Thermal Engineering: Basic and Applied

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Lecture – 07
Description of Steam Power Plant: Application of First and Second Laws to Different Processes

I welcome you all to the session of Thermal Engineering and the topic of our today's discussion is the Description of a Steam Power Plant. You know that we have discussed about the basic of thermodynamics and we have done this recapitulation or we have done this exercise only to recap, what we have learned from the basic thermodynamics and those laws which we have learned that is first law, second law in particular combine these two laws, the mathematical form of these two laws will be required to analyse several processes which are there in a steam power plant. So, today we shall briefly discuss about the steam power plant. Because we shall be discussing several thermodynamic cycles which are used to describe the processes of steam power plant. We shall discuss about several pertinent issues required to modify and also to have smooth operation of the power plant in greater detail in our subsequent classes. But today just for the understanding we will discuss the different processes that constitute to form a cycle which is used to describe the performance and operation of the power plant.

Alongside you know that whatever we have learned from our previous classes that is first law applied to steady state steady flow process and the second law, we shall see the applicability of these two laws in the context of the analysis of several processes which are there in a steam power plant. So, what I will do today, just I will try to describe several processes in a thermal power plant. But if you try to recall, in one of the previous classes I have listed down a few important points. One of the important points is if you would like to analyse the process or processes which are there in a system, our first objective should be to have the schematic depiction of the system. Only then we can easily go to the next steps essentially to have and not just qualitative rather both qualitative as well as quantitative estimation of the efficiency.

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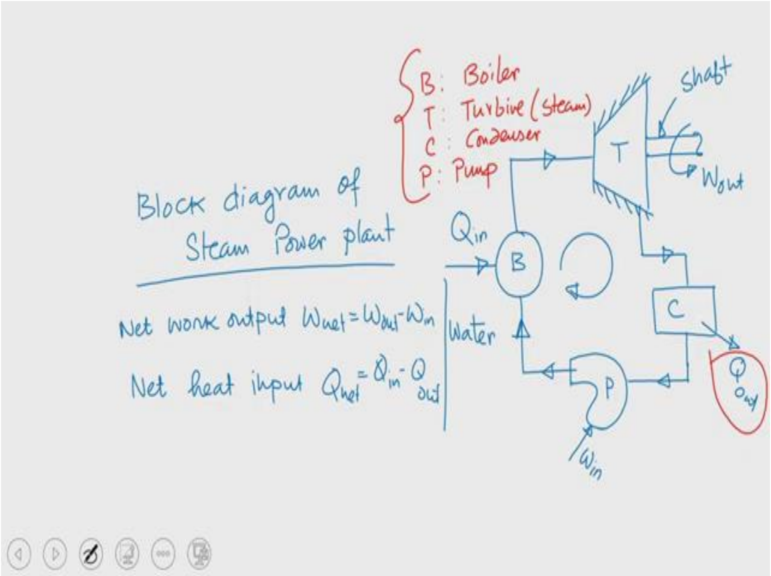

So, we try to discuss today the block diagram of steam power plant. So, I am trying to just represent not all components but the major components which are used in the power plant. So, the first component is boiler and next important component is turbine. And I would like to discuss a few important issues before I go to discuss about the rest of the components of this particular system.

So, in this particular device, mechanical device or component, there is the working substance which is again another important points if you try to recall, we have discussed. So, first we need to depict the system schematically then we need to identify what is the working substance. So, in this steam power plant the working substance is rather steam or steam water mixture.

So, we allow water to go into the boiler, this is a mechanical device. When the working substance is entering into the boiler, upon receiving heat from an external source, converted into steam. And that steam is taken into another mechanical device or component that is called turbine, of course, steam turbine wherein that steam is allowed to flow. And while steam is flowing through this turbine it does work on the rotating part of this device. So, you know that it is not so, straightforward and I have drawn it schematically by just showing these two components. But in real, application, you will find that the steam which is coming out from boiler is not directly taken into turbine rather steam is allowed to pass through flow nozzles of course, to achieve some stated purpose and then only when steam is coming out from the flow nozzle it is directed to the turbine. And it impinges the turbine blades and by virtue of momentum change the rotating part of this turbine that is called runner rotates. And you know that the turbine blades are mounted on this shaft so, that is called turbine shaft.

So, these blades are mounted on this shaft and as blades are rotating, turbine shaft will rotate and this shaft is common. So, the shaft is connected to the shaft of an alternator through mechanical coupling. So, you all have studied coupling in machine design course. So, basically this shaft is connected to the shaft of an alternator through mechanical coupling. Since the turbine shaft is rotating so, the shaft of an alternator will rotate and from there we will be getting electricity. We do not discuss that part because that is beyond the scope of the discussion in this course. So, what we can understand that upon receiving some amount of energy in the form of heat that energy is getting converted into work. So, basically you know that if it is a system, in this system we are supplying energy in terms of heat or by heat and we are getting work output from the turbine so that is energy out from the system in the form of work.

So, what I would like to tell you that I did not complete the circuit. So, I did not complete the circuit but I would like to discuss an important issue. So today, we shall try to discuss about the applicability of first and second laws in the context of the description of several processes which are there in a steam power plant.

So, if it is as system like this as discussed earlier, we are supplying water, we are supplying heat maybe by burning coal if it is the thermal power plant, if it is diesel fired boiler; so, maybe diesel will be used to burn. And out of this combustion process, energy will be utilized to heat up the water which is circulated through the boiler. And when it is being circulated through the boiler it will be converted into steam and that steam is taken to turbine through flow nozzles.

I did not show the flow nozzles, rather I will be discussing this flow nozzle again in one of the subsequent lectures. So, we are getting work output but here the second law is coming into the picture. So, the first law is nothing but the statement of energy conservation is valid. What we can see that we are supplying energy in the form of heat, we are extracting energy in the form of work. So, what second law tells us? I will be coming to that particular point. But let us again look at it, see this is not a case that we need work output to be precise electricity from this particular system only for a single time, rather we need to have it in a cyclic or constantly. So, we need constant work output from the system which in turn will ensure that the electricity that will be produced from the alternator will supply constantly.

So, if we need to have constant work output, then you have to have continuous supply of water. It is very unlikely to believe that while steam is expanding in the turbine that steam will come out. So, after doing some amount of work, when steam is coming out from the turbine, it is having less energy. Because steam is doing work while flowing through the turbine. But after doing work that steam will come out from the turbine. You have studied in thermodynamics that though we are trying to discuss that heat and work are the two different forms of energy, but you know that there is a distinction between these two energies that is one is low grade energy, other is the high grade energy.

So, try to understand, the amount of energy which is added to the boiler in the form of heat is not equal to the amount of energy, what we are extracting from the turbine in the form of work. So, all the energies, all the thermal energy to be precise that is entering into the turbine is not getting converted equally to another form of energy that is in the form of work while certain amount of energy is coming out.

So, in a way it is trying to say something that we have learned from second law, if you try to recall the Kelvin-Planck statement. What is Kelvin-Planck statement? The statement is that it is impossible to construct a device which will operate in a cycle and the sole effect will be raising weight or producing work, while exchanging heat with a single thermal reservoir. So, boiler is the single thermal reservoir, because this is a device where heat interaction is there. This/Turbine is a device in which we can see only work interaction is there. Though I will be discussing but for the time being I can tell you that turbine surface is insulated, only to ensure that while steam is expanding there will not be loss of energy. So, there will not be any loss of thermal energy from the flowing steam because of this transfer from turbine to the ambience. So that is why turbine surface is insulated. So, even then you can see this is only the work interacting device because no heat interaction between system and surroundings.

Boiler is on the other hand a device in which heat interaction takes place. So, you know that in this device there is no work interaction between system and surroundings, only heat is supplied to the system from the surroundings from an external source. I would like to tell you that following second law of thermodynamics if we need to have constant work output, that means this will be a cyclic process or if we need to run it in a cyclic manner, it is not possible to construct only with a single temperature thermal reservoir. So, we must have another thermal reservoir in which heat must be rejected to the surroundings.

So that is what I would like to tell you. So, try to understand what I am telling that if it is one such case, we are supplying water, we are getting work output for a particular duration and then after doing some work steam is ejected to the surroundings. If it is that case then this is fine. But if you would like to ensure that the work output will be continuous and then only second law is putting a restriction that this is not possible at all while exchanging heat with a single thermal reservoir. So, there must be another device or reservoir in which heat must be rejected. So, this is known as condenser in which heat is rejected. So, if Q_{in} that is heat is added to the system and this heat Q_{out} is the heat that is coming out from the system or is getting rejected.

And you know that this is not possible because after rejecting heat, the steam which is coming out from the turbine is still having some thermal energy in the form of heat. And that heat energy is getting rejected, while it is coming in this device that is called condenser. And the collected condensate can be pumped back to the boiler to make it a cyclic device. So, we should have one pump.

So, this is the basic description of the steam power plant. We shall be using rather we shall be drawing this basic schematic diagram frequently when we will be discussing several issues related to this particular thermal power plant system. So, this is a cyclic system, so, all the processes are executed in a cyclic manner. So, basically you know that till now it is not completed. If we have such a system, we can ensure that the work output from the turbine will be continuous, second law permits that. So, there is a thermal reservoir in which heat is added, there is another thermal reservoir in which heat is rejected. So, this is permitting us to construct this device which will operate in a cycle. If we can ensure that this will operate in a cycle, we also can ensure that the work output from the turbine will be continuous. If it is so then there will not be intermittent supply of electricity. So, basically electricity that we are expecting to get from this plant will be continuous.

So now, I will say that heat is added to the system, work is coming out from the system, and heat is rejected from the system, but also to run this particular device that is called pump, we also need to supply some amount of energy.

So, we need to supply energy in the form of work so, this is called W_{in}. So this amount of work addition is required to operate pump that will be used to supply condensate from condenser to the boiler pressure. That I will come to later but for the timing you please do not consider what is boiler pressure. So, this pump will be required to supply condensate from condenser to the boiler and for that we must require some amount of work that would be added to this device. So, this is W_{in} and this is W_{out}. So, effective work output should be $W_{out} - W_{in}$. But try to understand a fraction of that work output will be required to operate the pump. So, eventually the net work output will be $W_{out} - W_{in}$.

So, what is the conclusion? Now, I will be coming to the first and second law and to see their applicability to describe the processes. But to understand that to operate this system in a cyclic manner, essentially to ensure that the work output from the turbine will be continuous, there must be a thermal reservoir in which some amount of heat must be rejected.

See this is again something contradicting, why? We are supplying energy in the form of heat to the boiler, as I have said that this energy supply will be through burning of coal or by burning diesel. Whatever is the case, we are supplying energy and a part of that energy is used to convert work to another form of energy, while remaining part of energy is rejected to the surrounding. So, it is somehow contradicting, the feasibility of operating a power plant essentially from the economical point of view.

So, you know that by burning coal, we are supplying energy and out of that energy, part of the energy is again rejected to the surrounding. We will discuss how this energy is getting rejected to the surrounding, but what I need to discuss at this point is that, it is something contradictory. So, this burning coal for that again some mechanical arrangement is required, the energy which is supplied to the boiler for that again mechanical arrangement is required.

So, by so many mechanical arrangements, the energy supplied but after supplying energy we can see that some amount of energy is getting rejected. Our objective should be to reduce this amount but we can see that second law puts a restriction that there must be heat sink, otherwise we cannot run this in a cyclic manner.

From there I am telling that compressor is an essential component for this system to run this system in a cyclic manner. But rather the system is acting just like a heat sink. So, our objective should be to minimize this quantity essentially to maximize the efficiency of this plant. So, upon minimizing this quantity we can maximize the system performance so, aim should be taken to minimize this quantity.

So, there are several issues, several modifications we will discuss. But now, second law is putting a restriction on this. So, if we need to go for minimization of this quantity Q_{out} keeping in mind that the efficiency or performance of the plant will be maximum, we need to invoke the first law which is used to the flow processes.

Why? So now, try to understand that the water is continuously flowing through the tubes which are there inside the boiler. And heat is supplied or heat flow is there over the tube. So, by virtue of heat exchange, water will be converted into steam. Again, steam is coming from the flow nozzle and it is entering into the turbine, again it is a flow process. So, if we know that amount of heat which is added in the boiler, the amount of work which is coming out from the turbine. So, you would like to calculate the amount of work which you are getting out of this energy conversion. But we only can calculate by applying first law of thermodynamics to a process which is steady state steady flow. So now, you have understood that the second law is very much needed to understand that we cannot run this device without cyclic manner if we do not reject heat to the surroundings.

Next is having established the fact that we must reject some amount of heat to the surroundings, next question is cannot we try to reduce or minimize it? Why? Because our objective to maximize the system performance. If you are planning to do so, at least we must know what are the different processes inside all these four different components. And then only the amount of work output, what is the amount of heat is added to the system can be estimated.

So, by doing that we can minimize this quantity. But if you would like to know the amount of work that we are getting out of this particular process which is there in the turbine, the amount of energy which must be supplied to the boiler to convert steam; all these processes are important to know. So, the amount of energy added in boiler, amount of energy you are getting in turbine, amount of energy rejected in compressor and amount of energy is added in pump, all these four devices' energy either is added or energy is extracted; so, to know that we need to apply first law of thermodynamics but applied to the steady state steady flow processes across the control volume. So, here you know that you cannot treat the control mass system. Because even though you can consider that at any particular instant when we are trying to have this energy balance, mass is remaining constant, but this is not a control mass system. So, this is basically control volume system. Similarly, we can write here that the net heat input is $Q_{net} = Q_{in} - Q_{out}$.

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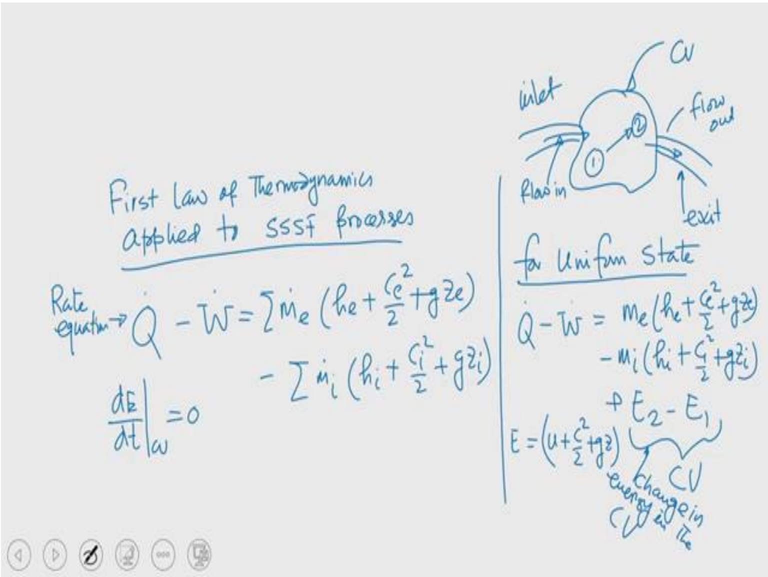

Next we will be discussing about, the first law of thermodynamics applied to steady state steady flow processes (SSSF). So, we have derived this expression. So, this is a process across the control volume. The first law of thermodynamics which is applied to a steady state steady flow process and this is applied across the control volume, for that we can write,

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

We have not considered $\left(\frac{dE}{dt}\right)_{CV}$ because this is steady state steady flow process. The state is steady and also flow is steady so, the total E that is the product of energy and mass within the system is not getting change or is not changing with time. So, product of mass as well as energy, specific energy of course, within the control volume is not changing with time. That is why we did not consider $\left(\frac{dE}{dt}\right)_{CV}$ that is change of energy within the control volume. So, in this equation we have ignored $\left(\frac{dE}{dt}\right)_{CV}$. So, energy is an exact differential and we have not considered it.

If the state is uniform state then I am writing for the sake of completeness, we have one control volume and we are having energy in, we are having energy out. And the control volume is undergoing through a process. So, basically say the system is changing from states 1 to 2. So, there is exit and inlet. Here the control volume is undergoing through a process and by virtue of which it is changing its state from state 1 to state 2 and the process is following uniform state uniform flow that means maybe this control volume is changing state from state 1 to state 2 but at any instant of time energy state is uniform throughout the control volume. If it is the case then basically for uniform state & if we have single exit and single entry together with the mass balance, we can write

$$\dot{Q} - \dot{W} = m_e\left(h_e + \frac{c_e^2}{2} + gz_e\right) - m_i\left(h_i + \frac{c_i^2}{2} + gz_i\right) + E_2 - E_1$$

Since it is uniform state, we cannot make this term trivial $\left(\frac{dE}{dt}\right)_{CV}$ is 0.

$$\dot{Q} = \text{energy into the system or control volume by heat}$$

$$\dot{W} = \text{ energy out from the control volume by work}$$

$$m_e\left(h_e + \frac{c_e^2}{2} + gz_e\right) = \text{energy out from the control volume due to flow}$$

$$m_i\left(h_i + \frac{c_i^2}{2} + gz_i\right) = \text{energy into the control volume due to flow}$$

$$E_2 - E_1 = \text{change in energy within the control volume}$$

$$E = u + \frac{c^2}{2} + gz$$

But, this E is not h because it is the thermal energy for the non-flow system. So, this is basically

$$E_1 = u_1 + \frac{c_1^2}{2} + gz_1 \;\&\; E_2 = u_2 + \frac{c_2^2}{2} + gz_2$$

So, basically this is the change in energy within the control volume and this change in energy has nothing to do with change in energy due to flow.

For most of the processes which we shall consider to describe for this system, we shall assume that the process is or processes are steady state steady flow processes. In that case there is no change in energy within the control volume and as I told you that in steady state the energy state is steady. Energy state does not change with time but energy conservation is not done in an isolated manner, it has to be coupled with the mass balance.

So, basically if we try to differentiate the equation for the steady state steady flow process from this uniform state, then $E_2 - E_1$ term is there for the later case because this is change in energy within the control volume. So that term is 0 for this SSSF case. So, this is the first law of thermodynamics applied to steady state steady flow processes and as I told you that we shall be assuming that all processes are steady state study flow processes.

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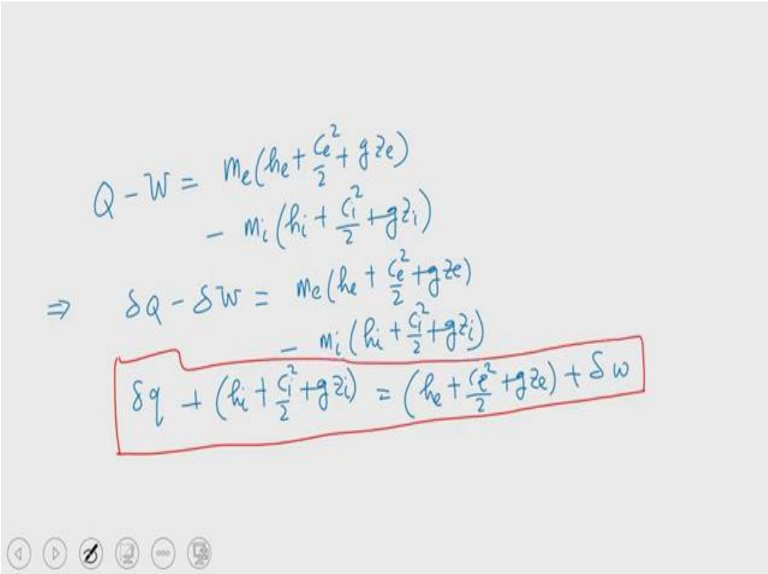

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \left(h_e + \frac{c_e^2}{2} + gz_e\right) - \sum \dot{m}_i \left(h_i + \frac{c_i^2}{2} + gz_i\right)$$

So, this is rate equation, if we integrate it over time then we will be getting

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

So, you know that here also we have assumed that we have taken only single entry, single exit. Let me tell you, this equation is valid only under an important assumption that is h, velocity c and z are the three properties that do not vary across each flow section. If you can recall that when we have derived this expression, we have taken this out of the integral. So, if we try to write in differential form

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

We also can try to write in specific form

$$\delta q + \left(h_i + \frac{c_i^2}{2} + gz_i\right) = \left(h_e + \frac{c_e^2}{2} + gz_e\right) + \delta w$$

So, this is very important and we shall be applying this particular equation while describing several processes in this particular system.

So now, I shall try to discuss about why we need to know the energy which is added to the system or Boiler. We also need to know what is the amount of work we are getting from the system or Turbine we also need to know what is the work added to the device or Pump. So, basically if we know that what is W_{out} & W_{in}, we know what is Q_{in} from there we can easily calculate what is Q_{out}. This particular quantity Q_{out} is very crucial because our objective should be to minimize that particular quantity to ensure that the efficiency of the system will be maximum.

Steady State Steady Flow Process in the Boiler

So now, let us first focus on this particular device that is boiler. So, again we assume that the process which is there inside the boiler follows, the steady state steady flow process.

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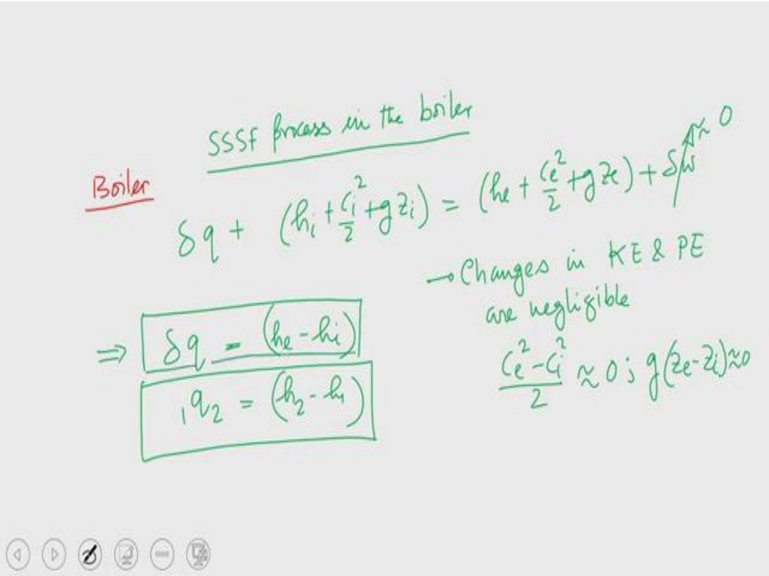

So, here you know that B stands for boiler, T stands for turbine; definitely it is steam turbine, C stands for condenser and P stands for pump. So, basically I have used short form to identify. So, now, let us go to this particular case boiler. So, if we try to write this equation, we write

SSSF Process in the Boiler

$$\delta q + \left(h_i + \frac{c_i^2}{2} + gz_i\right) = \left(h_e + \frac{c_e^2}{2} + gz_e\right) + \delta w$$

What I told that this is the equation, we shall be applying so that steady state steady flow equation applied to the process which is there inside the boiler. In this equation we have considered, the work done required to maintain the flow in the presence of pressure and that work is coming in this term $h + \frac{c^2}{2} + gz$. But here in this term control volume is not doing any work. So, this δw takes care of any work that is either the work done on the control volume or the work is done by the control volume. So that is taken care by this term δw.

While you may argue that while water is flowing through the steam definitely we need to do work. Because we need to maintain the flow in the presence of pressure. But since there is no work done by the control volume so, the term δw is equal to 0. So that is why boiler is not a work interacting device, control volume does not do any work. And also if we consider that the changes in kinetic energy and potential energy are negligible, then

$$\frac{c_e^2 - c_i^2}{2} \approx 0 \text{ and } g(z_e - z_i) \approx 0$$

So that is changes in kinetic and potential energy. So, if this is the case then we can straight away write

$$\Rightarrow \delta q = (h_e - h_i)$$
$$\Rightarrow {}_1^2q = (h_2 - h_1)$$

So, you must know that this heat and work are not the exact differential. So, the amount of heat addition, the amount of heat that must be added to the boiler will be change in enthalpy of working substance between inlet and outlet. So, if we can calculate the enthalpy of water at the inlet to the boiler and enthalpy of the working substance at the exit of the boiler. The change in enthalpy is nothing but the amount of work that must be added to the boiler provided the changes in kinetic and potential energy are negligible. So, this is for the boiler. So, you know that similar way, we also can apply the steady state steady flow processes in the turbine. So, let us briefly discuss about that.

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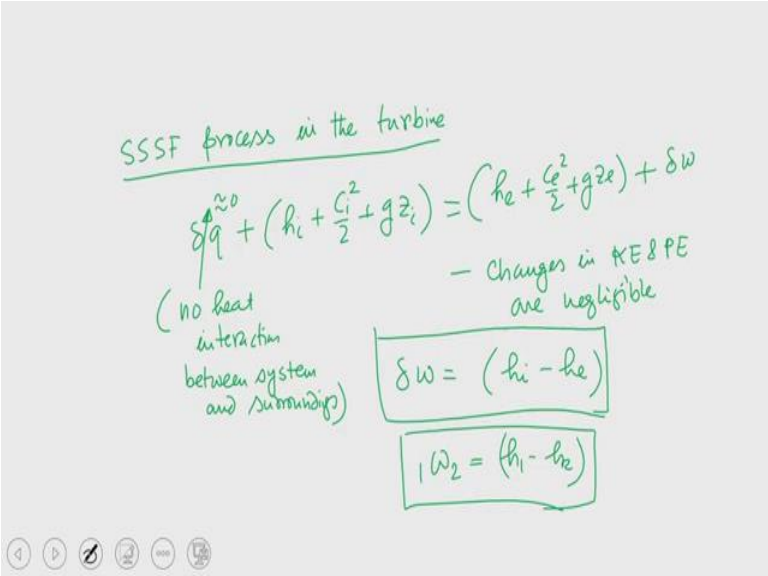

Steady state steady flow process in the turbine

So, we are assuming that the process that is there inside the turbine follows the steady state steady flow process. So, we can we really do not know whether turbine is a work interacting device or the heat interacting device. Let us first write the generic equation that is

$$\delta q + \left(h_i + \frac{c_i^2}{2} + gz_i\right) = \left(h_e + \frac{c_e^2}{2} + gz_e\right) + \delta w$$

$$\delta q = \text{energy addition to the control volume in the form of heat}$$

$$\left(h_i + \frac{c_i^2}{2} + gz_i\right) = \text{energy addition to the control volume due to flow}$$

$$\left(h_e + \frac{c_e^2}{2} + gz_e\right) = \text{energy out from the control volume by the flow}$$

$$\delta w = \text{energy out from the control volume by work}$$

So now, let’s recall the previous slide wherein, we have discussed about the schematic depiction. You know that in the boiler just we have added heat from an external source. In a turbine there is no heat interaction and only to prevent heat loss from the turbine, you know walls are insulated, while we are getting work output. So, W_{out} is the work which is done by the control volume, we also need to do some amount of work to maintain the flow, while steam is entering to the turbine and while steam is coming out from the turbine. So, work done needed to maintain the flow at the inlet as well as at the outlet of the turbine, in the presence of pressure some amount I mean and that is already taken care of by this term h_e& h_i. But there is this additional amount of work that is the work output from the turbine. So, on the top of this flow work this is the amount of work done by the control volume and that is important.

It is because of this work we are getting net work output. But the work done to maintain the flow either at the inlet to the turbine or at the outlet of the turbine has already been taken care by this term h_e& h_i. Since in turbine, there is no heat interaction between system and surroundings, so $\delta q = 0$. So, basically you also can consider this changes in kinetic energy and potential energy are negligible.

In the last slide also we have used e and i but mind it that there e stands for exit from the boiler this i stands for inlet to the boiler. Similarly, since we are applying this equation to the turbine, so, here e stands for exit of the turbine and i is the inlet to the turbine.

So, taking this particular assumption that KE & PE are negligible and as there is no heat interaction between system and surroundings, when you are applying this equation to the process inside the turbine, I can write that

$$\Rightarrow \delta w = (h_i - h_e)$$

$$\Rightarrow {}_1^{}{}_2^{}w = (h_1 - h_2)$$

$$h_1 = \text{enthalpy of steam entering into the turbine}$$

$$h_2 = \text{enthalpy of steam leaving the turbine}$$

So, the work done by the turbine will depend on the enthalpy drop inside the turbine $(h_1 - h_2)$. So that equation we are getting from the first law of thermodynamics, applied to steady state steady flow processes across the control volume.

So that basically we could see that amount of heat addition will depend on the enthalpy of steam at the exit of the boiler minus enthalpy of steam at the inlet to the boiler, while work output from the turbine will depend on the enthalpy of steam at the inlet to the turbine minus enthalpy of steam at the exit of the turbine. So, our objective should be to maximize this quantity δw. If we try to maximize this quantity δw, can you do something, so that the enthalpy at the exit of the turbine should be minimum? If it is minimum so, we will be having maximum work output. You know that these are the several issues that we will come to know only if we can frame the equation mathematically.

So, we have discussed about the steady state steady flow process in the turbine as well as in the boiler. If we go back to this previous slide we also need to apply the steady state steady flow process across the condenser. You can see because I am not going to do this. You can understand that again this is a device in which there is no work interaction, only heat is subtracted or heat is rejected from the particular device.

So, this is your home task, you can try. Again you can understand that we assume that the changes in kinetic and potential energies are negligible and this is not a work interacting device. So, the heat rejected from the condenser should be the drop in enthalpy that you can try. Most critical part is this Pump because the addition of work needed to operate this device is very important.

So, the work which is needed to run this pump, will it depend if the process is adiabatic or process is isothermal? You can understand the temperature of the condensed water which is coming from the condenser is not very high and that will be pumped back to the boiler. So, while it is pumping whether the process is a reversible adiabatic process or reversible isothermal process, we need to identify.

By identifying the process then we will try to estimate the work done needed and it will be quite interesting to see that in the work done calculation, it is immaterial whether it is a reversible adiabatic process or reversible isothermal process. So, the work done for both this reversible adiabatic and reversible isothermal processes will be same and that we will do in the next class.

So, if you would like to summarize, today we have discussed about several components at least major components which are there in the power plant. We have also discussed about the applicability of second law to describe the processes. Then by applying the first law of thermodynamics, applied to steady state steady flow process across the control volume, we could establish the amount of heat that should be added to the boiler and the amount of work that we are getting from the turbine.

The amount of heat which is being rejected from these condenser is also a very important part. But that you can easily calculate by applying the steady state study flow equation and suitably invoking the assumptions that we have already considered. But the work which is added to the pump is also an important issue because the net work output from the system will depend on the quantity of this W_{in}.

So, in the next class, we shall try to see the process which is there in the pump and also what is the quantity of this W_{in}. So, with this I stop here today and we shall continue our discussion in the next class. Thank you.