Basic Thermodynamics
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Lecture - 20
Vapors Power Cycle - I

We will start, today, the vapor power cycles. What is a vapor power cycle? Now, let us think in this way that vapor power cycle is a particular type of cycles of the general thermodynamic cycles.

Now, the very first thing, what is a thermodynamic cycle? Thermodynamic cycle constitutes a number of processes so that the initial states and the final states are identical. If all the processes in a cycle are reversible then the thermodynamic cycle is a reversible cycle. We can show in a thermodynamic coordinate as a closed loop. It starts from one initial state and come back to the same initial state; that means, initial and end states are equal. That is known as thermodynamic cycle.

Now, next question comes that why thermodynamic cycles are so important in the studies of thermodynamics? We have discussed, while describing the first and second laws of thermodynamics that the need is a continuous conversion of work from heat or heat from work. For example, we have stated the second law in this fashion that total heat cannot be converted into the complete work in a continuous cyclic process. In a particular process, we can convert heat into work, but in a continuous cyclic process, when conversion of heat and work takes places, heat cannot be converted continuously into work.

For a continuous conversion of work from heat or heat from work, we require a cyclic process to be performed; without a cyclic process a continuous conversion of work to heat or heat to work is not possible. So, implications of a cyclic process that means a cyclic process has to be performed by a system to convert heat to work or work to heat continuously. The cyclic process where heat is being converted into work that means the net work is obtained from the cycle, where there is a heat input to the cycle is known as heat engine cycles. These devices are known as heat engines.

Similarly, the cycle which converts work into heat are known as continuously heat pump or refrigeration cycles and these devices are known as heat pump or refrigerators. So, if we divide thermodynamic cycles into two broad categories, one category is heat engine cycles, another category is the refrigeration or heat pump cycles. Since heat engine cycles develops mechanical power or mechanical work, that is why, this is called as simple power cycles, because heating engine cycles produce power. Now, depending upon the phase of the working or state of the working systems, these power cycles are divided into two categories; one vapor power cycles, another one is gas power cycles.

In certain cases, it is found that the system executing the cyclic process changes its phase; that means, in different processes of the cycles the change of phase takes place. In some process, it is liquid. Some process, it is vapor. Phase means only liquid and vapor. So, these cycles are known as vapor power cycles, whereas in the cyclic processes, the state of the system or the phase of the system is only in gas phase, the cycles are known as gas power cycles. We see the thermodynamic cycles, its implications in thermodynamics that is on thermodynamics. So, they can be divided into two broad categories; one is the power cycles or heat engine cycles, another is the refrigeration or heat pump cycles. Power cycles depending upon the state of the system, we have vapor power cycles or gas power cycles.

Now come to thing that vapor power cycles, if we consider that means these cycles correspond to certain devices, where power is being developed from heat and the system executing the cyclic process undergoes a change of phase from liquid to vapor. The most popular and the most important device is the thermal power plant, where this happens is a typical thermal power plant. Therefore, before studying a vapor power cycle which represents the different processes in a thermal power plant, we must have a look of the thermal power plant. What are the different components and overall idea of a thermal power plant?

So, let us come to that thermal power plant.

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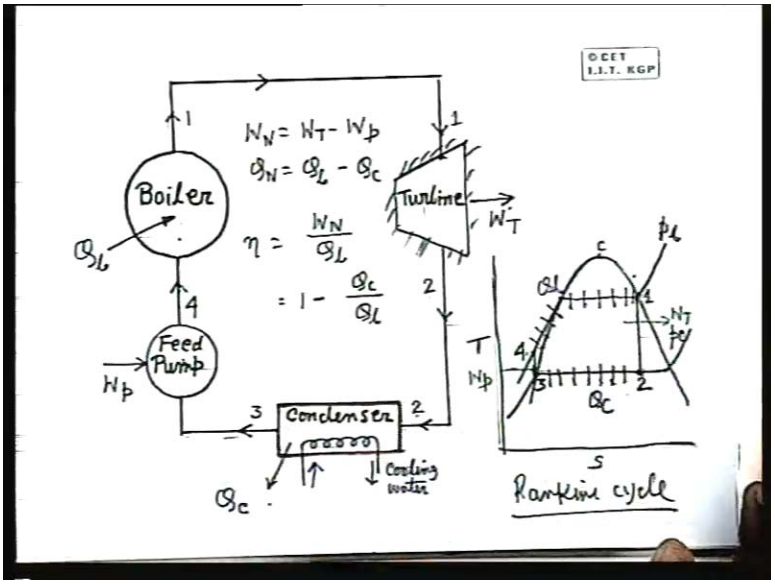

So this is a thermal power plant. We see the different components of the thermal power plant. So before discussing that I like to tell another important thing just I have told that the cycles are of two types, the vapor power cycles and gas power cycles, thermodynamic cycles, heat engine cycles and refrigeration cycles, the vapor power, gas power.

So, why do we read cycles? Because of this, the cyclic operation is a must for continuous conversion of heat into work and work into heat. Next thing is that, if we look from other angles that if we want to design a power plant, for example, where thermal energy is being converted to mechanical energy. I am not going into detail of this. How the thermal energy is being converted? Actually, we convert the chemical energy in the fossil fuel; The fuel is the natural resource of energy and then burn it and generate high thermal energy in terms of high temperature and pressure. Then we heat a working system which takes the heat from this burning gases and it executes the cyclic process and develops power.

Sometimes, this burnt products itself performs as a system of the cyclic process and produce power. This happens in IC engine. Sometimes, this burnt product produces the source of heat where heat is given to another fluid or another system executing the cyclic process which happens in a steam power plant and produces power. So, these are the typical power plants, IC engine, gas turbine power plants, steam power plants.

Now the very first phase of the design of this power plant is the thermodynamic design, you must know because otherwise what will happen, you will not get interest that why we will be reading this thermodynamic cycle.

Now, the first phase of thermodynamic design tells that which should be the ideal cycle for this particular power plant. That means the power plant will consist of different processes which will constitute a thermodynamic cycle, because continuous production of power from heat, conversion of heat to work or work to heat in refrigeration cycles or refrigeration processes it from cycles or it from processes, we have different processes that means we have a cycle. So, first of all, we have to fix, which cycle it should follow; means, what should be the ideal process performed by each component so that this particular power plant runs at its maximum efficiency within the available operating conditions. Within the available operating conditions, which should be the ideal cycle?

For an example, when we design an automobile car, we design it either on the basis of diesel cycles or auto cycles. I will take this thing afterwards. These are real standard cycles not on Brayton cycles. While we are designing a gas turbine power plant or aircraft engines, we design on the basis of the Brayton cycle. Why? I will be discussing that.

When a steam power plant is designed, it is always intended that all the operations in the steam power plant in different components should perform the processes which ultimately follow the processes of a particular cycle known as Rankine cycle. Therefore, the power plant is first designed from the thermodynamic view point which is known as thermodynamic design of power plant, on the basis of a theoretical cycle which is known as thermodynamically performance criterion of that plant, which should follow this ideal cycle to give its best performance. With this in mind, we must appreciate that why one should read or study the analysis of particular cycles, because from that only, we can find out the influence of the operating parameters on the performance of a power plant. So, a vapor powers cycle which we will be discussing is a performance criterion or an ideal cycle of a steam power plant.

So, we first have a look overall look of a steam power plant which will be taught in detail afterwards in applied thermodynamics. This is a part of your course curriculum for mechanical engineering student. So, just I tell you, what a steam power plant is? What are the components?

Let us look here that steam power plant essentially consist of a boiler, turbine, condenser and feed pump.

Let us start from point one, this goes in this direction, that entry to the turbine. (Refer Slide Time:10:23 min) Let us consider a steam at high pressure and temperature enters a turbine where steam expands. There is an expansion from high pressure and temperature to a low pressure and temperature by which work is being developed. So, this is a component which develops work by receiving steam at high pressure and temperature and by rejecting steam at low pressure and temperature. This is the point two. So the principle behind it, what this expansion to get mechanical work falls under the domain of turbo machines.

How a high pressure and steam expands through? What are the passages? There are several blades mounted on it, they are several rotor blades, all these things had fall into the domain of turbo machines. We are not going into detail of it. But due that expansion, by the principles of turbo machines, this turbine produces work. So work is being developed in this device. We will be only studying the thermodynamics of this power plant. This low pressure and temperature steam, there are two possible states, when the steam at one, either dry saturated in usual practice or super heated. In all usual practical application, it is super heated steam, but sometimes it may dry saturated steam also. After the expansion at low pressure and temperature, this steam becomes wet steam at a relatively low pressure and temperature.

This wet steam ultimately is condensed in a condenser; that means, this is the typical heat exchanger where the latent heat of this steam is taken away from this wet steam. This is the condition at two and it is converted into saturated liquid state. That means it only takes away the latent heat in this condenser as in heat exchanger. So, cooling water passes through this which takes away the latent heat from the steam, the corresponding enthalpy differences so that it comes out as a saturated liquid and its pressure is same. Two and three pressure is same, because it is a steady flow process. There is no change in pressure except a very negligible amount due to the frictional pressure drop. So, whenever there is a steady flow process, ideally we will consider the pressure remain same. So, two and three at the the same pressure and also at the same temperature, because there is a phase change only from two to three.

Then we have a small pump; this is a typical centrifugal pump which also operates that as on the principle of turbo machines. It accepts liquid water at a low pressure and temperature at point three and then pumps it at a higher pressure and temperature may not be very high. As we know, when water is an incompressible liquid and if we pressurize it to high pressure, the temperature rise will be very less. So, at a high pressure four, this is the same as that of the turbine inlet pressure. Then this goes to a device boiler where heat is supplied to the steam.

When it goes to four, the state is also water. Then heat is supplied to this water at constant pressure because it is a steady flow device in the boiler similar to that in the condenser. Therefore water is heated. Heat is being supplied and is converted to steam at the condition one and it comes here and enters the turbine. So, condenser and boiler operate on constant pressure, where turbine there is a drop in pressure. Though it is a steady flow process, that drop in pressure is responsible for work extraction.

Similarly, there is a rise in pressure, though it is a steady flow process because of the absorption of work from outside. So if we consider this as a cyclic process very well, we can explain that this is the heat addition, one process. This is the heat rejection process, because we have to respect the second law. Heat has to be rejected. So, this is the work producing that may work is developed here, work is absorbed there. So, this is more than this. So there is a net work from this plant; that means, the net work is equal to W_T minus W_p and the net heat is equal to Q_b which is given in the boiler minus Q_c and these two are equal. (Refer Slide Time: 14:45 min) The efficiency of the plant is defined as W net divided by gross heat or we can write one minus heat rejected by heat added. All these things, we have learnt in the first law of thermodynamics and also in the second law that heat has to be rejected and how to define the thermal efficiency of a heating in cycle. So, this is the thermal power plant.

Now, here heat is added to the steam. This heat comes from the products of combustion, burning the fuel in air; that is not our point of discussion. This is a typical layout or block diagram of a power plant. Now, we will represent the processes in Ts diagram then what should be the ideal cycle, if we plot it first in Ts diagram. Let us draw the Ts diagram. This is the vapor dome. This is the critical point.

Here, the processes are so designed that there are two pressure levels of this cycle. One is that the pressure here and that is from four to one the pressure is same, because this is the final pressure, this is the constant pressure, heat addition process then it comes then here; four to one, the pressure remains same.

Similarly, from two to three, pressure remains same. This pressure is the pressure at which the condensation is taking place or the pressure after the expansion from turbine. So, that is why, pressure which exists in the working system from two to three, known as condenser pressure. The pressure at which this liquid is boosted up by the feed pump and being maintained till the entry of the turbine is known as boiler pressure. The pressure which is being generated to feed the water or the pressure at which the water is fed to the boiler and this water is known as feed water with respect to the boiler, because this is being fed to the boiler. Therefore, this pump is known as feed pump.

Therefore, we show first, the two constant pressure lines, one is the boiler pressure and another is the condenser pressure. This works under these two constant pressure curves. Now, if we start, similarly from one and let us consider first that one is at dry saturated state that means this one is here. (Refer Slide Time: 17:16 min) One, two is an expansion from which we get the work. So, what should be our ideal target? The expansion should be free from all dissipation and in fact in practice, the turbine is insulated. Why unnecessarily we will allow there loss of thermal energy outside in the form of heat? So it is insulated, because I want exclusively work from this. There should be as small as possible dissipation while doing the work that means the entire process, whatever happens there by the principle of turbo machines. If I look in terms of an overall expansion, that expansion should be isentropic; that means, free from friction and free from heat transfer.

Heat transfer means if we allow heat to be transferred then heat will be lost only. It will not come into the system, because this is very hot. So, it is insulated. It is adiabatic and reversible, so isentropic. So, my ideal process will be this. (Refer Slide Time: 18:12 min) So, this will be the two. So, obviously the point two corresponds to a weighed steam at a relatively low pressure. At two, it enters a condenser that is the heat transfer, where heat is being rejected by this steam to come to the saturated liquid. This condenser is designed in such a way and the circulating cooling water is controlled in such a way that only this takes the latent heat; that means, the difference of enthalpy from point two to three so that it comes only in the saturated liquid state.

Then three to four is again a pumping, where we will consider an isentropic compression. Why? Because if there is an isentropic expansion, we will get the theoretically maximum work and if this gives an isentropic compression, we will get a theoretically minimum work to be given into the compressor. Therefore, this is one, two, three, four is the cyclic process.

Now, four to one occurs in the boiler; that means, heat is added; heat addition process is four to one. One to two, there is no heat addition that means one to two is work output $W_{T,}$ four to three is W_p and heat rejection is there in the condenser that means this is the $Q_{c.}$ Therefore, this one to four corresponds to the process, four to one boiler, one to two turbine, two to three condenser and three to four feed pump. So, this way, we can represent the Ts diagram. So this one, two, three, four, one constitute a cyclic process.

If we do not correlate with the thermal power plant, this is for our understanding, because this is the ideal cycle for the power plant. Then, we study this cycle only to know how the power plant operates and what are the influences of inlet pressure, inlet temperature and condenser pressure on the efficiency of the power plant? This is our basic objective, but even without that, one can tell that this is a cycle, if I give the name of the cycle. The name of the cycle is according to a scientist known as Rankin's. This cycle is known as Rankin cycle.

If I ask what is a Rankine cycle? Even without referring power plant, we can tell, Rankine cycle is the cycle which constitutes a constant pressure heating then an isentropic process, then a constant pressure and temperature cooling or heat rejection and an isentropic compression. That also goes fine. I do not know which particular plant is represented by this thermodynamic cycle as the theoretical cycle for its performance, I don't know but this is the cycle. Now, I will go one step further.

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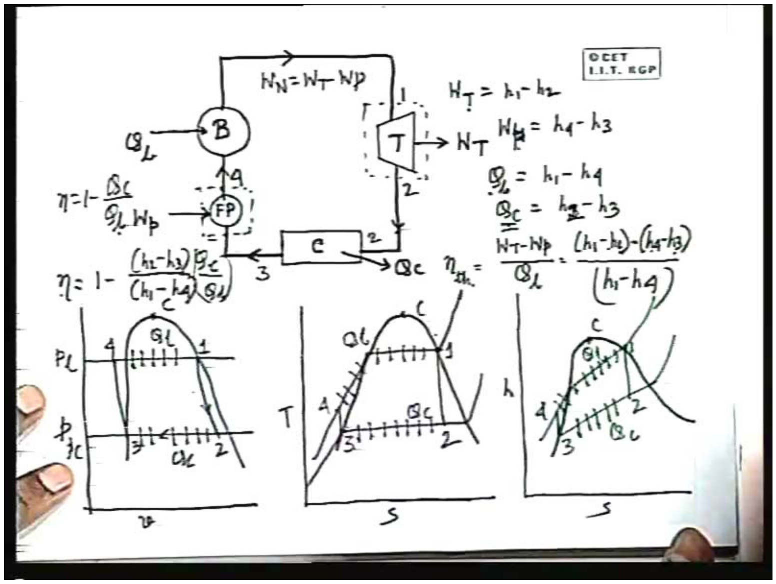

Let us now see that in a small scale, this is the thermal power plant that same thing the components of a thermal power plant. Now I draw this is the point one. This is the point two as usual, so this is the point three, this is the point four. Now, I draw each and every curve on different diagram. This is very important pv, then it is Ts, then it is hs, very simple thing.

Now in pv diagram, let me draw this. In Ts diagram, let me draw only the vapor dome. In hs diagram, it looks like this. It is difficult sometimes to draw the hs diagram, however these are the typical critical points. These operate on two pressures. Let us first recognize these two pressures here. This is p_b and this is p_c in pv diagram.

How to draw Rankine cycle? This is the starting point one. Let us consider one is a dry saturated. So, an isentropic process will be like this. So, this is one and two, this direction. Two to three this direction and again three to four, this is in sub cooled or compressed state. So, this is the one, two, three, four, four-one is the heat addition process. Two-three is the heat rejection process. Here is the Q_b and this is Q_c.

Now, I draw the same curve in Ts diagram. Let us draw the constant pressure line like this. This is the liquid portion, constant pressure line. Now my point is here. I can draw with this. Now this is one. So this is one-two that means the isentropic process in pv diagram corresponds to a vertical line on Ts diagram then three already I have drawn this four. So, it shows the Q_b and it shows Q_c and this is W_T and W_N, I am not showing that now Q_b and Q_c only. Similarly, here also I can draw the diagram like this. Here, the constant pressure lines are like this. So I can show that one, two, then three, then four. So here the heat is added. Q_b here the heat is rejected $Q_{c.}$ So, these are the diagrams on the three different cycles.

Now, if I write the expressions for $W_{T,}$ W_p. So, now see I start from turbine work. Now, if we write this steady flow, since this is a steady flow device, all equations will be written in terms of per unit mass that means per kg basis. So, per unit mass, what is the work done by the turbine? If we write steady flow energy equations by considering turbine itself as a control volume, a control volume enclosing the turbine, W_T becomes equal to h_1 minus $h_{2.}$ Let us come here. Work given to the feed pump is h_4 minus $h_{3.}$

Here, I am not taking negative signs, because I am designating W_N as the work required by the feed pump, not work done by the feed pumps not h_3 minus $h_{4.}$ It is h_4 minus h_3 because h_4 is more than $h_{3.}$ Then the heat quantities, what is Q_b? A steady flow energy equation, if we apply enclosing the feed pump, the work W_p in this direction equals to h_4 minus $h_{3.}$

Conversation between professor and student (Refer Slide Time: 26:23)

Then next $Q_{b,}$ what is Q_b? h_4. That is Q_b is equal to h_1 minus $h_{4.}$What is Q_c? Q_c is equal to h_2 minus $h_{3,}$ because I am designating Q_c as the heat rejected.

Now I can develop the expression, I can write eta thermal, thermal efficiency as the net work; that means, W_T minus W_p which I wrote earlier is the net work W_N, W_N is W_T minus W_p divided by the heat added and that becomes equals to h_1 minus h_2 minus h_4 minus h_3 by h_1 minus h_4.

If we just adjust this thing, we can show this way also. If we write h_1 minus h_4 minus h_2 minus $h_{3;}$ that fashion also we can write. In that case, we can write, one minus h_1 minus h_4 minus h_2 minus $h_{3;}$ that means h_2 minus $h_{3.}$ in the same place, I am writing. I am not going to write in a different paper. So, that you can see as a whole the space is very limited in this paper, that’s why.

So, this can be written. This is nothing but Q_c and this is $Q_{b;}$ that means, this is not product that this is eta is 1 minus Q_c by Q_b, as we know that thermal efficiency is one minus heat rejected by heat added; same thing, because heat added minus heat rejected is the net work, h_1 minus h_2 minus h_4 minus h_3. So, first law of thermodynamics is well valid and we can define the thermal efficiency according to his definition as this. Anyway, we can define the thermal efficiencies.

From this, to know the thermal efficiency work output of the turbine, work input to the pump, heat added to the boiler or heat rejected from the condensers, we have to know the enthalpy values at each and every terminal points of the cycle. If we know these things, you can find out thermal efficiency and all other heat and work quantities. So, how to know this?

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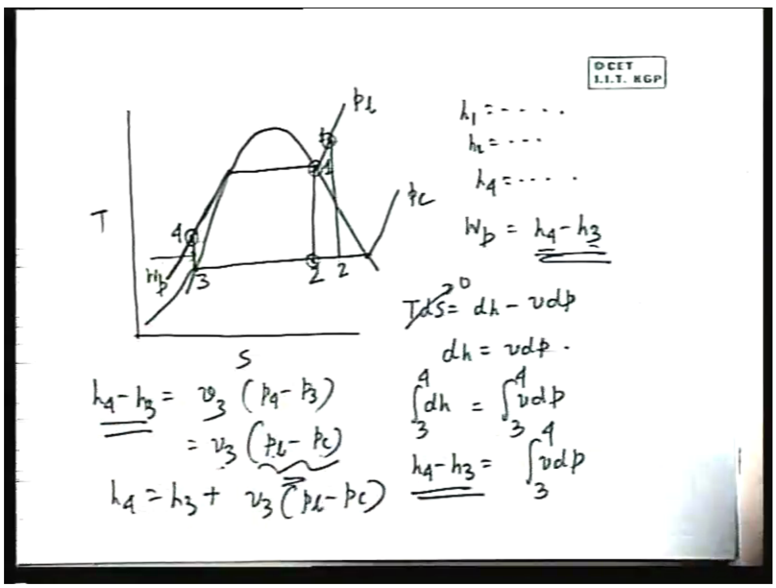

Now to know this, again, I draw the Ts diagram only. Ts diagram is the most convenient diagram until and unless it is asked for, I think it will be always better to draw the Ts diagram. Let us consider the Ts diagram again. This is the constant pressure. Now, let us consider the inlet state is dry saturated. Two then three, this is this line will be like this, so this is four. Now, how to know h_1? h_1 will be known if I know this boiler pressure and if the state is told as dry saturated state, I know h_1; h_1 will correspond to the dry saturated vapor enthalpy.

Now, sometimes, the state is superheated, one may be here in that case it is like this, then two will be like this, then one has to tell the temperature also. If it is at super-heated state, only the boiler pressure will not be sufficient. So, the temperature at the inlet to the turbine or temperature at the outlet of the boiler has to be told; that means, the state of super heat has to be given to know the initial state.

Now, how to find out h_2? We have solved this type of problem if the condenser pressure is told. By an isentropic expansion, I can find out what is this h_2, because the entropy is same. So, I can equate this entropy with the entropy of the saturated vapor here and saturated liquid here to find out what is the dryness fraction, because my only objective is to find the dryness fraction at this point so that I can find out all property.

Therefore, if I consider an isentropic process then only thing I have to know is the pressure up to which the expansion will take place. Then equating the entropy, I can find out the dryness fraction and immediately I can find out h_2. h_3 corresponds to the saturated water enthalpy at the condenser pressure. So, condenser pressure is given; that is also sufficient.

We require boiler pressure initial state, super heat or dry saturated. For super heat state, I require the temperature, and then I require only the condenser pressure things are over. But ask me, sir how you calculate four? Four is difficult to know that is because h_3 h_4, how you do it? We cannot equate entropy in the liquid water phase and all these things which will be difficult. So, the easiest way to find out h_4 is this way. Our main objective is to find out W_p, not the h_4. h_4 will automatically be calculated. Our main objective is to find out W_p for which we want h_4, because the h_3 we know from the table. That is the enthalpy of the saturated liquid, but where the point four will lie so that we can find out the enthalpy of the water at this pressure.

This is a compressed state or sub cool state, but we have to know its temperature; that is also not known before. Therefore, the best way to do is that or it is the usual way or conventional way. Now, I write the thermodynamic property relation Tds is dh minus vdp. So, I see that an isentropic process dh is vdp. Therefore, if I integrate it from three to four, I get h_4 minush_3, because h_4 minus h_3 is our W_p from this steady flow energy equation. That means I can substitute this quantity h_4 minus h_3, the difference of these enthalpies in the liquid state; this is the saturated liquid, this is the sub cooled liquid. This temperature is more this but it is sub cooled, because the saturation temperature is at a much lower temperature corresponding to the saturated temperature or it is at compressed state.

So, this h_4 minus h_3 is vdp, this specific volume of the water changes by a negligible small amount, because water is in compressive. Even if we increase this pressure by a large value or manifold times its initial pressure, the change in the specific volume will be very less. So, I can write h_4 minus h_3 as I take v out and write at v_3 which I know from the table, specific volume of the saturated liquid and therefore del dp three to four means p_4 minus p_3, p_b minus p_c that means if I know the delta p of the pump which is p_b minus p_c because, this is p_b line boiler pressure, condenser pressure.

If I know this specific volume, I can just multiply v_3 times the delta p to get the h_4 minus $h_{3;}$ my objective is to get h_4 minus $h_{3.}$ If I have to find out h_1 minus h_4 then of course h_4 is equal toh_3 plus v_3 into p_b minus $p_{c,}$ separately we can find out. Therefore, explicitly h_1, $h_{2,}$ $h_{3,}$ h_4 provided boiler pressure is given, the upper pressure of the cycle explicit state of the point at the inlet to the turbine and only the condenser pressures. Now, I compare this with a Carnot cycle. Again and again, I tell you this is a very important concept of thermodynamics, that reversible heat engine efficiency is the maximum amongst all other irreversible engines, provided it works between the same two temperature limits. So, now reversible heat engine or reversible cycle, whatever you call heat engine is a particular type of cycle where power is produced.

Now, what is the reversible cycle? Are all processes that are reversible? So, there should not be any confusion that Carnot cycle is the only reversible cycle, Rankine cycle is also a reversible cycle. I told you earlier also, because heat can be transferred reversibly with varying temperature of the working fluid or the working system also. So, all the processes is in the Carnot cycles are reversible process, so it is a reversible cycle also. Now if we compare that means it has the maximum efficiency amongst all other cycles, practical cycles which operates on the same temperature limits. Now tell me what are the temperature limits?

I discussed these earlier, that temperature limit means the temperature or heat rejection. Here, the temperature or heat rejection is fixed; that is, this temperature T_2 or $T_{3,}$ because this is happening at constant temperature. But the heat addition is happening at varying temperature. So, there is no constant temperature. Then we have to define a mean temperature of heat addition. We tell that this is the temperature of heat addition. So, we have to compare with this mean temperature of heat addition. Now, with this philosophy, I compared it with a Carnot cycle. How to do it?

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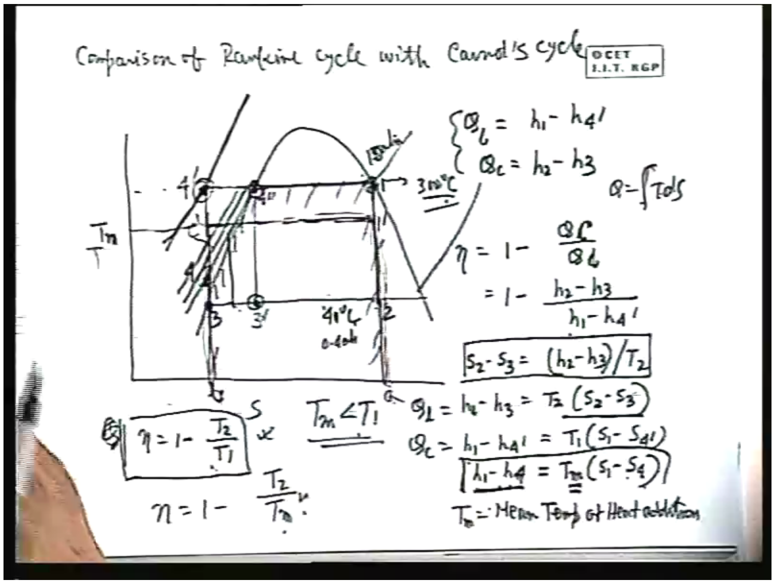

Let us see comparisons of Rankine cycles with Carnot cycles, very important.

Conversation between professor and student (Refer Slide Time: 37:30)

Temperature of heat, it is a condenser temperature. In practice, it is 40 degree Celsius roughly, 30, 40 40 degree Celsius, that depends upon the availability of the temperature of the cooling water it is usually 30, 40 40 degree Celsius. So, the pressure is very low there. Now, comparison of Rankine cycle with Carnot cycle; let us compare first Rankine cycle with Carnot cycle. Then I will discuss all those things.

Now, let us draw the T_S diagram. It is very important. Let us draw the Ts diagram, let us draw the Rankine cycle with the saturated, dry saturated vapor. So, this is the pressure line. This is the cycle 1,2,3,4. Now, if I compare this cycle with a Carnot cycle whose maximum temperature is T_1, here the maximum temperature of the cycle is T_1. Now, that is the difference between Carnot cycles with all other reversible cycle.

That is one category that class one citizen type of thing all reversible cycles. Another category is the bigger citizen type that all irreversible are practical cycles. Now, amongst the reversible cycles, Carnot cycle has got one thing superior, but which is not always superior; that will be proved now. One thing, one differentiable feature is that all the heat added in the cycle is at the maximum temperature, because Carnot cycle heat addition process is isothermal process.

So, the maximum temperature of the cycle is the temperature of the heat addition of the cycle; that means, all the heat is added at the maximum temperature of the cycle. Whereas for other reversible cycles, we will read so many reversible cycles; afterwards air standard cycles, auto cycles, diesel cycles will come. But all other reversible cycles, for example, a Rankine cycle there is a maximum temperature of the cycle; all cycle will have a maximum temperature.

The state point, whose temperature is maximum of the cycle, but the heat addition process, is at a varying temperature. All the heat is not added at the maximum temperature, some part is added at the maximum temperature, because heat is added continuously from a temperature below the maximum temperature to the maximum temperature. All the heat is not added at the maximum temperature. That is the reason for which if we compare any reversible cycle with the Carnot cycle at the same maximum temperature, Carnot's cycle is giving the maximum efficiency obviously, because efficiency is 1 minus T_2 by T_1.

T_1 is the temperature of heat addition is the maximum temperature of the Carnot cycle, but the temperature of heat addition for other cycle is not its maximum temperature, some temperature below the maximum temperature. Therefore, if we compare the Carnot cycle with other reversible cycle with the same maximum temperature, obviously, Carnot cycle will give the better efficiency, higher efficiency. Therefore, we will have to specify it. But if we compare the Carnot cycle with other cycles such that the maximum temperature of Carnot cycle equals to the mean temperature of heat addition of other reversible cycles, then they will be giving the same efficiency.

Even more than Carnot cycles, if the maximum temperature of Carnot cycle is larger than the mean temperature of heat addition of the other reversible cycles, now with this in mind, if I now consider a Carnot cycles, what will be a Carnot cycle? This red one is the Carnot cycle, so this part is coinciding. So 1,2,3,4 dash is Carnot cycle. So, I can design a Carnot cycle like that or I can design another Carnot cycle like this. 2, 3 dash 4 double dash. So, in both the cases in the Carnot cycles, the efficiency will be same.

Let us prove the efficiency, now in Carnot cycles. If I do with any Carnot cycle, for example, 1,2,3,4 dash, we can do for other Carnot cycle that means we can draw two rectangles simply a Carnot cycle is the rectangle in Ts diagram. Now for this, what is the heat added? That means Q_b is h_1 minus h_4 dash.

What is heat rejected in this case is same h_2 minus $h_{3.}$ This is the cycle 1,2,3,4 dash. Only difference is that from three to four dash, it will not go to four, it will go to a pressure line which corresponds to this whose saturation; that means, this pressure line is that, where the temperature will become equal to this $T_{1.}$ So, that is the only difference. So, that 1,2,3,4 dash is the Carnot cycles for which Q_b is this Q_c, so what is the efficiency of this cycle? 1 minus Q_c by $Q_{b;}$ so, one minus h_2 minus h_3 divided by h_1 minus h_4 dash. Now, we can write, for these two three process, s_2 minus s_3 is equal to h_2 minus h_3 by $T_{2,}$ because delta s is delta Q by T h_2 minus h_3 is equal to T2 into s_2 minus s_3. Similarly, for one four dash process, we can write h_1 minus $h_{4;}$ that means heat added, this is the heat added is integral Tds that means T is constant.

T_1 into s_1 minus s_4 dash; this step is redundant. It is not required. I Just showed the definition of entropy, but straight away, we can write this heat added is equal to [.] in terms of the enthalpy difference and in terms of the entropy and temperature, because Q is integral d Tds. So, T is constant. If we substitute this and consider that s_1 is s_2 and s_4 dash is s_3, s_2 is s_1, s_3 is s_4 dash. That means these two will be cancelled out and eta is 1 minus T_2 by $T_{1;}$ that means, for a Carnot cycle we know since the heat is added at the maximum temperature; that means 1 minus T_2 by $T_{1.}$ T_2 is the minimum temperature. T_1 is the maximum temperature or temperature of heat addition which I cannot do for the Rankine cycle.

If we do it for the Rankine cycle, what is the difference? Difference is this; the numerator is the same T_2 s_2 minus $s_{3,}$ but denominator will be h_1 minus h_4 which we cannot write T_1 s_1 minus $s_{4,}$ because T is varying. So, integral Tds that means Q is integral Tds I cannot take T out, so I cannot do that. Therefore, obviously, the Rankine cycle will be maximum efficiency.

Let us prove it. I do it with T_m into s_1 minus s_4. For example, I define some temperature so that h_1 minus h_4 can be written as this to make equivalence so that I can compare; that is, T_2 by $T_{m.}$ That means in analogy to this, I define a temperature. What is that temperature physically from this equation? It will be equivalent constant temperature. It is such a constant so that if the same heat could have been added to this, temperature could have made the same change of entropy. The change of entropy in the actual Rankine cycle is h_1 minus h_4, which cannot be written as T_1 into s_1 minus s_4.

It can be written as a constant temperature into s_1 minus $s_{4.}$ So, this is the definition of mean temperature of heat addition. This is a temperature, constant temperature at which if the same heat is added, gives the same change in the entropy. Now, we have to prove that T_m is less than $T_{1.}$ We understand from our physical concept that the mean temperature or heat addition will be something lower than one, something more than four. It has to be in between this. T, mean temperature with that addition cannot be something which is higher than the maximum temperature of heat addition or lower than the minimum temperature of heat rejection, a boy of class two can take. Therefore, it will be in between, somewhere in between. So, this is also proved from this expression. Tm has to be less than T, because this h_1 minus h_4 is the heat added. What is this heat addition? This is the diagram and this is the area; that is why Ts diagram is so much important; that means, this is the area that means this area one let this is a, this is b that means one a b four.

So, this is the area under the curve one four is under the s axis and represents geometrically the heat transfer. If I define a mean temperature Tm; if this is Tm, then this will give the same heat transfer with the same change in entropy. I have to construct another rectangle which will give the area of this rectangle will be same as the area of this curve. The area one a, b, four, four dash will be same as area, if I do it here one dash a, b and here c dash. For example, c dash that means this, which means that this ordinate will be lower than this ordinate, because it will give T_m into s_1 minus $s_{4,}$ which is this area which will be equal to the h_1 minus $h_{4;}$ actual heat transfer that means the h_1 minus h_4 that means the area under this curve, the area one, a, b, c dash. Therefore, this way, we define the mean temperature of heat addition which is the ratio of this enthalpy changes divided by the entropy changes.

In any heat transfer process, therefore, the conclusion is that if the temperature is varying, we can define a mean temperature of heat addition which becomes equal to the ratio of the enthalpy changes by entropy changes. If at a constant temperature, the same heat could have been added, it could have given the same entropy change. So, if that way we compare these two, Tm is less than T_1. Therefore, definitely Carnot cycle is having higher efficiency than the Rankine cycle. Why the designers in thermodynamics do not design the power plant, steam power plant on the basis of Rankine at Carnot cycles. But not on the basis of Rankine cycle.

Why a steam power plant is not designed on the basis of Carnot cycles? Now, if we have the Carnot cycle, if we work with this rectangle also 1,2,3 dash,4 dash as another Carnot cycle, then they will give the same expression of the efficiency 1 minus T_2 by T_1. So, any of these two Carnot cycles which will be giving the same efficiencies within the same pressure limits, that we can have two rectangles, we can implement in practice. We should implement in practice from the efficiency point of view, but it cannot be implemented in practice. If we see that 1,2,3,4 dash this thing, then we will see from geometry.

The constant pressure lines are very closely spaced which cannot be seen in the same scale in any cyclic diagram, whenever I draw the constant pressure line on the liquid phase and also in the gas phase in the same diagram. We will always consider that this scale is changed, in the same scale it cannot be shown or if we have to show with some slide spacing in this diagram, these two pressures even with a small difference cannot be shown in an ordinary page. Therefore, if we draw this isentropic line geometrically, it will cut a constant pressure line which will indicate some 10 to the power 10. The pressure ratio with this, is an enormous infinite pressure.

Now, I give you the physical example, so this temperature let 300 degree Celsius. Steam is supplied at some pressure at 300 degree Celsius at dry saturated state. Now, therefore, here let it be expanded to a vacuum pressure in the condenser. So, the temperature corresponding is 40 degree Celsius, usually it is done in practice like that.

This pressure is very low; 0.2, 0.1 atmospheric pressure so that the temperature is 40 degree Celsius. Saturation temperature is 40 degree Celsius. Therefore, here we are ending with 40 degree Celsius temperature. So, we will have to isentropically compress or any way we have to compress. It may not be isentropic; that I will come afterwards. There are certain deviations in practice from the ideal cycle.

Some compression device you will have to maintain, or ideally isentropic compression we have to conceive, which will raise its temperature from 40 degree Celsius to 300 degree Celsius. So, we can imagine that we have to compress air in such a way that its temperature will be raised by 30 to 40 degree Celsius, not by heating just by compressing. It being an in compressible fluid, so we will require some 10 to the power 20 atmospheric pressure or 10 to the power 30 the pressure, we will have to increase, compress to infinite pressure, to reach that three 300 degree Celsius temperature so that water reaches at 300 degree Celsius temperature. So, now we continuously heat it at that infinite pressure so that it will be heated; that is not possible. Therefore this is discarded, what is happening?

We do not have to compress. We stop here and here pressure is corresponding to 40 degree Celsius and it is a vapor, it is not liquid. Simply compress it from this pressure for example, this is 0.4 atmospheric pressure and compresses it to some 5 atmospheric pressure or 10 atmospheric pressure that is not difficult and we just compress a vapor. So why not do this one, this is difficult to end up to this point. If we cannot end up this particular point which will ultimately end up to this state, will not achieve a Carnot cycles. For example, here if we do it, we will achieve another Rankine cycle. So, in both the cases, we see the two rectangles cannot be achieved in practice so that therefore in spite of the fact that Carnot cycle will be giving the higher efficiency, if we compare with the maximum temperature, it cannot be incorporated because of this difficulty.

Next is the actual loss in these processes so that I will explain these things. How this ideal cycle diagrams that is the Rankine cycle changes little bit in practice to represent the actual cycle in a steam power plant?

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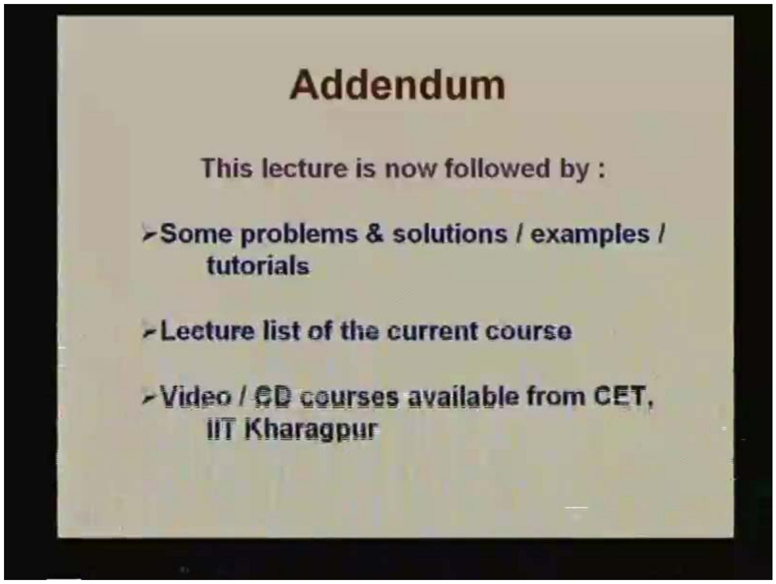

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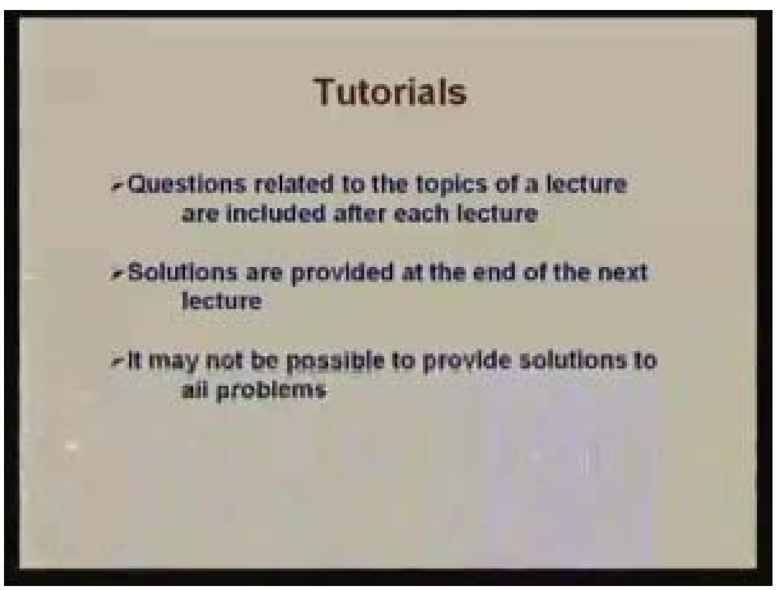

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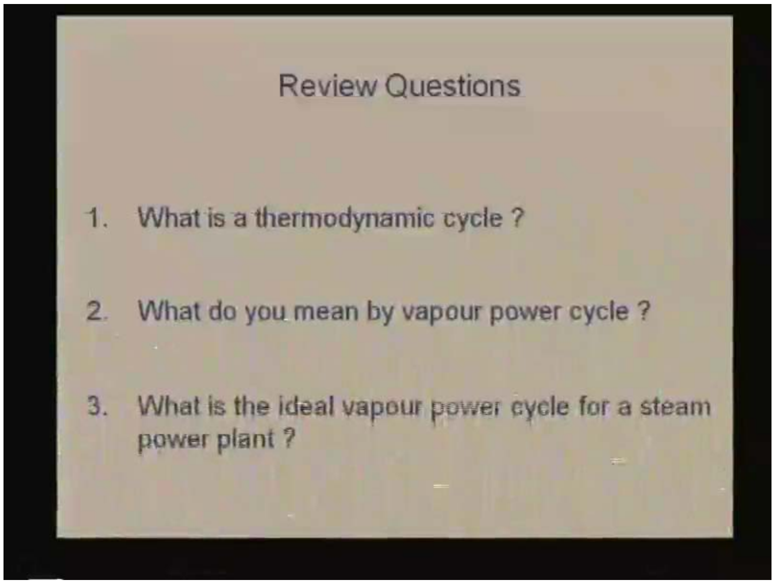

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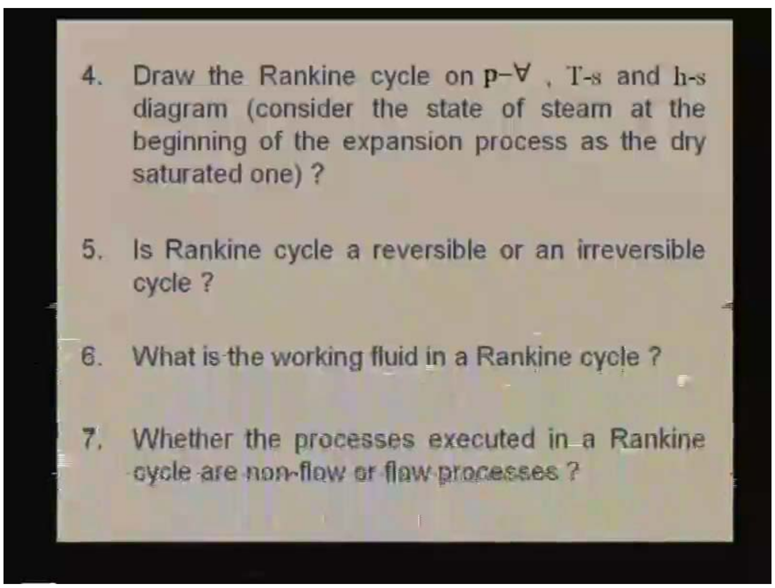

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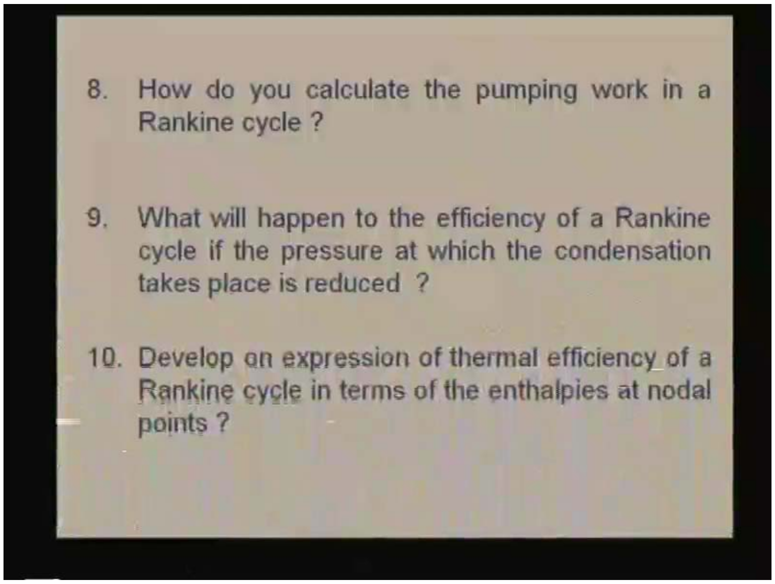

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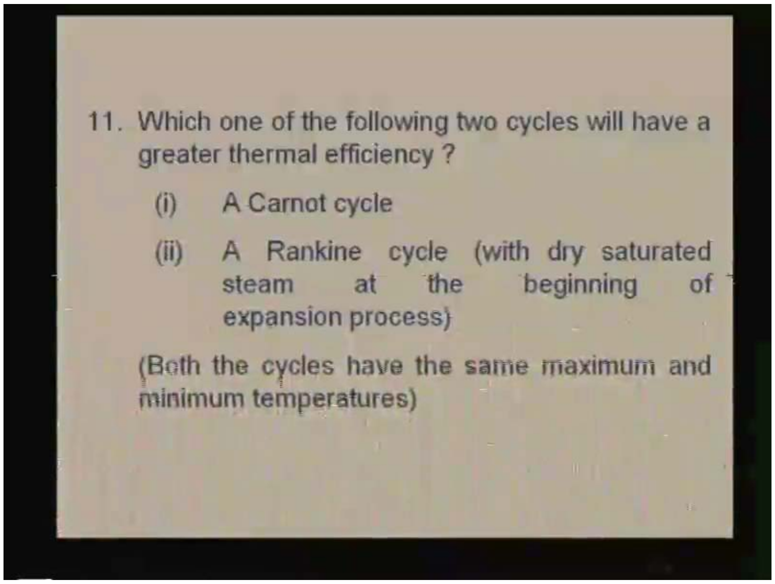

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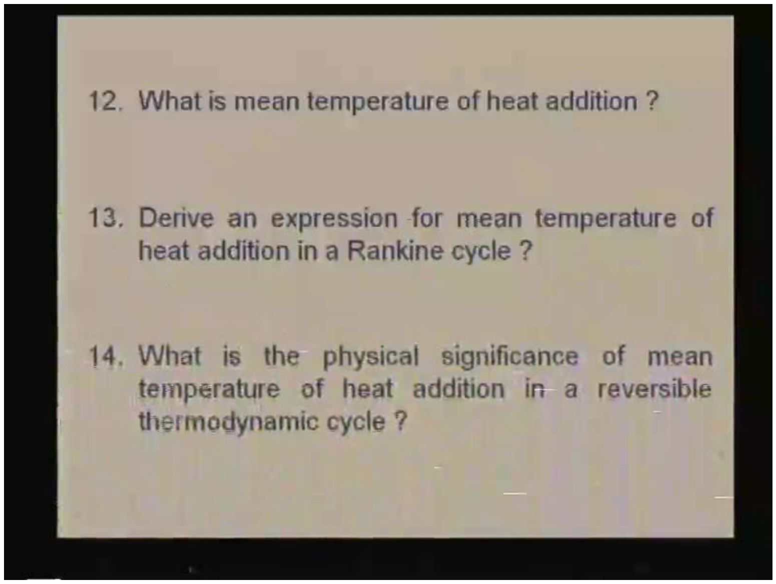

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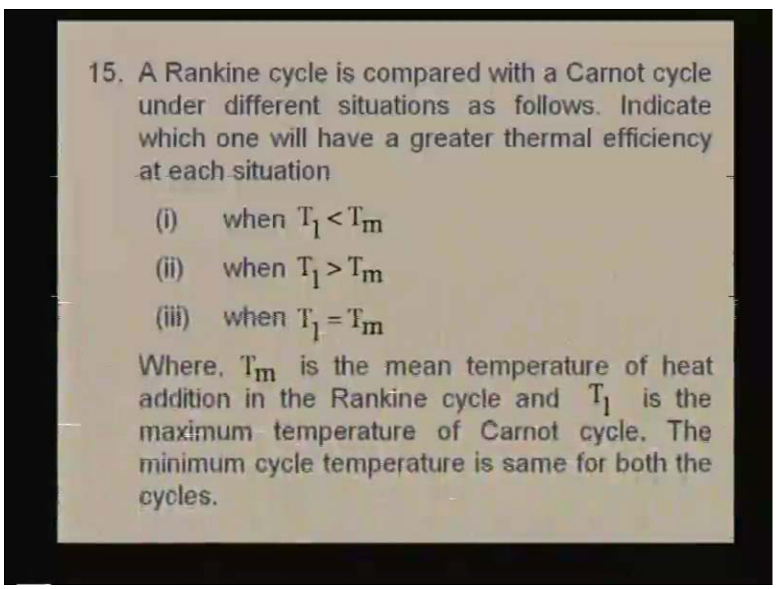

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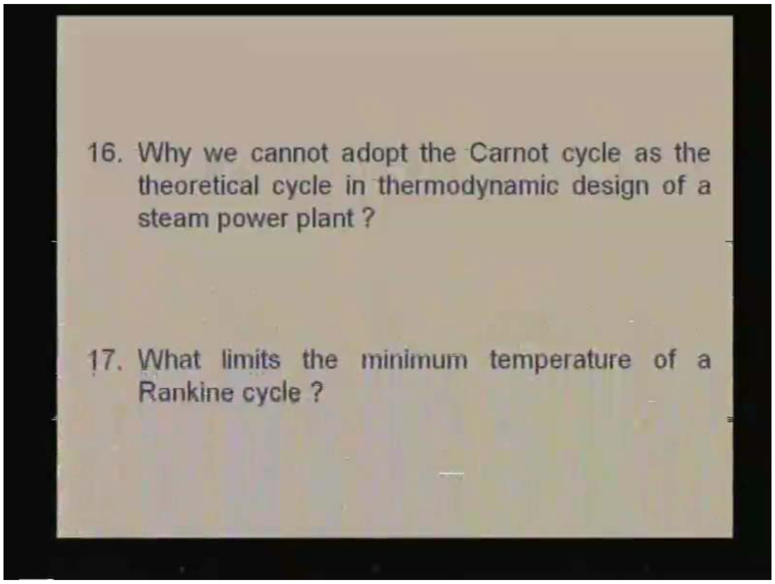

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