Applied Thermodynamics

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Steam Power System

Lecture - 07

Rankine Cycle and its analysis

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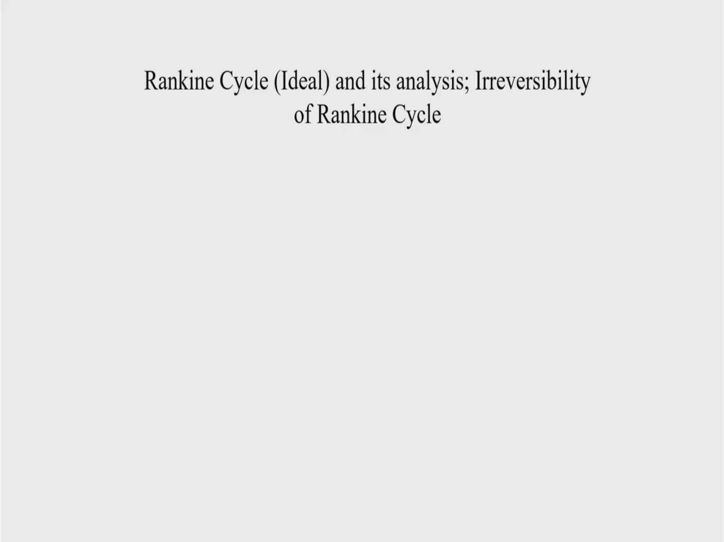

Rankine Cycle (Ideal) and its analysis; Irreversibility of Rankine Cycle

We shall start our discussion on Rankine Cycle and in today's class we will try to see the advantageous feature of the Rankine cycle in the context of vapour power cycle and finally, we will try to discuss about the irreversibility associated with this cycle.

So, I mean if you try to recall in the last class we have talked about the Carnot cycle that is the ideal cycle. In fact, this is one of the important ideal cycles which you need to study. In fact, we have studied in our thermodynamics course and from the discussion of the Carnot cycle we have listed down a few serious drawbacks if you try to run this steam power plant using the Carnot cycle.

What are the problems or drawbacks of the Carnot vapour cycle? That means, if you try to run the vapour cycle using the Carnot or ideal cycle we have seen there are four important drawbacks; one is the partial condensation. So, before coming to the Rankine cycle let us briefly recapitulate those aspects.

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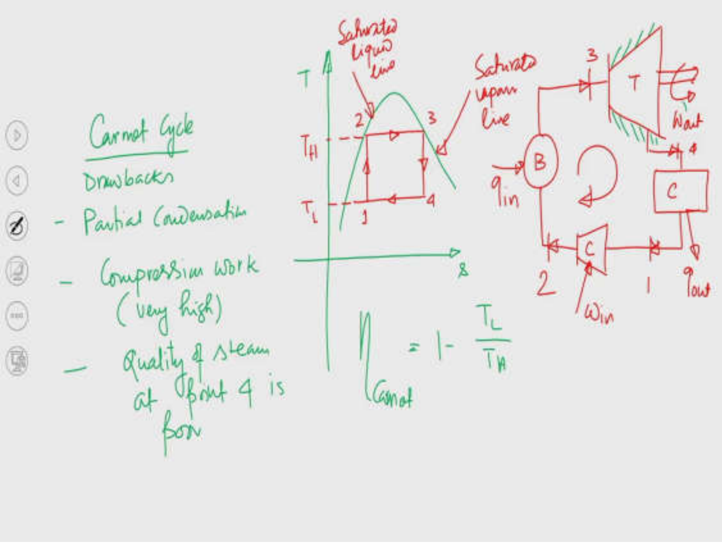

Carnot Cycle

Drawbacks

- Partial Condensation
- Compression work (very high)
- Quality of steam at point 4 is poor

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

First is partial condensation. In fact, let us first draw the T-s diagram and in the right hand side we can try to have the schematic depiction of the steam power plant.

So, this is boiler, say this is compressor, we have turbine and we have one condenser. So, this is the processes which constitute this cycle I mean we have identified in the last class. So, there is heat addition q_{in}, this is work input, this is heat rejection q_{out} and this is work output w_{out}.

So, we have discussed in detail about the cycle. Now, today for the recapitulation I would like to discuss about the drawbacks. First of all, you try to understand this is the compressor. So, the collected condensate will be compressed and it will be taken to the boiler to complete the cycle. Since, we can understand the process 4 to 1 that is the condensation process.

Now, what we can see from the T-s diagram is that the point 1 that is the condensation process is getting terminated at point 1 and that is still two phase mixture. So, it is not so easy to have a control on the condensation process as it is partial condensation. It is not the case that the condensation process is extended up to the saturated liquid line. So, this is the saturated liquid line and this is the saturated vapour line and this is the critical point.

These two lines meet together and that is the critical point those we have studied in our thermodynamics course. So, first drawback is that the partial condensation it is very difficult. So, we need to design the condenser in such a way and you also need to have a control on the condensation process itself so that the condensation process will terminate at point 1. So, that is partial condensation.

Number 2 is work ratio. So, what is the work ratio? Work ratio is basically the network by the input work that you have studied that we have discussed in the last class. So, work ratio is the network by the positive work. If you need to compress this two phase mixture we can see the process 1 to 2 that is the compression process. So, basically we need to compress the two phase mixture and eventually it will be terminated at point 2 that is saturated liquid.

So, to design a compressor which will compress a two phase mixture and at the end of the compression process we will be getting saturated liquid. So, again it is very difficult task to have a compressor which will perform the process like this. Not only that as I told you work ratio that is network by the positive work. So, positive work from the cycle is the work output from the turbine.

Our entire objective to get work output from the turbine because this turbine shaft that I have drawn over here will be connected to the shaft of an alternator and from there we will be getting electricity. Since our objective is to maximize the work output, but out of this positive work we also having some in work input to the system.

So, when we will try to analyze the cycle we will see that this work will be supplied to the compressor and we are getting work output from the turbine. So, what is the fraction of the positive work output that we need to measure. Since compressor will be handling two phase mixture and you know that the specific volume of vapour is very high then the work input to the compressor will be very high.

Since compressor will be handling two phase mixture, I am not even going to the design aspect of the compressor. So, there are two difficulties. First of all it will handle two phase mixture and the compressor eventually will be designed in such a way that that at the end of the compression we will be getting saturated liquid if we need to run the vapour power cycle following the Carnot cycle that is the ideal cycle.

So, that is the difficulty from the perspective of the design aspect of the compressor. Number 2 is that, compressor will be handling two phase mixture since the specific volume of vapour is very very high as compared to the specific volume of liquid. If the quality or thermodynamic state at point 1 had it been completely liquid, then probably we could have needed relatively lesser work input to the process.

So, since at state point one substantial amount is vapour, so, to compress vapour we need to supply more work input. Since we need to supply more work input that that will reduce the work output I mean work ratio. So, that is called compression work which is very high.

Number 3 is again important that is steam quality at the exit. So, basically 3 to 4 the process which occurs inside the turbine that is nothing but entropy is remaining constant from 3 to 4. So, we really do not know, but still it is reversible adiabatic process.

So, turbine walls are insulated. So, there is no heat loss from the turbine wall to the surroundings because at the inlet to the turbine. The steam which is entering is having high enthalpy and when steam is expanding it does work on the rotating part of the turbine and from there we are getting work output.

Since, if we allow heat to transfer while steam is expanding inside the turbine and during the process of expansion if we allow heat to transfer from turbine to the surroundings then we will be getting less work output. So, that is why this is adiabatic process and we can see the process is internally reversible. So, this is reversible adiabatic process which is nothing but isentropic process and that is why you can see entropy at point 3 and entropy at point 4 these two entropies are equal.

Now, what we can see from the T-s plane that at point 4, what is the quality? It is again two phase mixture not only that it is away from the saturated vapour line. I mean more this point is away from the saturated vapour line more it is having moisture content and this will lead to the turbine blade erosion problem and pitting. So, quality of steam at point 4 is poor. So, steam quality at the exit is poor.

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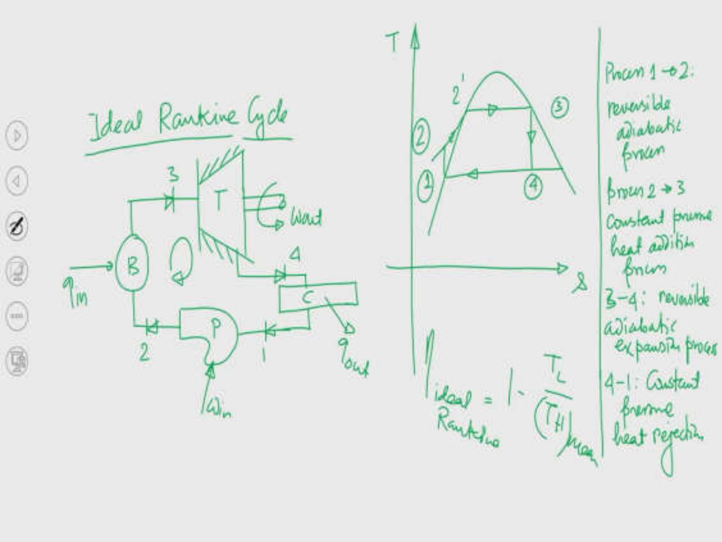

Ideal Rankine Cycle

Process 1→2: reversible adiabatic process

process 2→3 Constant pressure heat addition process

3-4: reversible adiabatic expansion process

4-1: Constant pressure heat rejection

$\eta_{\text{ideal Rankine}} = 1 - \frac{T_L}{(T_H)_{max}}$

So, having discussion on these drawbacks next we should move to discuss about the ideal Rankine cycle. So, the ideal Rankine cycle was first proposed by a Scottish mathematician William John Rankine. So, now, question is if we go back to the previous slide we have discussed about the partial condensation. So, partial condensation I mean it is problematic from two different perspectives. First of all, designing a compressor which will compress two phase mixture and at the end of the compression process it will deliver saturated liquid.

So, it is not so easy. On the top of that compressing two phase mixture it is a power consuming process. So, we need to supply high work input to the compressor for its operation. So, in the Rankine cycle that Scottish mathematician proposed that instead of compressor to put a pump.

So, this is boiler. So, this is pump and this is turbine. So, this is condenser. Again, this is the cyclic process we are having heat input, work output, this is turbine, this is condenser, this is heat rejection and this is work input to the pump. We will try to draw the T-s diagram again.

So, now let me discuss about this particular cycle. If we compare this schematic with the schematic that I have drawn over here you can see everything is remaining same except the compressor part. So, here again it is insulated no heat loss from the turbine to the surroundings.

So, here we are having pump. You know that pump can handle liquid since pump cannot handle two phase mixture. So, if we replace compressor by a pump we have to have the liquid state at point 1. So, while condensation process was the partial condensation that is it is getting terminated at point 1, now since pump cannot handle two phase mixture these condensations should be extended up to the saturated liquid line.

So, if we try to draw the process line that is the condensation process say this is point 1. Then 1 to 2 that is pumping process we have seen that is reversible adiabatic process. See while liquid is pumped from state 1 to state point 2 up to the boiler pressure so, there is no heat interaction.

So, pump is again a device which is work interacting device by taking work as input, it can pump liquid from state point 1 to state point 2 to the boiler pressure; so, from the condenser pressure to the boiler pressure. So, then 2 to boiler is operated at constant pressure.

So, when liquid is taken to the boiler, boiler is a heat interacting device, in boiler water will be converted into steam upon receiving heat from the external source. So, it is coal fired boiler in most of the thermal power plant.

So, the amount of heat that will be supplied to the boiler will come from burning coal. There are diesel fired boilers, but I mean in the coal fired boiler. So, heat will come from external source and which will come from burning of the coal and the process which is a constant pressure process.

So, water will be converted into steam following the constant pressure process. So, in the T-s line if you try to draw the constant pressure line so, it will be like this. So, this is point 2, this is point 1 and so, this process ends at point 3. Our objective should be to get steam which is coming out from the boiler before it enters into the turbine will be in a saturated vapour state. So, moisture content will be 0.

If the steam that we are getting from the boiler at the inlet to the turbine is having moisture content that will lead to the turbine blade erosion. So, it is not a good design to have the process, the constant pressure heat addition process. So, inside the boiler we are having constant pressure heat addition process and following that process water will be converted into the steam. So, this is 3 to 4 that is the expansion of the steam as it moves from inlet to the outlet of the turbine it does work. As I said you on the rotating part of the turbine and the enthalpy drops. Since enthalpy drops, temperature also will be reduced that we are getting at point 4. So, it is isentropic compression process.

So, process 1 to 2 is reversible adiabatic process; process 2 to 3 is constant pressure heat addition process, 3 to 4 that is reversible adiabatic expansion process and 4 to 1 that is constant pressure heat rejection. So, all these four processes we have identified. So, all these four processes constitute the cycle that we are talking about.

So, try to understand that if we now try to compare this ideal Rankine cycle, why we are calling ideal Rankine cycle because let me tell you something here. If we know that the Carnot cycle is the ideal cycle and you have studied that ideal things whether it is ideal fluid, ideal gas, ideal process so, this idealism; so, basically it is very difficult to implement those ideal things in reality, but having a proper understanding about the implementation difficulties of the ideal things, we need to understand about this ideal processes.

So, basically we know that whatever we can see in reality those are the actual things, but when we are trying to improve in a actual processes, there will be losses. So, the actual process can never meet the ideal processes, but our intention should be to improve the actual processes, actual systems, actual things to bring them closer to the ideal ones. So, it is very difficult to meet the ideal processes, but our intention should be to bring them closer to the ideal processes and that is why we should have a proper understanding about the ideal processes.

Similarly, in this particular topics also though we know the Carnot cycle is very difficult to implement, difficult to achieve in practice even then we are studying about this particular cycle only to know that we will be talking about the least efforts should be taken to bring those actual cycles closer to the ideal one.

If we need to bring them closer to the ideal ones what are the modification needed to design the actual cycles closer to the ideal one should be clear. So, that is why you are studying ideal cycle, but now if we compare this ideal Rankine cycle with the ideal Carnot cycle, why we are calling ideal Rankine cycle?

We are considering all the processes are internally reversible. Though it is very difficult to achieve I mean if you need to have a process to be internally reversible. So, the process should be quasi static process; that we have studied in classical thermodynamics.

If we need to have the process to be quasi-static process essentially to achieve the internally reversibility, then I mean if it is said to be quasi static process so, infinite slowness is the characteristic feature of the quasi-static process.

So, process will be very very slow. Even then at least we can bring this Rankine cycle and we are calling this ideal Rankine cycle so that efficiency of the Rankine cycle which is very very close to the ideal Carnot cycle and that is why it is called ideal Rankine cycle.

So, we will try to discuss the ideal Rankine cycle now, why it is calling ideal Rankine cycle because efficiency of this Rankine cycle is very very closer to the Carnot cycle and that is why it is called ideal Rankine cycle. Now, see why it is very very closer to the ideal Carnot cycle why not the efficiency of Rankine cycle is not equal to the equal to that of the Carnot cycle.

Try to understand one important thing. See, efficiency of the ideal Carnot cycle is $\eta_{carnot} = 1 - \frac{T_l}{T_h}$ that you have studied in thermodynamics course. So, this T_L is the temperature of heat rejection and this is temperature at which heat is added to the system.

So, process 2 to 3 in which heat transfer takes place that is the phase change heat transfer and phase change heat transfer is always efficient than the sensible heat transfer. So, the phase change heat transfer is always efficient than the sensible heat transfer. So, in the Carnot cycle process 2 to 3 that is the phase change heat transfer, but if we now go to the ideal Rankine cycle there is a part say it is 2`.

So, 2 to 2` that heat transfer is the sensible heat transfer while 2` to 3 that is the phase change heat transfer. So, the presence of this component of heat transfer will reduce the temperature at which heat is added to the system.

So, if we try to write the efficiency of the ideal Rankine cycle now, so, $\eta_{rankine} = 1 - \frac{T_l}{(T_h)_{mean}}$. So, this is you know that heat is rejected in this condenser during this condensation process. Now, this T_H is not T_H. So, this is $(T_H)_{mean}$. Why this is mean? Because a part of the heat addition process is heat addition at the sensible heat addition.

So, because of the sensible heat addition component, mean temperature of heat addition reduces as a result of if the mean temperature at which heat is added to the system is less than the temperature at which heat is added to the system for the ideal Carnot cycle, then you can understand the ideal Rankine cycle efficiency will be definitely lesser than the efficiency of the ideal Carnot cycle.

So, which is responsible is this latent heat addition component will reduce the average temperature at which heat is added to the system which in turn will reduce the efficiency of the ideal Rankine cycle. So, though we are talking about that all the processes are internally reversible we are trying to bring the efficiency of this Rankine cycle closer to the efficiency of the ideal Carnot cycle and that is why you are trying to give the name ideal Rankine cycle.

Yet because of this fellow sensible heat addition component average temperature at which heat is added will reduce which in turn will reduce the efficiency of the Rankine cycle. But, the problem which we had the condensation process that problem is not there we can design a condenser which will now have condensation up to the saturated liquid line. So, the problem associated with the partial condensation is no more.

Second thing is instead of a compressor as the case is following ideal Carnot cycle, we are now having pump. Since the condensation process terminates at point 4 which is saturated liquid, pump can easily handle that liquid and while we are having pump it is only handling saturated liquid. So, the work consumptions, the power consumption or work input to the pump is significantly less than the work which was added to the compressor for the equal power output.

For the same power output the work added to compressor only to handle substantial amount of vapour which is having high specific volume, the required work input to the pump is less. As a result of which the work ratio for following this ideal Rankine cycle will be very very high.

So, the problem associated with this partial condensation, problem associated with the high work input of compressing two phase mixture as was the case in case of a ideal Rankine cycle is not here. But, you can see the process 3 to 4 is again reversible adiabatic expansion process all these processes are reversible process internally reversible and that is why you can say it ideal Rankine cycle.

But, you can see these expansion process even terminates at point 4 which remain away from the saturated vapour line. So, at point 4 still the quality of the steam is not very good. So, basically towards the end of the expansion process, the quality of the steam will reduce which in turn will lead to the turbine blade erosion problem.

So, I mean we need to think about the modification of the simple Rankine cycle such that the problem associated with the high moisture content or moisture content of the steam at the outlet of the turbine can be eliminated. But, so far we have understood that the problem associated with the partial condensation process and also the high work input required for compressing two phase mixture for the case when we have discussed about the ideal Carnot cycle, these problems are not there in case of the ideal Rankine cycle.

But, still the problem of this moisture content of the stream at the exit of the turbine is there, but we can think of the modification of the ideal Rankine cycle.

We shall discuss those aspects again, but for the time being let us now discuss about if we have a thermal power plant and if the thermal power plant is designed to run following the ideal Rankine cycle what would be the efficiency for the given heat input.

So, we shall try to do the analysis of different processes which you have listed down over here and then we shall try to quantify the thermal efficiency of the ideal Rankine cycle. So, before that it would be convenient to understand if we discuss one important thing. So, all four processes constitute this cycle.

So, process 2 to 3 constant pressure heat addition process internally reversible, we are assuming; 3 to 4 that is again isentropic expansion process that is reversible adiabatic expansion internally reversible. Process 4 to 1 – constant pressure heat rejection, again we are assuming this is internally reversible; process 1 to 2 that is reversible adiabatic pumping reversible adiabatic process.

If you need to analyze all these four processes essentially to quantify the efficiency of the power plant which if we consider is operated based on this ideal Rankine cycle we have to consider all the processes are steady state steady flow processes.

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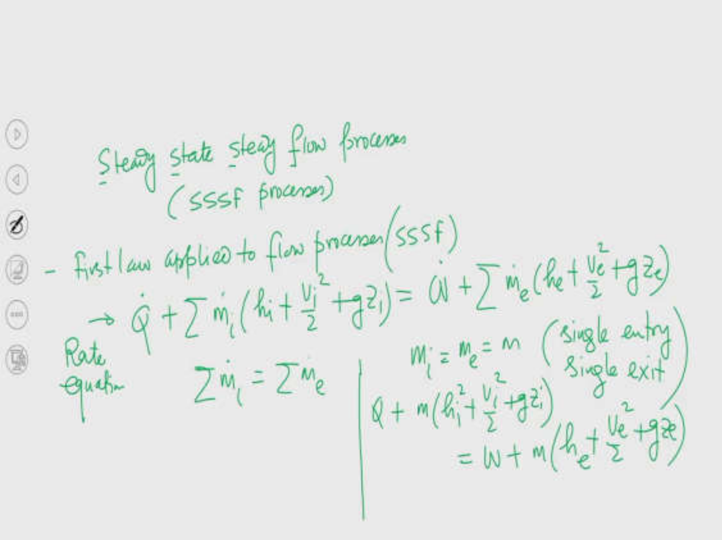

Steady state steady flow processes
(SSSF processes)

- first law applied to flow processes (SSSF)

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

Rate equation

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

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

(Single entry Single exit)

$$Q + m\left(h_i + \frac{V_i^2}{2} + gz_i\right) = W + m\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

So, if we consider steady state steady flow processes probably you have heard about this. So, you can understand steady state steady flow processes in short it is called SSSF processes. So, now, we have studied about first law of thermodynamics, second law of thermodynamics.

So, if we apply first law, if we consider all the processes are steady state steady flow processes and if we apply first law applied to steady state steady flow processes, what are those processes? Constant pressure heat addition, isentropic expansion, constant pressure heat rejection and reversible adiabatic pumping. So, let me write the first law applied to flow processes.

So, first law applied to flow processes. Processes are steady state steady flow. First law applied to flow processes to be precise steady state steady flow processes.

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

So, this is the generic equation I have written. As I told you that I am not going to derive this equation this is not included in the content of this course. Also, this is energy balance equation together with the mass conservation we can write $\sum \dot{m}_i = \sum \dot{m}_e$.

Because $dmC_v dt = 0$. So, there is no net rate of change of mass inside the control volume. So, this is flow processes. So, we are applying the equations to a control volume. So, now, we have written this equation that is $\dot{Q}, \dot{m}_i, \dot{m}_e$. So, this is rate equation.

But, if I want we can just remove dot and we can write the general form of the equation, but say we are not interested to write the equation in the rate form. So, what we can write? And we are having single inlet single exit. So, we can write $m_i = m_e = m$ for single entry and single exit.

See, it is quite obvious. So, now if liquid enters to the boiler through single inlet and steam is coming out from the boiler single outlet, similarly for the turbine and condenser and pump also. So, liquid enters to the pump through a single inlet and it comes out from the pump through the single outlet.

So, that is $m_i = m_e = m$ that is single entry, single exit. And if we have this and if we do not want to write the equation in the rate form rather in the normal form then we can write $Q + m\left(h_i + \frac{v_i^2}{2} + gz_i\right) = W + m\left(h_e + \frac{v_e^2}{2} + gz_e\right)$.

We can also write one step further. What we can do? We can take this m and we can write this in the specific form.

$$q + \left(h_i + \frac{v_i^2}{2} + gz_i\right) = w + \left(h_e + \frac{v_e^2}{2} + gz_e\right)$$

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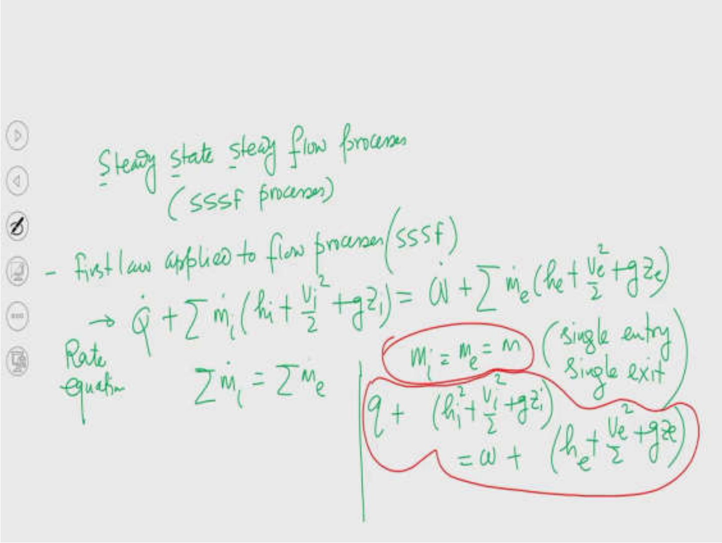

Steady state steady flow processes

(SSSF processes)

- first law applied to flow processes (SSSF)

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

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

$m_i = m_e = m$ (single entry single exit)

$q + \left(h_i + \frac{V_i^2}{2} + gz_i\right) = w + \left(h_e + \frac{V_e^2}{2} + gz_e\right)$

So, we are writing in the specific quantities. So, this part you have studied in thermodynamics I am not going to read.

Now, just we have listed down this important equation. We will be applying these two equations. So, first equation that is $m_i = m_e = m$, that we have already taken care in the final equation.

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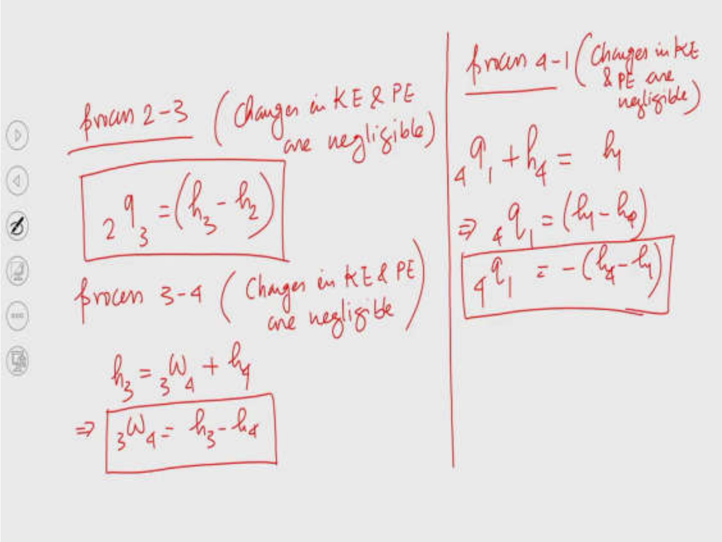

process 2-3 (Changes in KE & PE are negligible)

$\boxed{{}_2q_3 = (h_3 - h_2)}$

process 3-4 (Changes in KE & PE are negligible

$h_3 = {}_3W_4 + h_4$

$\Rightarrow \boxed{{}_3W_4 = h_3 - h_4}$

process 4-1 (Changes in KE & PE are negligible)

${}_4q_1 + h_4 = h_1$

$\Rightarrow {}_4q_1 = (h_1 - h_4)$

$\boxed{{}_4q_1 = -(h_4 - h_1)}$

So, if we apply the last equation to all the four processes. So, now, if I apply for the boiler so, here process 2 to 3 that is constant pressure heat addition process. Control volume is not doing any work; flow work is there. Try to understand. Again, I am discussing little bit about thermodynamics that you have studied I guess. In most of the text books I mean they are writing in different form.

But, try to understand in the boiler that is constant pressure heat addition. In this constant pressure heat addition we are applying first law applied to the flow process and if we consider a control volume that control volume is not doing any work, but the flow work is there. So, that is there is a steady flow always to maintain the flow in presence of pressure we need to do flow work.

So, this boiler is not a work interacting device to be precise. Since it is a heat interacting device, if we apply this law so, this w will be equal to 0 and if we consider the changes in kinetic and potential energy is negligible, then we can write ${}_2q_3 = h_3 - h_2$.

So, this is very important equation try to understand. So, we have discarded the changes in kinetic and potential energy; that means, we have ignored $\frac{v_e^2 - v_i^2}{2}$ and we have also ignored $g\left(z_e - z_i\right)$ and also we have noted that the control volume is not doing any work.

So, this is the work only due to the flow process and as a result of which this work we are getting enthalpy not the internal energy; had the case would have been first law applied to the control mass system then instead of h we would have written u that is the internal energy.

But, since the flow work is there, the work required to maintain the flow in presence of pressure so, that flow work component has now added with the internal energy u and u plus that flow work that is nothing, but the enthalpy. But, we have ignored the changes in kinetic and potential energies and since this is not the work interacting device. So, the control volume is not doing any work. So, only you are having q. So, this is the expression.

Now, what about process 3 to 4? Again, changes in kinetic energy and potential energy are negligible. We are not telling that the kinetic energy is neglected, but we are telling changes in kinetic and potential energies are neglected. So, we are telling that at the inlet of the turbine we are having velocity. We are having kinetic energy of the steam entering to the turbine. We are also considering kinetic energy of the steam leaving the turbine, but we are ignoring the changes in kinetic energy across the turbine, changes in kinetic energy of the steam across the turbine. So, the steam while flowing through the turbine we are having a process, it does work on the moving component of the turbine, but during expansion we are ignoring the changes in kinetic and potential energies.

So, if I apply this what we can write? So, you can see there is no heat interaction. If we consider the control volume, so, there is no heat loss. So, this reversible adiabatic process; so, q will be equal to 0. So, there is no heat interaction rather we are getting work output. So, turbine is a work interacting device not heat interacting device.

So, if that is the case this component will be equal to 0 plus the changes of these components will be equal to 0. So, we can write ${}_3w_4 = h_3 - h_4$. So, this is the equation. So, we have identified these two processes.

We are having another two processes. So, that is the condensation process 4 to 1. So, process 4 to 1, again changes in kinetic and potential energy are negligible. Here we are having no work interaction, control volume does not perform any work, but we are having heat rejection. So, if we apply this equation this component will be there, w will be equal to 0.

So, we can write ${}_4q_1 = h_1 - h_4 = -\left(h_4 - h_1\right)$. So, the minus sign indicates that is heat is getting rejected from the system; enthalpy at point 4 is higher than the enthalpy at point 1, but the negative sign is an indication of having heat rejection from the system.

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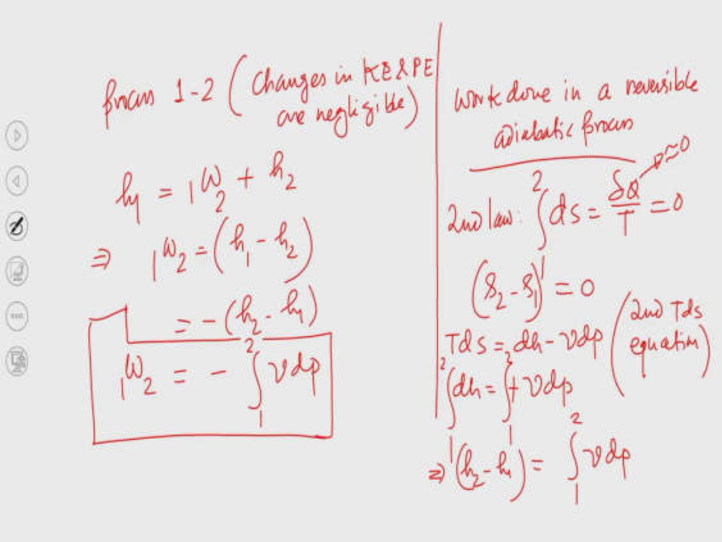

process 1-2 (Changes in KE & PE are negligible)

$h_1 = {}_1W_2 + h_2$

$\Rightarrow {}_1W_2 = (h_1 - h_2)$

$= -(h_2 - h_1)$

$$\boxed{{}_1W_2 = -\int_1^2 v\,dp}$$

Work done in a reversible adiabatic process

$\delta Q \approx 0$

2nd law: $\int_1^2 ds = \frac{\delta Q}{T} = 0$

$(s_2 - s_1) = 0$

$Tds = dh - vdp$ (2nd Tds equation)

$\int_1^2 dh = \int_1^2 + v\,dp$

$\Rightarrow (h_2 - h_1) = \int_1^2 v\,dp$

Finally, you are left with one process that is process 1 to 2 that is pumping process. Again, changes in kinetic energy and potential energy are negligible. So, again pump; there is no heat interaction, reversible adiabatic process internally reversible, but there is no heat interaction then if I apply this equation to steady state steady flow.

So, the first term will be equal to 0; here inlet is 1. So, ${}_1w_2 = h_1 - h_2$. See, here I will discuss about something which is very important; so, work done in a reversible adiabatic process. This is not pdV work, rather this is Vdp work by how we are getting? Work done in reversible adiabatic process, if we apply second law of thermodynamics.

So, $ds = \frac{\delta Q}{T}$; reversible adiabatic process no heat interaction. So, $ds = \frac{\delta Q}{T} = 0$. So, if I integrate it from process 1 to 2; so, $s_2 - s_1 = 0$, I am writing the specific quantities. Now, what I can write? The property relation $Tds = dh - vdp$ this is called second Tds equation. Again, I am not going to discuss because you have studied in thermodynamics. This quantity is 0. So, $dh = vdp$.

If I integrate from process 1 to 2 we are getting $h_2 - h_1 = \int_1^2 vdp$. What is here? So, we can write this is $-\left(h_2 - h_1\right) = -\int_1^2 vdp$. So, work done in a reversible adiabatic process is nothing, but *vdp* work only to make you understand that this work is not *pdv* work.

So, this work is *vdp*. Had it been *pdv* work, it would have been 0 because *pdv* is basically pressure is remaining constant, but in pump there is a change in pressure. And also had it been *pdv* work, there is no change in specific volume of the liquid which is being handled by the pump. Pump handles in compressible liquid. So, basically there is no change in specific volume of the liquid.

So, had it been *pdv* work, the work done would have been 0, but this is not the case here. So, this is -*vdp*. We have established that from where this work is coming. For your information whether it is reversible adiabatic or reversible isothermal process, the work is always *vdp* work and that we have derived. So, the work associated with reversible adiabatic process is *vdp* provided if we ignore the changes in kinetic and potential energies.

So, there is one important assumption is that we are going to ignore the changes in kinetic and potential energy, that is why the work done for any reversible adiabatic process can be written -*vdp*. As I told you for your information work done in a reversible isothermal process also can be written in the same form provided the changes in kinetic and potential energies are considered to be negligible.

To summarize we have tried to understand that if we try to eliminate the problem which we have seen in the ideal Carnot cycle, the ideal Rankine cycle is better the problem associated with those with the ideal Carnot cycle are not there in the ideal Rankine cycle, but still there are a few issues because of those the efficiency of the ideal Rankine cycle is always less than the ideal Carnot cycle.

But, as we have discussed that our objective should be to bring the efficiency of the actual cycle closer to the ideal Carnot cycle, for that we also need to find out several modifications. Before that we also need to understand that why the efficiency of the ideal Rankine cycle is lesser than the ideal Carnot cycle, for that we have also discussed about the mean temperature concept.

Mathematically we will try to show from the perspective of the role of the mean temperature while defining the efficiency of the vapour power cycle that because of the reduction of the mean temperature which is essentially due to the sensible heat component present in this particular ideal Rankine cycle we are getting slightly less efficiency.

Finally, though we have called it ideal Rankine cycle, but still we need to discuss about the presence of irreversibilities. Though the processes are internally reversible, but we need to identify whether the external irreversibilities are there or not. So, those aspects we shall discuss in the next class.

Thank you.