Applied Thermodynamics for Marine Systems

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Lecture - 10
Steam Power Cycle, Steam Nozzle

Good afternoon everybody. We were discussing regarding the steam power cycle, and so far we have seen one variation of or one modification of the basic Rankine steam power cycle that is the Rankine cycle with reheat. We have seen that or we have discussed that with reheat we can get more work output out of the same steam flow rate and one cannot tell apriori whether the efficiency of the plant will increase or not because that depends on other operating conditions. Now we will see another modification of the Rankine cycle which is very commonly used in practical steam power plant.

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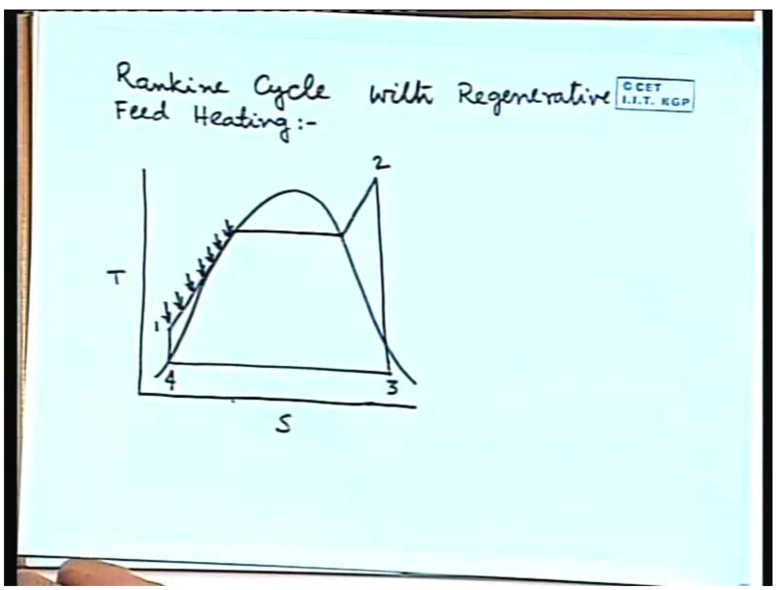

Rankine cycle with regenerative feed heating; as the name suggests, in this Rankine cycle, we will have some feed heating arrangement which will be done regeneratively. I will explain what is meant by regenerative heating. Before that, let us draw a basic Rankine cycle and let us see why this idea of feed heating or some special method for feed heating was emerged. This is the basic Rankine cycle in TS plane. We have 1 to 2 heating of the working fluid in the boiler, 2 to 3 expansion in the turbine, 3 to 4 is the condensation process and 4 to 1 is the pressure rise in the feed pump.

Now, we are interested in the process 1 to 2 that is the heating process of the working fluid. Here, we can see that the working fluid changes its state. Initially, it is in the sub-cooled condition. From the sub cooled condition it goes to the saturated condition; then, evaporation takes place, it is transformed into saturated vapour and then super heating takes place. There are quite a few stages and this total process takes place inside a boiler or a steam generator where we are having the flew gas or the hot product of combustion. Now, our motto is to improve this cycle efficiency. Again, if we look back at the postulates of Carnot, in the Carnot cycle, we had isothermal heat addition process and isothermal heat rejection process. In the Rankine cycle, we can see that only part of the heat addition is isothermal. In the rest of it, the temperature of the working fluid changes continuously. That means there is a deviation from Carnot cycle and we have to pay back for this deviation and the efficiency will be lower compared to an ideal cycle or a Carnot cycle.

Again, the Carnot cycle is made up of all reversible processes. We had discussed regarding the irreversibilities and the causes which make a process irreversible. There, I have told that heat transfers across a finite temperature gap or finite temperature difference that causes irreversibility. So, when the temperature difference for a process, when there is heat transfer is more, we will have a higher level of irreversibility. If we transfer heat across a small temperature gap, we will have a lower level of irreversibility, whereas if we have to transfer heat across a temperature difference which is large enough, then we will have a higher degree of irreversibility.

Now, if we analyse the total heating process of this working fluid in a steam power cycle, we can see when the fluid is getting transformed from the sub-cooled liquid state to the saturated liquid state, there, we have a large amount of temperature drop for the heat transfer process. If you assume more or less the product of combustion is having a constant temperature, though it is not so in actual process, there also you will see that the product of combustion will change its temperature as heat transfer takes place. But if we assume that the product of combustion or the heat source that is having a constant temperature, then the maximum temperature difference between the working fluid and the source will be at the point 1. This difference is quite large throughout the process when the fluid is in sub-cooled condition. In other words, in this process, when there is a heat transfer to the liquid and we need the heat transfer to transform this liquid to the saturated state, we will have a high degree of super heat. Somehow, if we can modify this process, then we can reduce the irreversibility and we can have a better cycle efficiency. It is almost taken as a rule that in a thermodynamic cycle in a heat power cycle, if the mean temperature of heat addition is raised then the cycle efficiency increases.

Similarly, if we reduce the mean temperature of heat rejection then our cycle efficiency increases. So, the mean temperature of heat addition in a Rankine cycle is low because, here, in this process we have to add heat at a low temperature. Somehow, if we can modify this process and this heat addition is not from any external agency, this heat transfer has to be there, but if we can avoid the heat transfer from any external agency then we can improve the cycle efficiency. So, this heat transfer can be done internally and if this heat transfer is done internally it is known as regenerative feed heating. This is the heating of feed water and it will be done internally by making some arrangement from some part of the cycle itself, we will take some thermal energy for heating this and we will call it regenerative feed heating.

We will see now how this regenerative feed heating can be done. Let me first draw the block diagram with regenerative feed heating.

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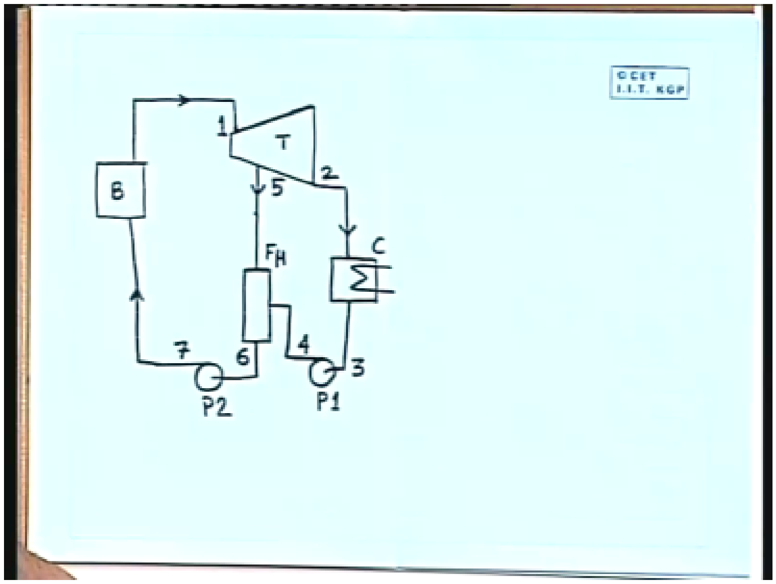

Basically, we have the boiler. From the boiler the super-heated steam will go to the turbine. In the turbine, the entire steam will not be allowed to expand up to the exhaust pressure. In between, we will extract certain amount of steam and then the rest of the steam will be allowed to expand to the exhaust pressure of the turbine. This steam will pass through a condenser as usual. Then, you need a pump for pumping it. But this condensate will be pumped to a heat exchanger where it mixes with the extracted steam from the turbine. The process will be controlled in such a manner, so that out of this heat exchanger we will get condensate or water at the saturated condition. You need another pump and with this pump it will go to the boiler. I have drawn the cycle with only one feed heating. This heat exchanger is called feed heater F_H. This is your boiler, this is the turbine, this is the condenser, this is pump 1 and this is pump 2.

At a different point where there is change of property, if I denote them by number, then steam enters the turbine at 1, it comes out at 2. Then, this exhaust steam is condensed and that condition is denoted as 3. The condensate is pressurised by the pump and that condition is denoted as 4. Then, from the turbine in between some steam was extracted, this steam is known as bleed steam. So, the condition of the extracted steam or bleed steam is denoted by 5. Steam at condition 5 and condensate at condition 4, they mix together and we get the mixture at condition 6 which is generally at saturated liquid condition. This saturated liquid at 6 is pumped to be at pressure of the boiler which is denoted by condition 7 and then in the boiler from condition 7 to condition 1, the water is raised to the super-heated steam and that is done by the heat addition in the boiler.

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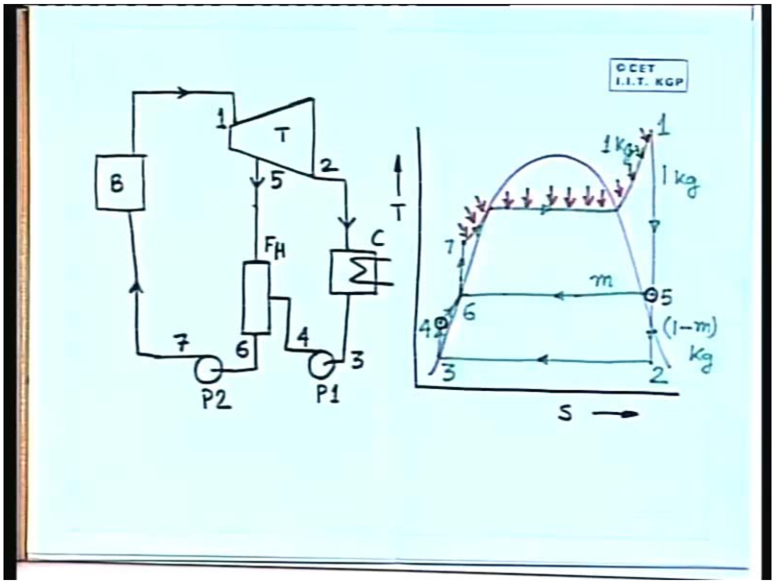

Side by side, we can have the TS diagram. Let us have the TS diagram side by side. This is the 2 phase dome. Let us take some other colour. At 1 steam enters the turbine, so 1 here. At 2, steam comes out of the turbine, at 3 it comes out of the condenser. Then, there is a pressure rise which is isentropic path. Then, 1 to 2 is the expansion process of this steam. But in between some bleed steam has been taken out at condition 5. So let us say this is condition 5. Here, this is the steam which has expanded up to point 2, it has been condensed to point 3 and then there is a feed pump; so this is 4. Condensate at 4 and steam at 5 mix together to produce a condition which is given by 6, so this point is 6. From here again, there is a pressurisation process with the help of pump P2, so this is point 7. From 7 to 1, is the heat transfer process inside the boiler. If we put some arrow to show the direction of the process it will be something like this. Now, our heat addition process by some external source is like this. So this is the heat addition process. We have increased the mean temperature of heat addition. This will have some effect on the efficiency of the cycle and efficiency of the cycle will increase.

Now, we will do some analysis of this modified Rankine cycle where we have gone for regenerative feed heating. We have to fix some flow rate. Let us say, 1 kg of working fluid is passing through this cycle. 1 kg of working fluid is coming out of the boiler and the same 1 kg of working fluid is going to the turbine. Here, a part of this working fluid is taken as bleed steam or extracted steam. Let us say this part is m. So, the rest of the working fluid that is 1 minus m kg that will pass through the turbine and will expand up to the exhaust pressure. This is how the steam will be divided into two streams. One will be extracted and one will expand.

We want to calculate the work done during this process or in this cycle.

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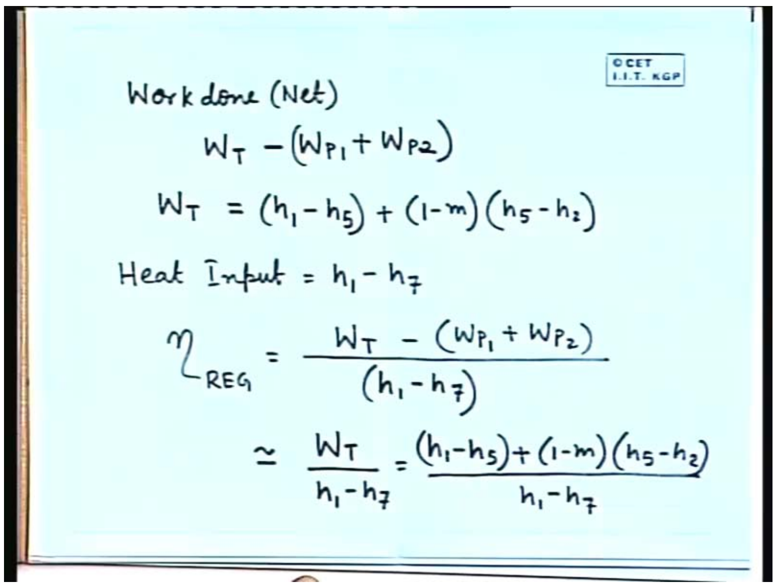

Let us say this is the net work done. If we want to determine the net work done that is equal to turbine work minus W_{p1} plus W_{p2}. This is the net work done. W_T turbine work is equal to, if we see the previous diagram, 1 kg of steam has expanded from condition 1 to condition 5. We can write for the first part of it that is, h_1 minus h_5. Then 1 minus m kg of steam expanded from condition 5 to condition 2. We can write plus 1 minus m h_5 minus h_2. So, this is the work done by the turbine.

What is the heat input? The heat input, though there is heating process here also 4 to 6, here also some heating process is there, but this heating is internal heating or regenerative heating. External heating is only from 7 to 1. Here, the entire amount of working fluid was heated by the external agents. So we will have h_1 minus h_7; this is the heat input. Efficiency, we can write efficiency regenerative as equal to W_T minus W_{p1} plus W_{p2} and then heat input is h_1 minus h_7.

Now, again, depending on the pressure level one can neglect the pump work and one can approximately write it as W turbine by h_1 minus h_7. That is equal to h_1 minus h_5 plus 1 minus m h_5 minus h_2 this divided by h_1 minus h_7.This is the approximate expression for efficiency with a regenerative feed heating.

Now if we see this expression, then we can see that we can determine this efficiency once we know m. m is still unknown. So is it arbitrary? No, it is not. There is some method for determining m. I have mentioned earlier also that steam is taken at condition 5 and the condensate from the condenser is going through the feed pump and ultimately it is available at condition 4. So, steam is at condition 5 and the condensate after the feed pump, is at condition 4. These two are mixing together and ultimately we are getting the mixture at condition 6. This information can be made or can be utilised to find out the mass of the extracted steam.

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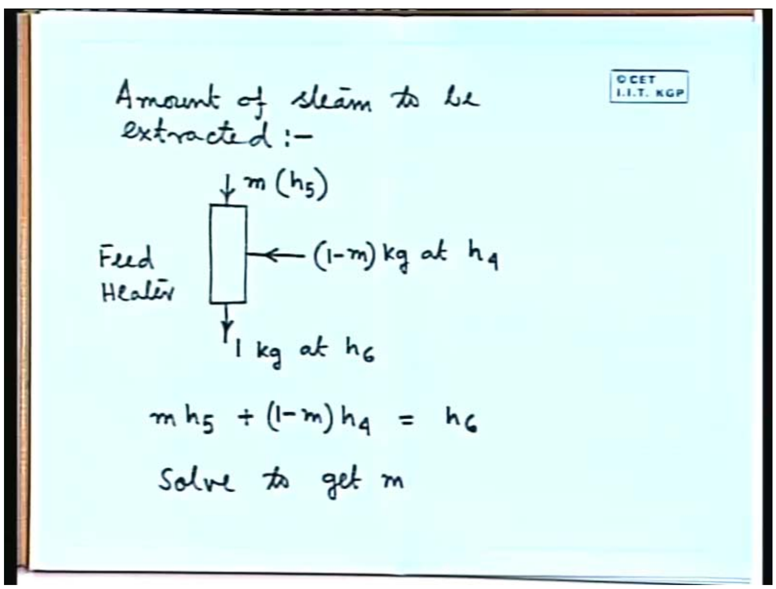

Let me write the amount of steam to be extracted. How to determine the amount of steam to be extracted? It is like this. If we see this, here, m kg of steam is coming and its condition is h_5. Here 1 minus m kg of water is coming, its condition is 4. So, 1 minus m kg at h_4 and then, we are getting 1 kg at h_6. Right? mh_5 plus 1 minus m into h_4 that is equal to h_6. Solving this equation one can determine m. So solve to get m.

The arrangement which I have shown, this is your feed heater. The arrangement which I have shown for this feed heater it is known as an open type feed heater. Here, this steam directly mixes with water to produce water or condensate at the saturated condition. Now, there are other designs also which are closed type feed heater but similar type of energy balance can be applicable in case of closed type feed heater also. But, the way I have shown it in the block diagram, it is for open type feed heater. So, we have made the analysis for regenerative feed heating.

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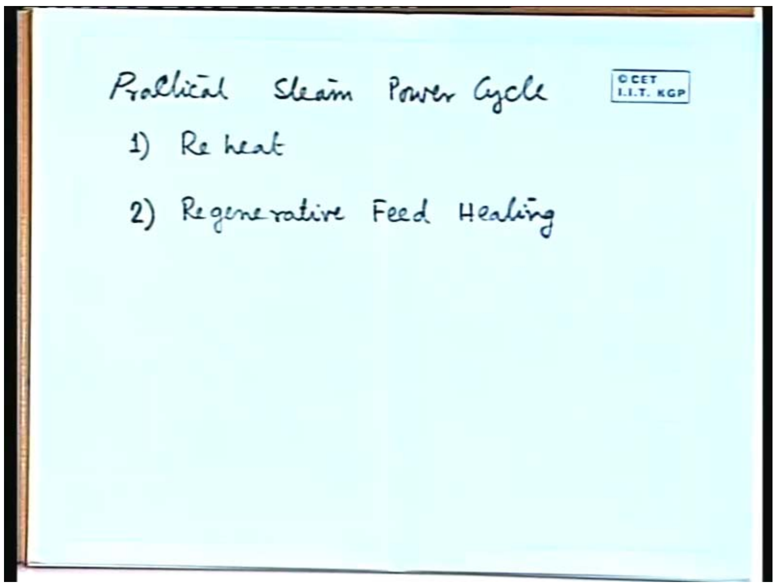

A practical steam power cycle will have both reheat and regenerative feed heating. If we see regenerative feed heating, we are increasing the mean temperature of heat addition and I told that we are increasing the efficiency. For the sake of simplicity, what I have shown is only one feed heater.

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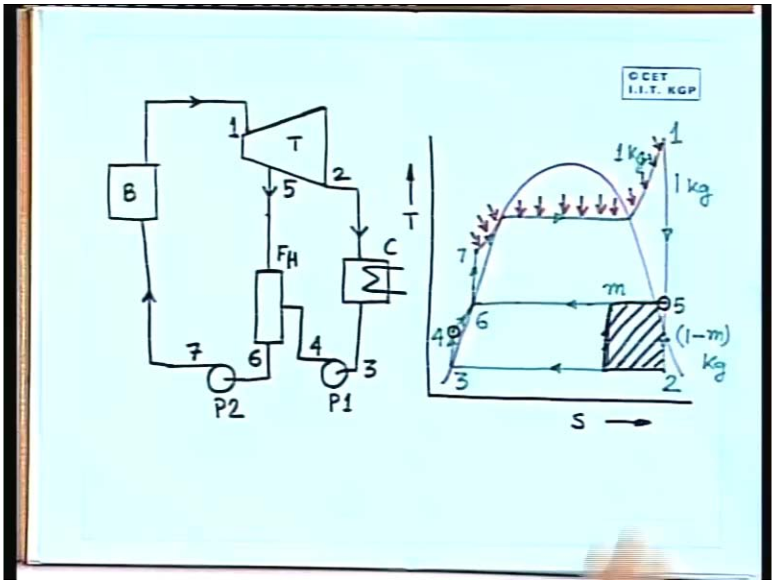

In practice, if we increase the number of feed heater the efficiency increases. Again, the incremental increase in the efficiency, that decreases as the number of the feed heater increases. That means, the first feed heater you add you will get a large increase in the efficiency. The second feed heater you add, you will get slightly less increase in efficiency; third feed heater still slightly less increase in efficiency. That is why we do not go for very large number of feed heater. So, maximum 3 to 4 feed heaters are added in a cycle, so that we can get a good compromise between the increase in efficiency and the cost of feed heater and extra piping, extra pump, etc.

In a practical cycle, we will have a mixture of both open and closed type feed heater. Both the types will be used and we will have both closed and open type feed heaters. When we are going for regenerative feed heating we are gaining in efficiency but we are losing in work output. When the entire amount of steam is allowed to expand from point 1 to point 2, we get more work output. But, here, what happens is that, up to point 5 we get the amount of work output out of 1 kg of steam but beyond point 5 we are getting work output out of 1 minus m kg of steam. Sometimes, in some books, you will find that they show the diagram like this to indicate that here we get some less amount of work output and here, only 1 minus m kg of steam expands through this process. In regenerative feed heating we are losing in work output that can be compensated if we have side by side the reheating. Again, reheating also needs some extra cost for piping etc; the plant becomes too much cumbersome. So, one reheat or maximum two reheats are used, not more than that. We will have 3 to 4 regenerative feed heating, 1 to 2 reheat and that is what a practical steam power cycle will comprise of. I think here we will stop our discussion regarding the steam power cycle.

Basically we use the Rankine cycle which is the ideally suited for steam as the working fluid. It is different from Carnot cycle. Particularly, the heating process is different from Carnot cycle. It is a constant pressure heating process, whereas in the Carnot cycle you have constant temperature heating process. The ideal Rankine cycle will not give a very good efficiency. So, we go for different modifications of it. Two modifications are extensively used in steam power cycle. One is re heat and second one is regenerative feed heating. Actually, a combination of reheat and regenerative feed heating is used in practical steam power cycle. Reheat will increase the work output for the same amount of steam flow rate and regenerative feed heating will increase the efficiency though, there is some decrease in the work output. That is regarding our steam power cycle.

Now, with this discussion, I like to go for another topic, which is a logical extension of our discussion and now we can switch over to steam turbine.

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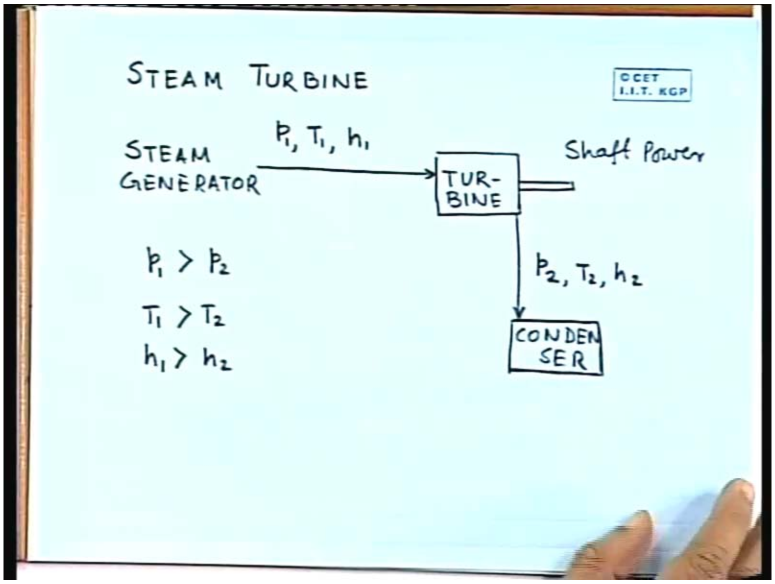

The steam turbine is the prime mover where steam is the working fluid. With steam as the working fluid, in the earlier days of steam power, people had steam engine as the prime mover. But, the steam engine has got lot of demerits or limitations. Being a reciprocating type of machine, it is low speed and there will be lot of losses due to friction, etc. Though in the earlier days of steam power, people used to think steam engine was a very great invention of engineering and a lot of use of steam engine was there, with the passage of time slowly steam engine was phased out. Still steam is used for production of power as a working fluid and the prime mover here is not the steam engine but the steam turbine.

Basically, you have steam generator and then it will go to the turbine. This will give shaft power. Then this is supply steam, this is exhaust steam and it will go to the condenser. Here, steam is at condition 1. Let us say, it is p_1, T_1, h_1 and here it is at condition 2, so it is p_2, T_2 and h_2, such that, p_1 is greater than p_2, T_1 is greater than T_2 and h_1 is greater than h_2. High energy steam generally at high pressure and temperature is entering the turbine. It is passing through the turbine. It is expanding. Why we call it expanding because, at the exhaust we will have low pressure steam and at the same time it will also have lower energy content and in this process it will create mechanical work and then it will work continuously. The steam turbine is such a prime mover that it will work continuously and it will produce power continuously as long as supply of steam is there. So, this is how the working of a steam turbine can be expressed with the help of a block diagram.

Basically, what we can see is that the energy of the working fluid, which is steam that will be converted into mechanical work and there are two steps by which this energy of the fluid will be converted into mechanical work.

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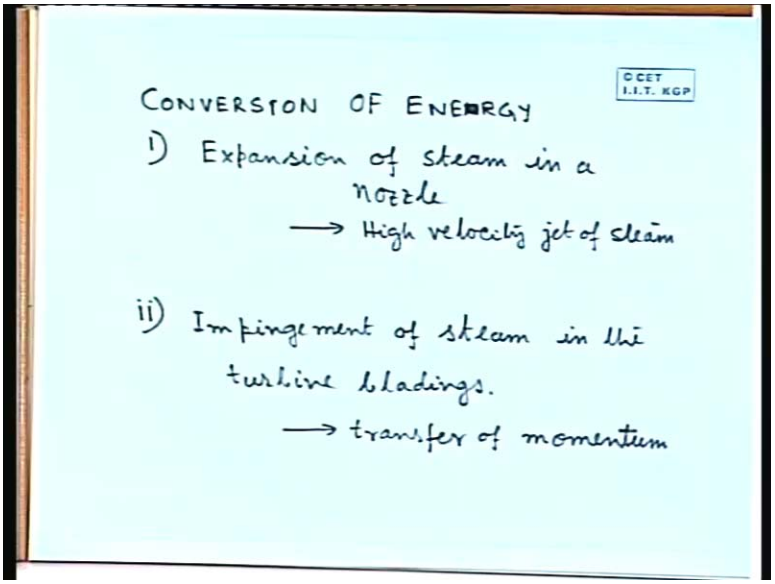

The conversion of energy- first, there is expansion of steam in a nozzle. In the steam turbine, we will see that, invariably initially we expand the steam in a nozzle. The first conversion takes place in the nozzle where the steam expands and what will happen here is that we will get a high velocity jet of steam. That is what we will get out of this process.

Next, what we will have is this; impingement of steam in the turbine bladings. Basically, we will have transfer of momentum. In this case we will have transfer of moment. So by these two methods, we will see that the energy of steam will be converted into shaft work. Shaft work means mechanical work. Either it can be the output that can be directly obtained as mechanical work or it can be connected to a turbo alternator to get the electrical energy. This is how we will have the energy conversion in a steam turbine.

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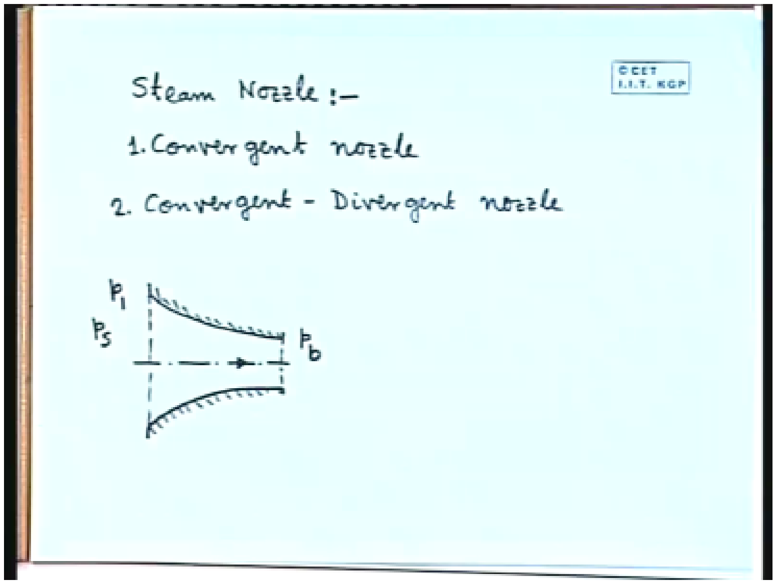

We have already studied regarding the steam nozzle. Basically, steam nozzle can be of two types. The first one is convergent nozzle and the second one is convergent - divergent nozzle. In steam turbine either we can have convergent nozzle or we can have convergent divergent nozzle. One can represent the convergent nozzle schematically like this. Basically there is a reduction of area in the direction of flow. This is the convergent nozzle. From Bernoulli's principle we know that as the area is reducing we will have an increase in velocity and at the same time there will be a decrease in pressure. Let us say this side we call the pressure as p_1 and at the nozzle exit this pressure is known as p_b or back pressure. The steam expands from p_1 to p_b.

Generally at the inlet of the nozzle, the pressure of the steam is very high but at the same time its velocity is negligibly small. Sometimes, this is also called p_s or stagnation pressure and at the exit of the nozzle we call it back pressure. The characteristic of the expansion phenomenon through a nozzle is different for compressible fluid and incompressible fluid. Let us say we have got some incompressible fluid or liquid. If it passes through a nozzle we will see its velocity will increase; pressure will fall and velocity will increase. If we go on decreasing the back pressure the velocity will go on increasing continuously. But in case of a compressible fluid let us say for any gas or a vapour the phenomenon is slightly different.

Initially, what we will see is, if we go on decreasing the back pressure the velocity will increase. But at one point we will find that we are decreasing the back pressure but there is no further increase in velocity anywhere inside the nozzle. So, we will not have any increase in mass flow rate also. That means we will have a decrease in the back pressure but the mass flow rate is not increasing, as if the nozzle has got choked. This is called the choking condition or critical condition of the nozzle. This happens only in case of vapour or in case of gas. So, in case of steam also we will have this phenomenon.

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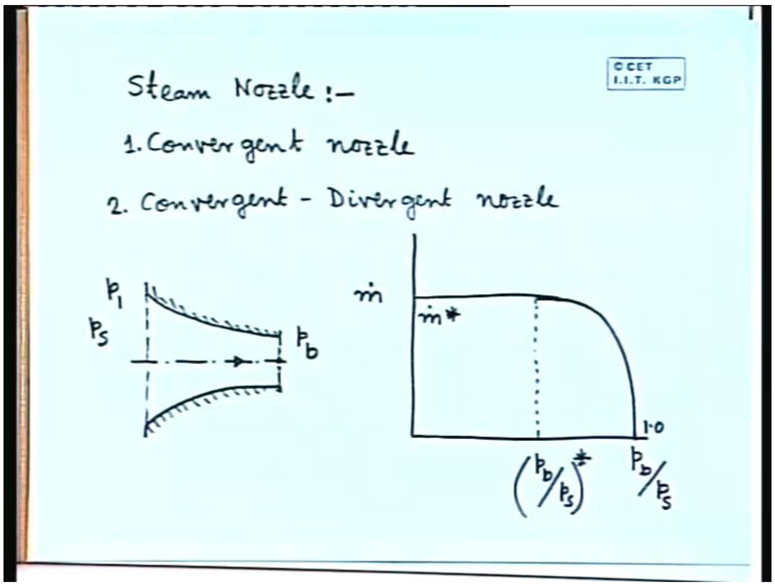

Let us say, this is the mass flow rate through the nozzle and the back pressure, we are expressing in a non-dimensional form p_b by p_s, back pressure by stagnation pressure. This point is 1; that means at this point back pressure and stagnation pressure are the same or back pressure is equal to the stagnation pressure. What will happen? At this point we will not have any flow. After that back pressure is reducing that means we are going towards this direction of the graph. You will find that mass flow rate is increasing but at this point let's say you will have p_b by p_s star, a typical value of p_b by p_s. Beyond this, whatever may be the decrease in your back pressure, we will not have any increase in the mass flow rate.

This is a typical characteristic of a convergent nozzle with a compressible fluid as the working medium or medium which is expanding through it. This mass flow rate we can call it m dot star. This is the critical mass flow rate and this ratio p_b by p_s star is the critical pressure ratio. At this point what happens is that we will have local sonic velocity at the exit plane of the nozzle. The fluid velocity here will be equal to the local sonic velocity. If you have a convergent type of nozzle, the maximum velocity will be at the exit of the nozzle and that velocity you can have as high as local sonic velocity. Beyond that you cannot increase the velocity. As the area is constant and maximum velocity is the local sonic velocity, you cannot increase the mass flow rate through this nozzle. The maximum mass flow rate through this nozzle is also fixed. The sound travels with a velocity and that depends on the medium through which the sound is moving or the sound wave is moving. Let me write it down.

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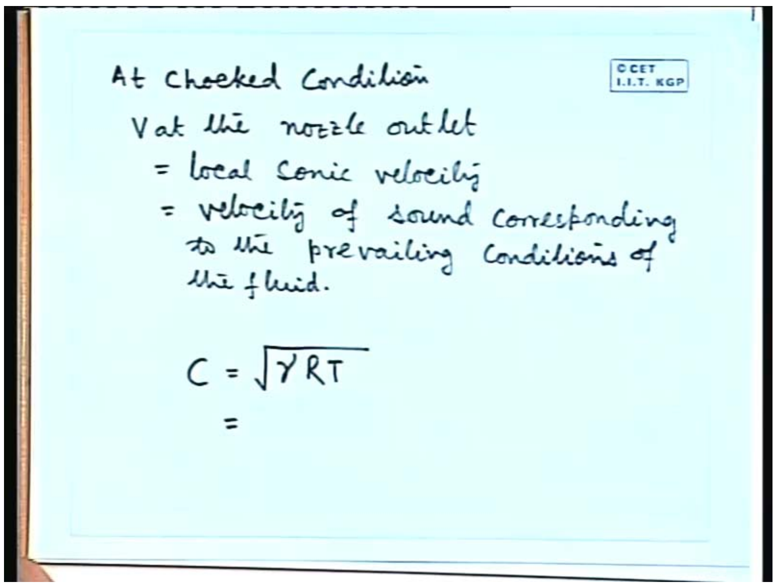

At choked condition V, at the nozzle outlet is equal to local sonic velocity which is equal to velocity of sound corresponding to the prevailing conditions of the fluid. If it is a compressible fluid, then the velocity of sound, let us say at this point, will depend on the fluid properties at this point itself. So that’s why we call it local sonic velocity. You will recall that sonic velocity is denoted by C and in an ideal gas, it is given by gamma RT where gamma is CT by CV, R is the gas constant and T is the local temperature. It depends on the fluid property.

The same relationship will not be valid for steam because it is not an ideal gas, but here also it depends on the local properties of the steam. We can see that, when we are using a steam nozzle and we are using this geometry of the nozzle that is the convergent nozzle, we want to have maximum flow rate out of the nozzle. So what maximum we can have, that depends on the geometry of the nozzle and on the stagnation pressure. At the maximum flow rate you will have sonic velocity at the nozzle outlet. So this is very important to bear in mind that, that is how a convergent nozzle for steam will work. In this nozzle we will have limitation for both the maximum mass flow rate and maximum velocity. Well, we will continue in the next lecture.