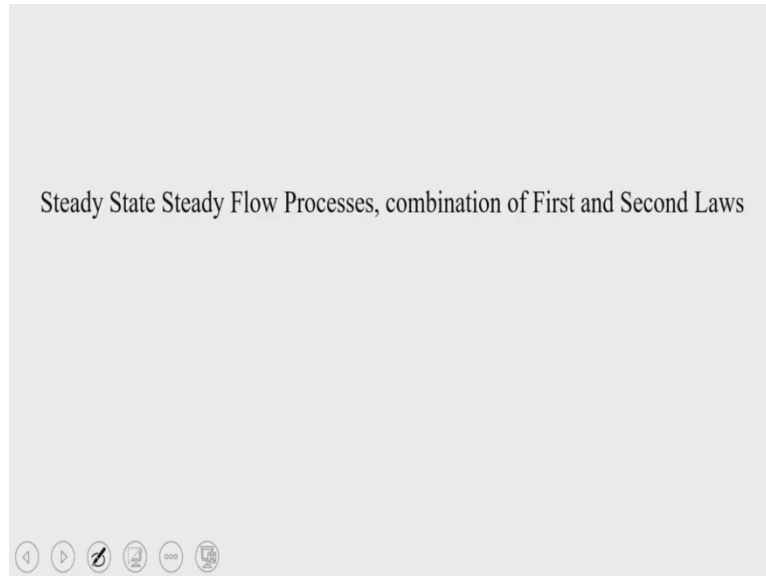


Thermal Engineering: Basic and Applied
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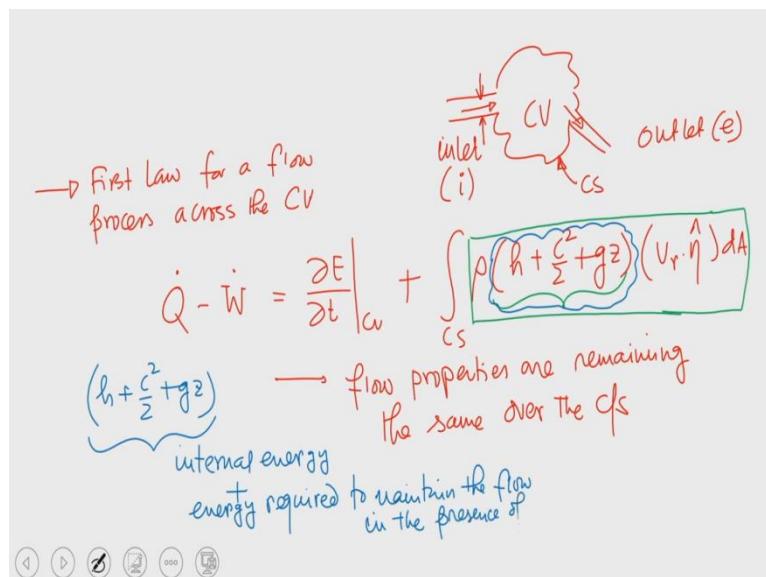
Lecture – 03
Steady State Steady Flow Processes Combination of First and Second Laws

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Today we shall discuss about the first law of thermodynamics for a flow process across the control volume. You know that in the last class, we were discussing about the first law of thermodynamics for of flow process across the control volume and we have established the mathematical expression of this equation in the rate form.

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So, if we try to write that equation first law for a flow process across the control volume, in fact in the last class we have derived the expression that is

$$\dot{Q} - \dot{W} = \frac{\partial E_{CV}}{\partial t} + \int \rho \left(h + \frac{1}{2}c^2 + gz \right) (V_r \cdot \hat{n}) dA$$

Today, we shall discuss that if this equation can be applied to a special process and that process is steady state steady flow process, then what will be the mathematical form of this equation.

We have also discussed that to arrive here, we have taken one important assumption that the properties are remaining invariant over the cross section through which flow is occurring. So, if we consider a control volume say, there is inlet i and there is outlet that is e or exit. So, the flow is taking place and this is the control volume. So, this is control surface and this is cv. So, over this cross section the flow properties are remaining same. So, this is one important assumption. If we have multiple inlets and multiple exits, we also need to consider this assumption that the flow properties do not vary over the cross section. So, now taking this assumption, so, we could arrive here. And in the equation, basically the term $\rho (V_r \cdot \hat{n}) dA$ is mass flux, which is multiply by another term. And that term $\left(h + \frac{1}{2}c^2 + gz \right)$ basically the internal energy plus the energy required to maintain flow in the presence of pressure both at the inlet and exit. So, this is very important to know because, the equation that we are going to derive today is an important equation and we shall be using this equation in different cycles that will be discussed in this course particularly in the power cycle.

So, this term $\rho (V_r \cdot \hat{n}) dA$, if we integrate over the control surface, it is the mass flux. So, that is mass flux in minus mass flux out and this term is multiplied by these term $\left(h + \frac{1}{2}c^2 + gz \right)$. So, this is specific energy that is specific internal energy plus energy required to maintain the flow in the presence of pressure.

$$\left(h + \frac{1}{2}c^2 + gz \right) = \text{Internal energy} + \text{Flow energy}$$

Flow energy = (energy required to maintain flow in the presence of pressure)

So, about the flow energy, you have probably studied in fluid mechanics course. So today just you have recapitulated what we have discussed in the last class, starting from this equation, if we try to go to derive the equation for the special process and the special process is steady state

steady flow process. So, if the process is steady state steady flow, then what will be the form of this equation?

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First Law of Thermodynamics
for a steady state steady flow
process across the CV

Energy balance $\dot{Q} - \dot{W} = \frac{\partial E}{\partial t} \Big|_{cv} + \sum \dot{m}_e (h_e + \frac{c_e^2}{2} + gz_e) - \sum \dot{m}_i (h_i + \frac{c_i^2}{2} + gz_i)$

mass balance $0 = \frac{\partial m_{cv}}{\partial t} + \sum \dot{m}_e - \sum \dot{m}_i$

flow properties (h, c, g, z) do not vary over the cs

So, I am writing for first law of thermodynamics for a steady state steady flow process across the control volume. You know that, I have underlined these 2 coupled keywords that is steady state steady flow. So, we shall discuss the significance of this particular 2 keywords in the context of the analysis that we are going to do today. So, again let us assume that we are having control volume with this inlet i and exit e.

So, flow is going into the control volume and flow is coming out from the control volume. So, this is control surface and this is cv. And if we use this particular assumption that the flow properties do not vary over the cross section, we may have multiple inlets and exits. So, even if we have multiple inlets and exits, flow properties like enthalpy, velocity, z/g that is height of the cross section and g. So, basically these four properties like h, c, g and z do not vary over the cross section. So, if this is not varying over the cross section and the mass flow in and mass flow out that means this $\int \rho (\mathbf{V}_r \cdot \hat{n}) dA$ that is nothing but the mass flux. So, if we apply this at the inlet, so, this is mass flux into the control value, if we apply at the outlet that is mass flux out from the control volume.

So, I mean if this properties are not varying over the cross sectional area A through which the flow is flowing and entering into the control volume then we can take it out and simply we can write the following equation. As I told you that I can take it out and $(\mathbf{V}_r \cdot \hat{n})$ is positive for the outflow or at the exit and is negative at the inlet because this is a normal pointing outwards

from the control surface. So, the dot product will be negative for the inlet and it will be positive for the outlet.

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

So, if we take this at the exit so, we can denote enthalpy velocity and z at the exit. I have taken this summation sign because we may have multiple inlets and multiple exits. So, accounting for the possibility of having multiple inlets and multiple exits, we have considered the summation sign. So, basically this is the first law of thermodynamics. Till now, we did not say anything about the process is steady state or steady flow, but this is the first law of thermodynamics for any process across the control volume and we have written another form of this equation over here.

So, here one important assumption is that the flow properties do not vary over the cross section through which either flow is entering into the control volume or flow is getting out from the control volume that is at e. So, now we also can write the mass balance equation. So, mass balance equation if we write that you have seen in the last class that is

$$0 = \frac{\partial m_{CV}}{\partial t} + \sum \dot{m}_e - \sum \dot{m}_i$$

So, this is mass balance and this is the equation which is essentially for the energy balance. So, we now apply this equation for the steady state steady flow process across the control volume and start with the mass balance equation.

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The slide contains handwritten notes in blue and red ink. At the top, it shows the general mass balance equation: $0 = \frac{\partial m_{CV}}{\partial t} + \sum \dot{m}_e - \sum \dot{m}_i$. A box labeled 'Steady flow' points to the equation $\frac{\partial m_{CV}}{\partial t} = 0$. To the right, a diagram of a control volume (CV) is shown with a boundary and the equation $\frac{\partial}{\partial t} \int_{CV} \rho(n) dt = 0$. Below this, a box contains the simplified mass balance equation $\sum \dot{m}_e = \sum \dot{m}_i$. The energy balance equation is written as $\dot{Q} - \dot{W} = \left(\frac{\partial E}{\partial t} \right)_{CV} + \sum \dot{m}_e \left(h_e + \frac{c_e^2}{2} + gz_e \right) - \sum \dot{m}_i \left(h_i + \frac{c_i^2}{2} + gz_i \right)$. A red circle highlights the $\frac{\partial E}{\partial t}$ term, with a red arrow pointing to it from the text 'Steady state' and 'steady energy state'. A note below says '(energy within CV does not vary with time)'. At the bottom of the slide, there are navigation icons and a timestamp '22:43:50.22'.

$$\text{Mass balance equation} \rightarrow 0 = \frac{\partial m_{CV}}{\partial t} + \sum \dot{m}_e - \sum \dot{m}_i$$

That is what we have discussed in the last class. Now, we are going to have the set of equations essentially for a process and that process is steady state steady flow. You have studied about steady flow in the context of our fluid mechanics course. So, what do we mean by steady flow? Steady flow is a flow in which the flow properties do not vary with time at any given location.

So, if it is steady flow, flow properties do not vary with time at any location. So, now you have considered the flow inside the control volume with this inlet and outlet. So, inlet and outlet is remaining fixed and if we apply the steady flow assumption so, we can write

$$\text{Steady Flow} \rightarrow \frac{\partial m_{CV}}{\partial t} = 0$$

So, try to recall the Reynolds transport equation. So, let's try to write the first term of the right hand side of the Reynolds transport equation, that is $\frac{\partial}{\partial t} \int \rho n dV$. (CV under integral sign) So, if we try to recall this in the context of the Reynolds transport theorem, we can write this equation. You know that from mass balance you can really write that $\frac{\partial m_{CV}}{\partial t} = 0$, if the flow is steady. So, this $n = 1$ so, if we try to write this equation, I mean to obtain the mass balance equation, we consider η , because n is abstract it could be any property if $n = \text{mass}$ then $n = m / m$ that is 1. So, essentially the first term is $\frac{\partial}{\partial t} \int \rho n dV$

So, now, question is what is in that is m_{CV} . Now, in steady flow that is flow properties do not vary with time. So, ρ is also an important property of the fluid. So, it will not vary with time. If ρ does not vary with time, then definitely m_{CV} will not vary with time, then this term will be equal to 0. So, the consequence of steady flow is that $\frac{\partial m_{CV}}{\partial t} = 0$. So from this mass balance equation we can write

$$\sum \dot{m}_e = \sum \dot{m}_i$$

So, this is the consequence. Remember it because when we shall start discussing about the cycles for example power cycles, refrigeration cycles, different mechanical cycles related to the thermal system, we shall be applying the steady state steady flow processes and if we apply steady state steady flow process assumption, then from the mass balance equation we can write directly that $\sum \dot{m}_e = \sum \dot{m}_i$.

We have taken summation considering the fact that we may have multiple inlets and multiple exits. So, now, let us go to the energy balance equation. So, now see we have already considered steady state assumption. So, basically the steady state steady flow process is a special process. We have already taken into account steady flow case. So, now remaining is steady state.

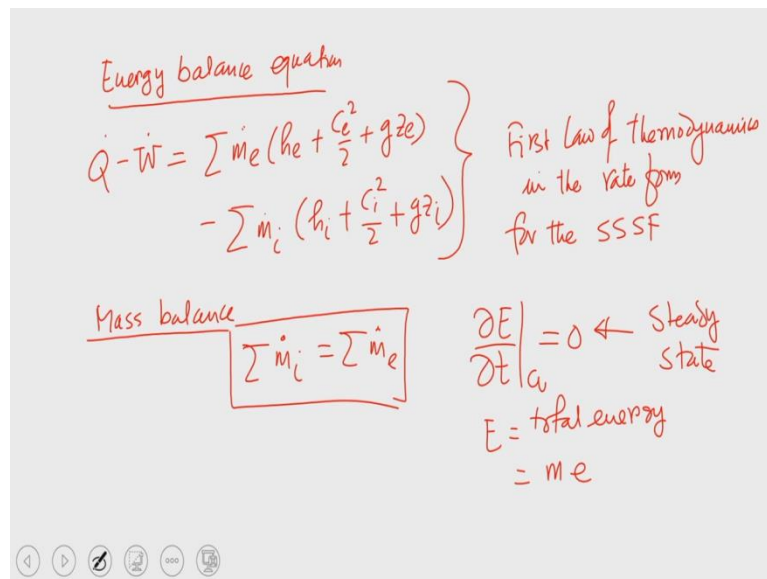
Energy balance equation \rightarrow

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

Now, we shall be using another coupled keyword that is steady state. So, what do mean by steady state? Here the steady state refers to the steady energy state. So, if I try to explain it even more then it indicates that energy within the control volume does not vary with time. So, basically steady energy state indicates that the energy within the control volume does not vary with time. So, if energy within the control volume is not varying with time we can make this term equal to 0. So, that means, accounting for this steady state case

$$\left(\frac{\partial E}{\partial t}\right)_{cv} = 0$$

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So, energy balance equation we can write

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

So, this is the equation which is obtained for the steady state case. I would like to discuss a few important critical issues which is involved with this particular equation. So, this is energy balance equation and from the last slide we have seen that mass balance equation can also be written like this.

$$\sum \dot{m}_e = \sum \dot{m}_i$$

Basically as first law talks about the conservation of energy, so this is first law of thermodynamics applied to the steady state steady flow processes, but in the rate form. So, this is the rate equation of the first law of thermodynamics applied for the steady state steady flow processes, I am writing SSSF.

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

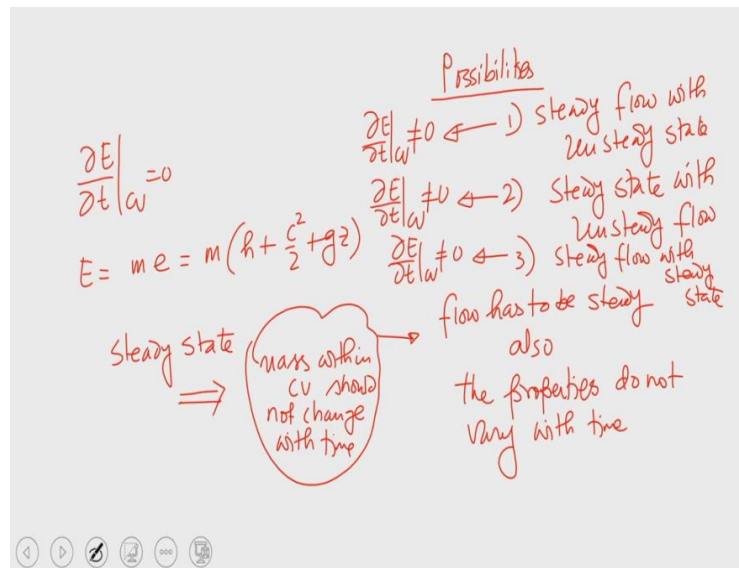
(First law of thermodynamics in the rate form for the SSSF)

So, for the steady state steady flow processes this will be the first law of thermodynamics in the rate form. We have written that for the energy state $\frac{\partial E}{\partial t}$ within control volume equal to 0 and this is essentially for the steady state. So, we are discussing this is for the steady state. Now, why I like to do this exercise? We know that this E is the total energy.

$$E = \text{Total energy} = me; e = \text{specific energy}$$

So, if this total energy is needed to be time independent means if the total energies does not vary within the control volume with time, that means, mass also should not vary within the control volume with time as well as e will not vary within the control volume with time.

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$$\text{Steady State} \rightarrow \frac{\partial E}{\partial t} = 0$$

$$\text{Total Energy, } E = me = m \left(h + \frac{c^2}{2} + gz \right)$$

So, what I did like to tell you is that if we need to make the quantity 0 considering the assumption of steady state, then you know that the total energy will not vary within the control volume that is what we have discussed. If total energy has to remain constant within the control volume, mass within the control volume should not change as well as the specific energy should not vary within the time. So, steady state implies that mass within the control volume will not change with time. If mass within the control volume has to remain constant, then density will not change with time that is what we have learned.

So, that means the steady state requires that mass within CV should not change with time. If mass does not change within the control volume with time, is it sufficient to ensure that we can write $\frac{\partial E}{\partial t} = 0$? No, because maybe mass does not change with time, but the properties may vary with time. So, the product may vary with time.

So, most important part is that if you need to ensure that the steady state that is steady energy state that means, total energy within the control volume will not change with time then it necessitates that the mass within the control volume should not change with time. So, what does it you know physically mean? Flow has to be steady. So, that means, try to understand if you would like to ensure that the state will be steady, which in a way requires that the flow has to be steady. So, that is why the couple keywords steady state steady flow came into the picture. So, if it might be a case that the mass within the control volume is not changing with time, but these properties you know vary with time. In that case, it would be steady flow with unsteady state.

So, what are the possibilities?

- 1) Steady flow with unsteady state.
- 2) Steady state with unsteady flow

So, maybe the properties are not varying within the control volume with time but mass is varying with time even then we shall not write that $\left(\frac{\partial E}{\partial t}\right) = 0$. So, to have you know $\left(\frac{\partial E}{\partial t}\right) = 0$, mass within the control volume should not change with time and also the properties do not vary with time. So, this is only important measures that we get from today's class is that if we need to have steady state, steady flow should be there, otherwise we cannot ensure that it would be steady state. So, even if the state is steady, but if the flow is unsteady that means steady flow

that means mass is not changing but unsteady state, so, these quantities that is properties are varying with time, in that case $\left(\frac{\partial E}{\partial t}\right)_{CV} \neq 0$.

1) Steady flow with unsteady state $\rightarrow \left(\frac{\partial E}{\partial t}\right)_{CV} \neq 0$

2) Steady state with unsteady flow $\rightarrow \left(\frac{\partial E}{\partial t}\right)_{CV} \neq 0$

This is because state is steady but flow is unsteady. So, maybe this quantity is not changing with time but mass will change with time. Last case say if we ensure

3) steady flow with steady state $\rightarrow \left(\frac{\partial E}{\partial t}\right)_{CV} = 0$

If the flow is steady m is not getting changed & if the state is steady properties are not varying with time. So, you can write $\left(\frac{\partial E}{\partial t}\right)_{CV} = 0$. But there again maybe a case that even though mass is not changing, properties are not changing but their product might change in that case also we cannot write that $\left(\frac{\partial E}{\partial t}\right)_{CV} = 0$.

So, it is important that steady state steady flow that means, if we need to have steady state within the control volume the product of the steady flow and steady state will be equal to 0. So, that means, flow has to be steady together with that the properties do not vary with time and their products should not vary with time. So, it is not a case that the steady flow is steady state, but as I told you that maybe m is not changing with time, properties are not varying with time, but their product may change with time. So, if we have to ensure that steady state steady flow then the product will not change with time.

So, whatever you have written that the energy balance equation that is first law of thermodynamics in the rate form applied to the steady state steady flow process across the control volume, if we need to attain this equation, so, this energy balance is not balanced in an isolated manner, but it has to be coupled with the mass balance. Because if mass is changing with time, then we cannot write that $\left(\frac{\partial E}{\partial t}\right)_{CV} = 0$. So, basically this equation we can write only when product of mass and properties will not change with time. So, this is very important, why I am telling this because you know that we shall be using this equation frequently maybe from the next week onwards. So, before applying this particular equation, we may not get enough

time to explain from where this equation is coming and why we are writing this particular equation in the context of that process, so I am discussing this part. So, these are the critical part. So, basically you should remember that this is the mass balance equation, this is the energy balance equation and for the steady state steady flow processes the energy balance is not a balance in an isolated manner, but it has to be coupled with the mass balance equation.

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The slide contains handwritten notes in red ink. At the top, it is titled "Energy balance equation". Below the title, the equation is written as $\dot{Q} - \dot{W} = \sum \dot{m}_e (h_e + \frac{C_e^2}{2} + g z_e) - \sum \dot{m}_i (h_i + \frac{C_i^2}{2} + g z_i)$. To the right of this equation, it says "First Law of Thermodynamics in the rate form for the SSSF". Below this, it is titled "Mass balance" and the equation $\sum \dot{m}_i = \sum \dot{m}_e$ is boxed. To the left of the box, it lists three assumptions: "1) Properties are not varying over the CS", "2) Steady state", and "3) Steady flow". To the right of the box, it says $\frac{\partial E}{\partial t} \Big|_c = 0 \leftarrow$ Steady state, and below that, $E = \text{total energy} = m e$. At the bottom of the slide, there are several small circular icons.

So, to arrive at this equation, we have taken up few assumptions

- 1) properties are not varying over the cross sections through which flow occurs
- 2) steady state
- 3) steady flow

So, consider all these assumptions, properties are not varying over the cross section through which flow occurs state is steady and flow is also steady and as I told you product of mass and properties should not change with time.

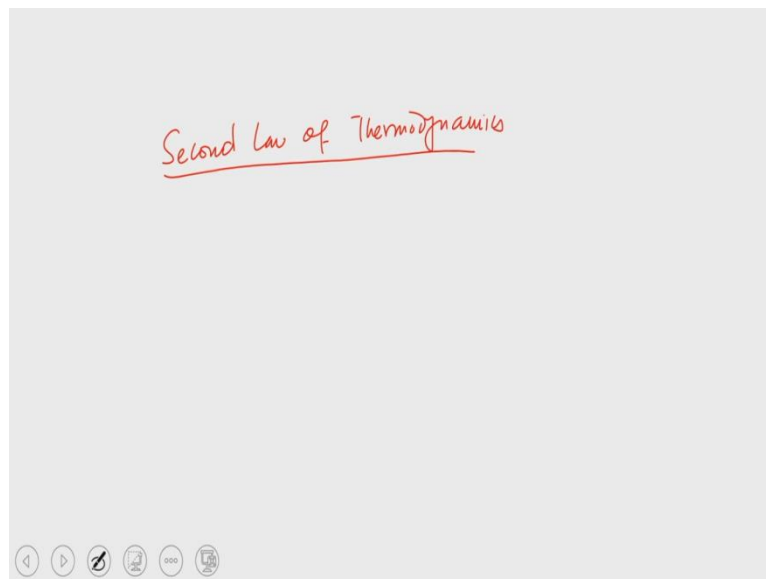
So, with this I would like to just complete the discussion related to the first law of thermodynamics because probably you have studied another important process that is unsteady state unsteady flow process USUF. So, if the state is unsteady and flow is also unsteady, then the form of the first law of thermodynamics is also an important equation.

But as I told you that in this particular course several processes will be discussed and whenever we would like to discuss all those processes, we will be taking this important assumption that the process is steady state steady flow. So, considering this just I wanted to have this discussion,

that what would be the form of the first law of thermodynamics for the steady state steady flow process.

So, before going to complete today's lecture, just I did like to briefly introduce what is second law? In fact in a few classes in this particular course, contents are designed in such a way that in the first of few classes, we shall be discussing about the combined first and second laws applied to several processes. So, before going to discuss that particular topic, let us briefly discuss about what is second law of thermodynamics.

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So, you have studied about 2 important statements of the second law that is Kelvin Planck and Clausius statement. Before coming to those statement, I would like to recapitulate although you have learned it from basic thermodynamics course, but I would like to discuss the need of the second law. We have discussed about first law then why second law is coming. So, definitely we need to know the limitations of the first law and probably there are a few limitations of the first law and it is because of this reason, the second law of thermodynamics is there. So, why second law is important, you know we have talked about the first law & you have seen that it is the statement of the conservation of energy. Now, we have discussed about energy transfer across the control surface, energy exchange between system and surroundings, when the system is a control mass system, but it mostly talks about the conservation of energy, but it does not provide the directionality of the processes. So, basically we have talked about that if energy is given by heat to the system, we can take it positive, if energy is coming out from the system by work it is taken as positive, whether the energy I mean heat will flow from the surrounding into the system or vice versa.

So, that means, when you are talking about if work is coming out from the system that is energy is coming out from the system by work we can take it positive. That means, if we take it positive, so, there is a possibility that work might go into the system. So, this directionality constraint cannot be described by using the first law of thermodynamics or by making use of the first law of thermodynamics.

So, one issue that second law provides permissible direction of all the processes in you know real applications. So, this is one. Number 2 is you have studied that, there are many properties including extensive and intensive properties, there are a few properties which you cannot directly measure. So, those properties are obtained from different thermodynamic relations. So, to quantify such properties like enthalpy, internal energy, we need second law of thermodynamics.

So, I mean first law, you know cannot provide the quantification or the ways by which we can quantify those properties which are not directly measurable. Second is that, as I was telling that in this particular course, we will be discussing about different thermal systems. Say for example, if it is a thermal power plant, probably there are several components in a power plant and these components are there to ascertain that certain processes can be executed through those components.

So, when we talked about the thermal power plant, essentially, one important part is the optimum design, why? Because we need to know the performance of the plant. So, if we try to quantify the performance or thermal performance of the power plant, we also need to look at the performance of individual components which are integrated to this particular plant.

So, to measure or to assess the performance of thermodynamic process second law is used. So, basically when there is a flow process, whether the process is occurring in a compressor or in a turbine or in a pump, we need to measure the performance or we need to assess the performance. So, second law is used to measure or to assess the performance of thermodynamic processes. And another important objective is that second law provides us the concept of an important quantity that is entropy. So, basically the concept of entropy is essentially coming from the second law of thermodynamics. So, there are maybe a few more. But at least we have discussed of few objectives which cannot be described by making use of the first law of thermodynamics and that is why second law of thermodynamics came into the picture. Now,

you know that just describing the statement of second law like Kelvin Planck statement or Clausius statement, I would like to recap those, but you have learned all those and you can get it from any classical book.

So, you know that what is Kelvin Planck statement and what is Clausius statement. So, basically, I mean the concept of heat engine and heat pump, or refrigerator. So, whether it is heat engine or if it is heat pump, the fundamental difference between these 2 cyclic devices is that one is work producing device, another is the work absorbing device.

So, we have seen whether it is work producing device or it is our work observing device, processes are involved. All those processes rather cyclic processes are not fully reversible. So, some degrees of irreversibility are associated with the processes, whether it is a work producing device or it is a work observing device or it is a heat interacting device.

So some degrees of irreversibility is there. So, basically the process is deviating from the reversible process. So to know the extent of the deviation of the process from the reversible process, second law of thermodynamics will give us a clue about one particular term which can be used to quantify the deviation of reversibility. So, when you are talking about irreversibility, the presence of irreversibility will destroy the performance of the processes which are there. I mean, just for example, if we talk about that to complete a cyclic process there are 4 or 5 sub processes & in all these sub processes, if some degrees of irreversibility is there, then it is definitely going to destroy the overall performance of the system.

So you know that some degrees of irreversibility is there, but, the processes are deviating from the reversible process. Now in what extent the processes are deviating from the reversible process, we need to know. So, it is the second law of thermodynamics by which we can quantify, we can define one important term which will give us a clue about the extent of deviation of that particular process from the reversible process.

And that aspect we shall discuss, I would like to discuss in greater detail before I go to discuss about several other modules of this course and this particular aspect we shall discuss in the next class. So, with this I stop here today. Thank you.