least if we can somehow schematically represent the major components and cyclic process, then it will help us to calculate the efficiency.

2) Knowing the schematic depiction then we need to identify what is the working substance. So, identification of the working substance that is whether it is pure substance like water or gas or air.

Why? Because if it is the pure substance like water then we can make use of the property tables to calculate properties. If it is an ideal gas then we can use the ideal gas relationship to calculate properties. Now we have schematically depicted the system, we have identified the working substance then you need to know whether the system is an open system or the closed system.

3) To identify whether system is an open system or closed system.

So, already these 3 steps, someone should remember to calculate the efficiency. If we can identify the process system is open system or closed system then after identifying it we need to identify the processes. So, next task is what are the processes and we need to map those processes in different thermodynamic planes.

4) So, identification of processes and mapping them in different thermodynamic planes.

So, we should identify the processes and then we said we shall immediately map those processes in different thermodynamic planes. What are the different dynamic planes it may be *p*-*V*, it may be *T*-*s*, it will be *H*-*s* it may be *T*-*V*. So, depending on the system, we have to map those processes in different thermodynamic planes.

Next is we have to identify if any property is remaining constant or not. I am underlining one important line over here, identification of processes; this particular task needs to know whether any particular properties remain in constant throughout the process or it is 0. So, this is very important. So, in a way identification of processes demands to know, whether any particular property is remaining constant throughout the process or not. Next, what you need to do; if we could identify the processes, and if we have mapped those processes, in different thermodynamic planes, then we need to know what properties are known for the initial and final state.

5) Identification of properties which are known at the initial and final states.

So, basically you know that we have identified if any particular property is remaining constant or not. So, for example, if is temperature remaining constant and this is an isothermal process, if the volume is remaining constant, this is a constant volume process. So, this is very important that is why we underline this particular line that identification of processes.

So, basically to get it at least someone should know any particular property or properties, I mean that will depend based on the system. So, basically to know whether any particular property is remaining constant throughout the process, if we know it, we can identify the process and then we can map the process in thermodynamic plane. Now, next task is identification of properties which are known at the initial and final state. I can give you an example, for a pumping process. Now, in a power plant, condensate hood which is collected from the condenser is pumped back to boiler. So, we need to identify properties which are known as the initial and final state. So, you know temperature of water at the inlet to the pump, you know that condensate which is collected at the basin of the condenser, so, at the inlet and the outlet. So, basically the process is almost an isothermal process. So, we can identify what is the temperature. Similarly, we also can calculate properties which are known as the initial and final states. So, we know that when water is pumped from the condenser pressure to the boiler pressure then temperature is remaining almost constant. So, we know that in a pumping process the temperature is remaining constant. So, basically this is the property temperature which is remaining constant at the initial and final states.

6) To identify the property which is to be calculated.
7) Write down combined first and second laws for that particular process.

So, as I talking about pumping process, we need to know; what is the property we have to calculate because you have to calculate the pressure at the outlet of the pump knowing fully that the temperature is not going to be changed during the course of pumping process. And then we need to write down the combined first and second laws.

8) Write down combined first and second laws for that particular process.

So, this is very important. Yet there are a few more steps someone should know before attempting to identify the process and calculate the property which is to be calculated.

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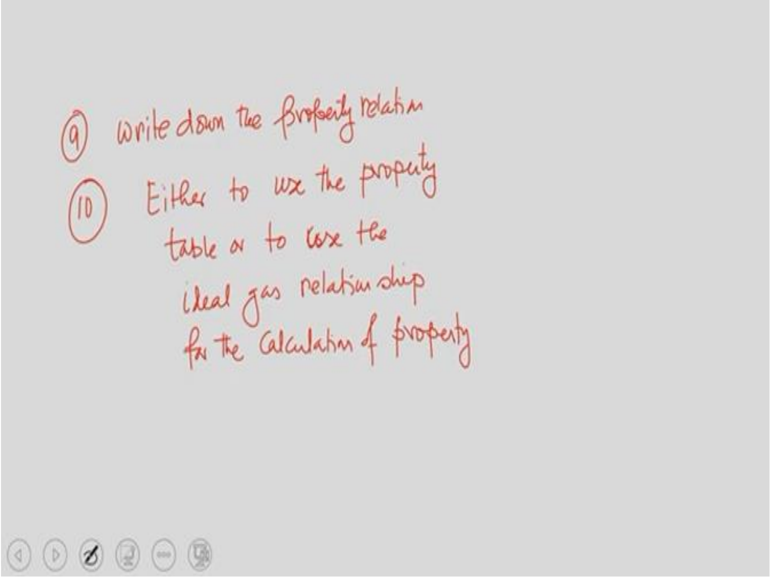

⑨ write down the property relation

⑩ Either to use the property table or to use the ideal gas relationship for the calculation of property

9) Write down the property relations.

As I told you, the property relations are useful to calculate properties which are not directly measurable. So, accounting for that particular aspect we can write this particular step 9. Number 10, the last point is very important point. Last point is very much connected to the point which we have mentioned in point 2 that is identification of the working substance. We can even write first law, second law, we have identified the property which is to be calculated & we are writing the combined first and second law. We are also writing the property relation.

Why we are doing so? We are doing so, to calculate the property which is not directly measurable or calculated. Now we need to consult with property table or not? So, basically the last point is connected to point 2 because if the working substance is pure substance like water, we can directly use the property tables to calculate the properties. If it is an ideal gas then we have to use the ideal gas relationship to calculate the properties.

10) Either to use the property table or to use the ideal gas relationship for the calculation of property.

So, this is very important. This we can identify from this particular point that whether the working substance is pure substance or it is an ideal gas. Why I have written so? I could have directly started my discussion from the identification of several processes, but I have discussed this particular topic in a particular aspect only to make you understand that we can use property table or we can use ideal gas equations to calculate properties. But, it should not be random, we need to proceed systematically by knowing the steps rather intermediate steps correctly. So, basically, these points which I have listed down over here will help you to proceed systematically in the right direction knowing the intermediate steps correctly.

So, now, let us first discuss about one particular process. I will be discussing several processes. So, let us first discuss about one important process that is the reversible constant volume process. So, if it is reversible constant volume process, then what would be the equations that we will be applying and then of course, if you would like to map the particular process in thermodynamic planes, then how can you do it.

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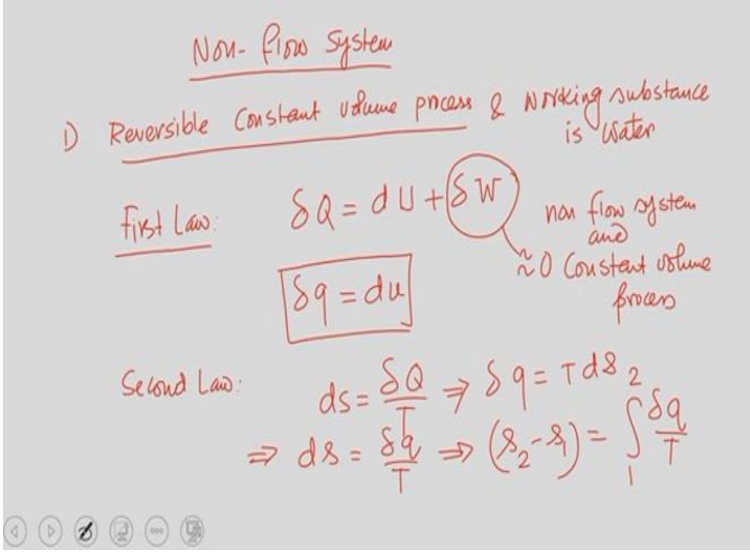

Non- flow System

1) Reversible Constant volume process & working substance is water

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

non flow system and constant volume process ≈ 0

$$\boxed{\delta q = du}$$

Second Law: $ds = \frac{\delta Q}{T} \Rightarrow \delta q = T ds$

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

So, if we write, first process that is 1) Reversible constant volume process. So, we have to write first law, we have to write second law and then we can write the combined first and second law. So, we shall be writing all these you know the relevant equation for all these processes for a non-flow process.

So, basically if we considered the system to be a non-flow system and if we are applying whatever we have learned from today's class. Let us discuss this process first and if the time permits, we will go to the next one otherwise, we shall discuss in the next class.

1) Reversible constant volume process & working substance is water

So, if we now go to these steps which we have written earlier; in this case first, second, third steps are not required because it is given that it is a non-flow system. Fourth is not also required, because identification of processes is not required because it is given reversible constant volume process. It is a non-flow system & working substance is given. So, now, we can directly write down first and second law, because nothing is said about or is given or which properties to be calculated. So, it is a generic discussion. So, from point 1 to point 6 are not required. So, straightaway we can go to point 7.

$$\text{First law for the non} - \text{flow system and the working substances water} \rightarrow$$

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

So, now for non-flow system and constant volume process $\delta W = pdV = 0$. So, if we consider the process is a quasi-equilibrium process and the volume is constant then $\delta W = pdV = 0$. So, the change in volume is not there, hence the term is equal to 0. So, we can write in specific form

$$\delta q = du$$

So, this is first law. So, you can understand the change in internal energy within the system is nothing but the amount of heat which is being added to the system. If heat is added to the system and the change in volume of the substance is 0, then the change in internal energy of the substance is nothing but the amount of heat which is being added to the system.

$$\text{Second law for reversible process } \rightarrow ds = \frac{\delta Q}{T}$$

We have not used the inequality sign. Why? We have accounted for this particular term that is reversible process. We can write in a specific form

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

We can write so as this is exact differential & this is point function. So, we can write the change in entropy between the initial and final states is nothing but equal to the amount of heat that is transferred to the system through that particular system boundary where T is the temperature of the system boundary. So, the second law gives that change in entropy which is nothing but the integration of $\frac{\delta q}{T}$ via reversible path, where T is the temperature of the system boundary through which heat is transferred to the system.

So, now, this is second law and let's go to the step 7 that is combined first and second law. Now for the reversible process, the combined first and second law does not give you any special equation. So, basically, the next equation that I will be writing is the property relation, it is not an additional equation for the reversible processes. It may be an extra or additional equation for the irreversible processes that we will discuss in the next class.

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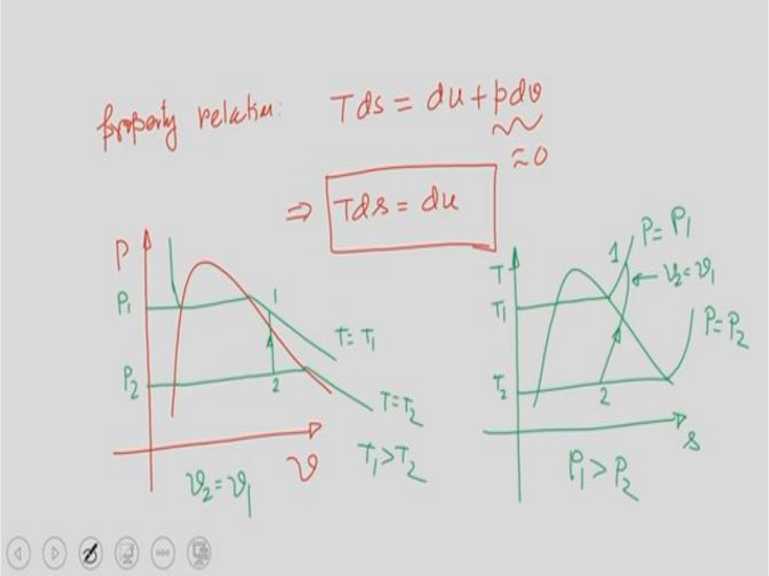

Property Relation in specific form → $Tds = du + pdv$

So, you know that this $pdv = 0$, so, $Tds = du$

So, this is the property relation. This is basically valid for any processes, but the process is reversible one. I have told you initially that even if this equation is valid for any processes, the clue is before applying this equation to any processes, we have to integrate it over the reversible path and the results of integration can be applied to any processes. Hence, as long as the process is reversible, that is not an issue.

So, you know that for this particular reversible constant volume process where the working substance is water, we have systematically written first law, second law and property relation.

If the working substance is not water & if it is air, we shall discuss it again when we shall be discussing about different mechanical cycles. For the time being, basically the first law, the second law, the property relation are stated above. You cannot say that the property relation is an additional equation, this is essentially the equality of the combined first and second law.

If we go back to the previous slide, so, in this equation, you can see that $Tds \geq du + pdv$. So, this is the combined first and second law, if you eliminate this inequality sign you are getting $Tds = du + pdv$ and this is the property relation that we have written. So, this is not an additional equation for the reversible processes, it may be an additional equation for the irreversible processes.

So, now, quickly try to map the processes in different thermodynamic planes. So, let us map it in p-v plane. So, if X is volume and Y is pressure, it is reversible constant volume process. Here at state 1, $T = T_1$ and at state 2 $T = T_2$. So, maybe this is the process, we are supplying heat to the system, temperature increases and this is reversible constant volume process, you know volume does not change. So, $v_2 = v_1$. So, we have to map this process in different thermodynamic planes. So, maybe at state 2 pressure is P_2 and at state 1 it is P_1. So you can see the pressure changes.

If we try to map this particular process in T-s plane, then what would be the process of constant volume. You know that there is temperature T_1& T_2. So, you can understand that$T_1 > T_2$. So, this is P = P1, this is P = P2. 54 00 I am assuming that you already have learned this P-T, T-V, P-V diagrams from your basic thermodynamics course. So, now, for reversible constant volume process, the process will be as shown in slide. There is state point 2 and 1. So, this is the reversible constant volume process and for this particular process $v_2 = v_1$. Here volume is remaining constant. Upon receiving heat, thermodynamic state is getting changed from 2 to point 1, so pressure increases from P_2 to P_1. So, here $P_1 > P_2$ temperature $T_1 > T_2$. This is quite normal that upon receiving heat, the state point is changing from state 2 to state 1, temperature increases, pressure also increases, but volume remaining constant.

So, this is all about the mapping a reversible constant volume process in this 2 thermodynamic planes. Now, if you would like to summarize today's lecture, we have discussed about the necessity of framing the mathematical formulation of the combined first and second laws, which will be applied to any processes. Having a little bit of discussion on this particular topic, we have moved to figure out a few points which will help us to calculate the overall performance of the system. And we have listed down all these points and these points are very much necessary before applying the combined first and second law to any particular process. And then, we have taken one particular example, that if the processes are reversible constant volume process & the substance is water and the process is occurring in a system which is a non-flow system.

And then we could write the first law, second law also the property relation. In fact, we also have discussed that the property relation for this particular category is not an additional equation rather it is the equality of the combined first and second law. Then, we have tried to map that particular process in P-V and T-V planes.

With this, I would like to stop here today. And in the next class we shall continue our discussion on this particular topic. And again we shall be identifying a few more processes for both non-flow and flow and then we shall try to map those processes in different thermodynamic planes. Thank you very much.