Thermal Engineering: Basic and Applied
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Lecture – 09
Steam Power Plant: Thermodynamic Aspects, Efficiency, Work Ratio and Ideal Cycle

I welcome you all to the session of Thermal Engineering and today we shall discuss about the ideal cycle of steam power plant. But before going to discuss about this particular cycle, I would like to discuss about a few thermodynamic aspects and also the performance measuring parameters essentially for the steam power plant. If we try to recall in the last two lectures we have discussed about the basic components, rather the major components of steam power plant.

We have seen the block diagram and by applying the combined first and second law to the processes of steam power plant, we could establish the amount of heat rather the amount of energy must be added to the system in the form of heat and also the amount of energy which will be obtained from the power plant in the form of net work. And we have seen that the second law together with the first law applied to reversible steady state steady flow processes, whether the process is adiabatic or process is isothermal, the expression of work done for both these processes is $-\int vdp$.

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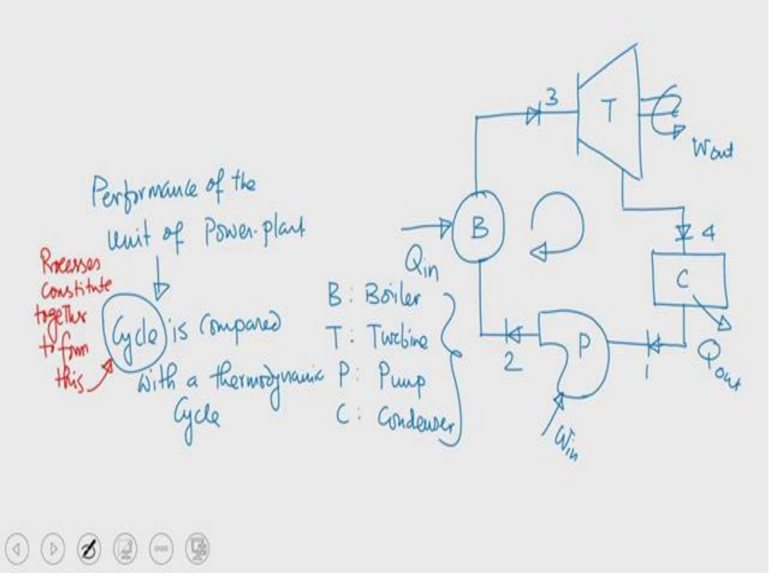

So, in continuation of that today let us again draw the block diagram of the thermal steam power plant. So, this is what we have seen in the last class. Now, you can see that this B stands for boiler, T for turbine, P for pump and C for condenser. So, what we can see from this particular block diagram that is the steam power plant? Though we can see only four major components, there will be several other minor components. But two important points I would like to mention today that if you would like to know the performance of the plant itself, we need to analyse all the processes I mean the pumping process, boiling of liquid, expansion of steam inside the turbine, and finally, condensation of steam in the condenser. So, to obtain the performance of the plant, we need to analyse all the processes.

And if we need to do that, we need to map all these processes in thermodynamic ordinate diagram. So that is we have seen. Also we can see that this unit of this power plant operates in a cyclic manner that you can easily see from the symbol in block diagram. This is a restriction posed by the second law of thermodynamics that if you would like to run this unit in a cyclic manner, essentially to have continuous work output, we must supply heat continuously to the system which is most important is that there must be a provision of rejection of heat from the system. So, this is very important.

Now, what I said that we would like to analyse the performance of this plant. We can analyse the performance of this plant or system by mapping all the processes in thermodynamic coordinate diagram. Importantly, whenever we will try to map all these processes in coordinate diagram, we need to compare this with a cycle because our unit of this plant is running in a cyclic manner. So, to obtain the performance, we need to compare the processes which constitute together to form the cycle by comparing with a thermodynamic cycle.

Performance of the unit of power plant

So, if you would like to obtain it, we have identified all the processes, all these processes constitute together to form this cycle and as if the system is running in a cyclic manner, and finally, we need to compare the cycle of this unit with a thermodynamic cycle. Now, what is the need of studying the thermodynamic cycle? You have studied this in the basic thermodynamic course that the purpose of studying the thermodynamic cycle is to either produce power or to produce refrigeration.

So, here the symbol represents that all the processes are getting executed in a cyclic manner, the working substance undergoes through several processes following this cycle and that cycle needs to be compared with a thermodynamic cycle essentially to obtain the performance of this plant. Because you know that in power plant our first and foremost objective should be to measure the performance, why? Because at the cost of this input energy you are getting some energy output. So, all this heat which is supplied to the boiler will not be converted equally to the work which is getting produced here. And perhaps it is because of this reason that this heat is referred to as the low grade energy and work is referred to as the high grade energy. So, try to understand, maybe a certain fraction of the input energy will be there in the form of work from the turbine. So, hence the efficiency is very, very important. So, by knowing the efficiency we can take several measures to improve the operational aspect of this plant to enhance the efficiency.

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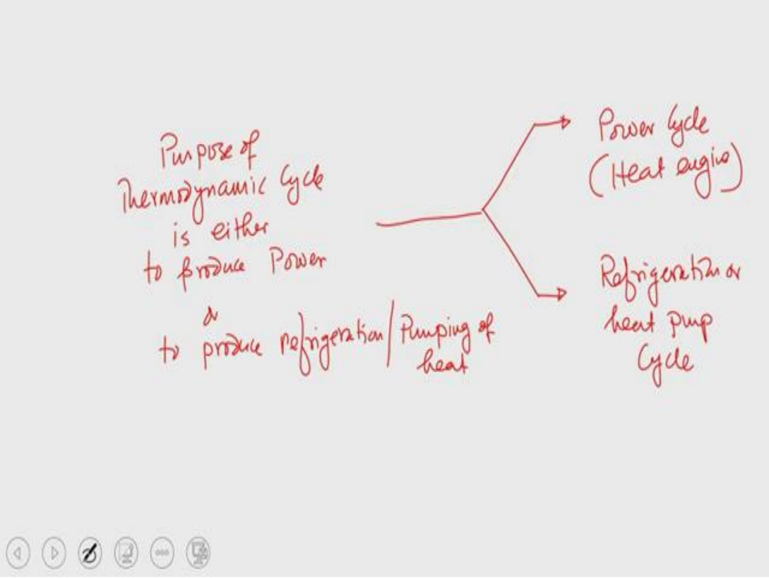

So, purpose of thermodynamic cycle is either to produce power or to produce refrigeration or pumping of it. If the objective is to produce power then the cycles are known as power cycles. If the objective is to produce refrigeration or pumping of it then it is known as refrigeration cycle or the heat pump cycle. So basically, you know that from there we can understand that thermodynamic cycle can be broadly classified into two categories. One is the power cycle another is refrigeration cycle or the heat pump cycle. I am just trying to recapitulate whatever you have learned from basic thermodynamic course, essentially to have a consistency in understanding whatever we are going to discuss today.

So, you know that power cycle is commonly known as heat engine. Since in this particular module of this course, we are going to discuss about the steam power cycle, so, you can understand we shall focus our attention on this power cycle. If we go to the previous slide, as we have written over here that the cycle should be compared with a thermodynamic cycle and that is thermodynamic cycle should be the power cycle that we can understand from this.

So, basically, the power cycles should be operated using a particular type of working substance. So, you can see that the working substance for this particular cycle is water and steam. So, whether it is power cycle or refrigeration or heat pump cycle, the working substance is important.

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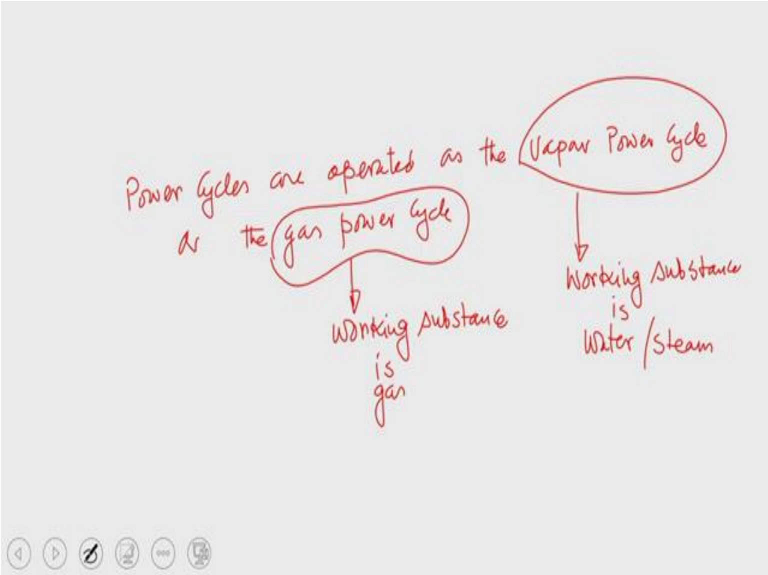

So, power cycles are operated as the vapour power cycle or the gas power cycle. This classification or sub classification is based on the type of the working substance that is used. So, whether the power cycle will be vapour power cycle or the power cycle will be gas power cycle, this sub classification depends on the type of the working fluid that is used.

For the vapour power cycle, the working substance is water and steam. Since the working substance is water and steam & as the name steam is there, sometimes this vapour power cycles are known as steam power cycles. So, I may use this terminology that is steam power cycle or vapour power cycle. So basically, the working substance is steam, so, we also can call it steam power cycle.

On the other hand, though, gas power cycle is not included in this particular syllabus but maybe in one of the module, I will briefly touch upon this particular aspect. But therein I will be discussing in detail but for the sake of completeness. Here in this particular cycle, working substance is gas. If it is air also so, specifically, you have studied air standard or air power cycle. So, our objective today would be to learn about steam power cycle.

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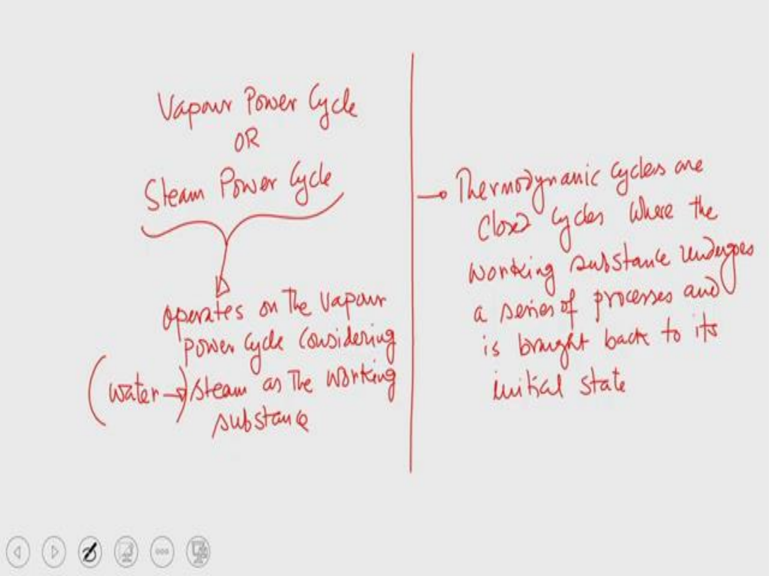

Steam power cycle or vapour power cycle

This steam power cycle or vapour power cycle basically, these two are the same. But this steam power cycle operates on the vapour power cycle considering steam as the working substance. Previously I have written about the thermodynamic cycle to produce power. Since power cycle is the thermodynamic cycle, we have to understand what do you mean by thermodynamic cycle? So you know that vapour power cycle is also a thermodynamic cycle. Since the working substance is steam we are calling it steam power cycle which operates on the vapour power cycle, considering steam as the working substance.

So, what do you mean by thermodynamic cycle? You know thermodynamic cycles are basically closed cycle. That means the working substance undergoes a series of processes and is brought back to the initial state.

Here the steam is converted from water only and that is why we also can call it water steam mixture. Now, thermodynamic cycles are closed cycle. This is also steam power cycle which operates from the vapour power cycle considering working substance is steam. So, here working substance is steam water or water or steam.

So, you know that in one part of the cycle working substance is remaining as water & in other part of the cycle the same working substance is getting converted into steam. But I would like to mention here that water is getting converted into steam but the composition is not getting changed. So basically, when I am talking about this thermodynamic cycles which are closed cycle, where the working substance undergoes a series of processes and is brought back to its initial state.

So, here try to understand if we start from say section 1, the state of the working substance is saturated liquid. This saturated liquid is pumped to the boiler and from the boiler to the turbine till condenser, the working substance state is vapour, steam. So basically, the working substance undergoes through several processes like pumping process, boiling and then expansion, finally condensation. So that all these processes are executed using either water or steam, but eventually at the end of the cycle again, we are getting water. So, it is a thermodynamic cycle, & it is closed cycle.

And most important point I would like to mention here that the composition of the working substance does not change at the end of the cycle. So, maybe we are starting from point 1 considering or taking the working substance as the saturated liquid, at the end of the cycle, again, we are going to get water only. And during the cycle, the composition of the walking substance is not getting changed, so, this is very important.

Now, so, the vapour power cycle or steam power cycle being a thermodynamic cycle, it is also a closed cycle.

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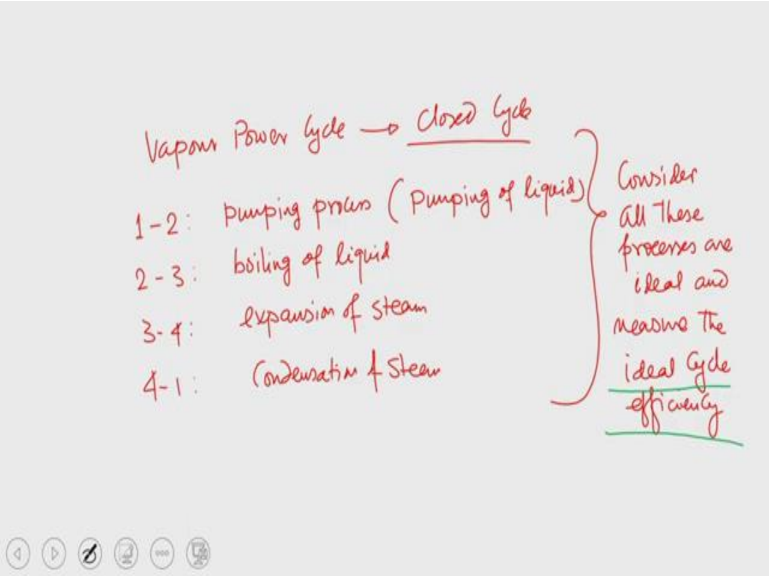

So, now I would like to discuss about one important point. Coming to the objective, if you try to recall that we need to discuss about ideal cycle so, why do we need to study this particular cycle? Because we need to measure the performance of the steam plant which is operating on this vapour power cycle. So, if we go back to the previous slide here we can list down several processes. What are the processes?

1-2 is a pumping process (pumping of liquid)
2-3 is the boiling
3 -4 is the reversible adiabatic expansion of steam inside the turbine and
4-1 is condensation.

So, pumping that is reversible adiabatic steady state steady flow process. Boiling is a constant pressure heat addition, expansion of steam is reversible adiabatic expansion. And finally, condensation of steam is again constant pressure heat reduction. So, I am not going to describe their thermodynamic name, but for the time being you can understand pumping, boiling expansion and finally, condensation. So, these are the mechanical names. Pumping process is reversible adiabatic steady state, steady flow process. All the processes are considered to be steady state steady flow only for the analysis purpose. Boiling of liquid is constant pressure, heat addition inside the boiler. Expansion of steam that is again reversible adiabatic expansion. And finally, condensation of steam is constant pressure heat rejection.

So, when we are trying to have the performance of the plant unit, we consider all the processes are ideal. So, considering all the processes ought to be ideal processes, we measure the ideal cycle efficiency. So, these are the mechanical names, considering all these processes are ideal and measuring the performance of the individual processes, we calculate the performance of the cycle which is constituted by all these processes. So, the efficiency that we will get following this exercise is the ideal cycle efficiency.

But you have studied this in thermodynamics. See why I am recalling that you have studied this in thermodynamics because this subject is applied thermal engineering, Thermal engineering basic and applied. So basically, the basic understanding of thermodynamics will be very much helpful to understand whenever we are trying to apply those concept in applied field.

So again, if I go back to the schematic depiction that will help us to understand that to some extent irreversibility will be there. Whether the liquid is pumped from 1- 2 and when the liquid is heated inside the boiler and it is converted into steam at state point 3 and when the steam is allowed to expand inside the turbine following reversible adiabatic process or even if we consider here that the steam which is taken to condenser for the release of heat to the ambience, all these processes are not ideal in reality. So, in real practice, we consider some degree of irreversibility is associated with all these processes.

So, knowing that some degree of reversibility will be there, we just cannot trivially ignore that the actual process should be different than the ideal process. Though we can consider all the processes are ideal but accounting for this particular issue that some degree of irreversibility will be there in all processes, all the processes will not be the ideal processes rather, I can tell you no process in reality is an ideal process.

So, what we need to do? Instead of considering the concept of ideal process, we must consider that all these processes are not ideal because irreversibility is there. So we need to consider actual process. So basically, the efficiency that we are calculating, considering all the processes are to be ideal, it is the ideal cycle efficiency. But at the same time, we need to consider that all the processes are not ideal rather they are actual. So, we need to introduce the concept of process efficiency.

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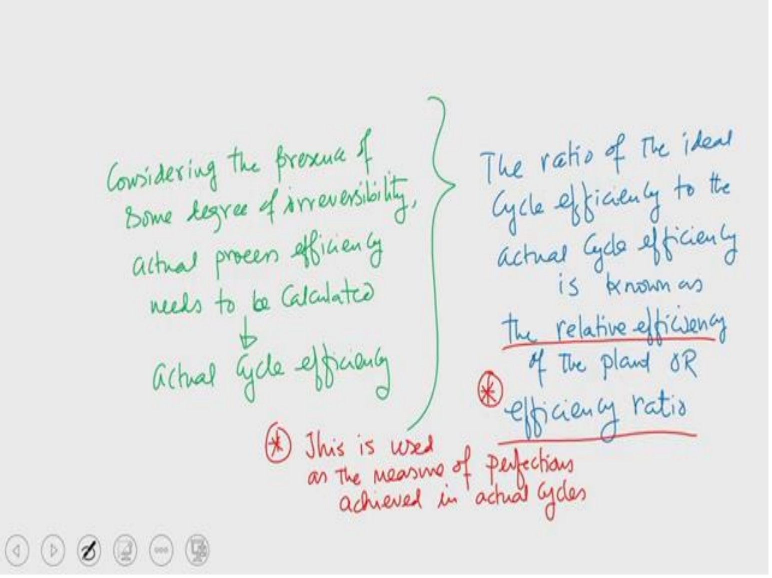

So considering the presence of some degree of irreversibility, actual process efficiency needs to be calculated. So, knowing fully that some degree of irreversibility is present in all these processes, what we can do, we can introduce the process efficiency, individual process efficiency that is actual process efficiency and if we integrate them for all these mechanical processes that we have listed down so, irreversibility is there in the pumping process, some degree of irreversibility there in the boiling of liquid process, some degree of irreversibility is there while steam is getting expanded in the turbine, some degree of irreversibility is there when steam is getting condensed inside the condenser.

So, considering all these irreversibility, what we need to do? We need to calculate individual process efficiency and then, if we integrate them, we can get actual cycle efficiency. So, there are four different processes we have so, far understood. So, calculating the actual process, efficiency for all these four processes, we can calculate the actual cycle efficiency because all these four processes constitute the cycle.

So basically, we have understood that we can consider all the processes are ideal. So if we need to map the processes in thermodynamic coordinate diagram, we have to consider that all these processes are ideal. And at the same time, we must admit that some degree of irreversibility will be there so, accounting for this particular thermodynamic issue, we need to calculate actual cycle efficiency

So now, the ratio of the ideal cycle efficiency to the actual cycle efficiency is known as the relative efficiency of the plant or efficiency ratio. So, can you tell me, knowing fully that in real practice, all the processes are not ideal, why do we need to study these ideal cycles efficiency? Why do we need to calculate this ideal cycle efficiency and consequently, the efficiency ratio? So, this is very, very important to understand because efficiency ratio is used as the measure of perfections of all real cycles.

Try to understand. Let me give you an example. See you have studied about fluid mechanics, you have studied about thermodynamics, and you have also studied about heat transfer, at least these three important subjects in thermal fluid sciences. So, you know that you have studied about ideal fluid; it is very difficult to obtain a fluid which is ideal but still we need to study the behaviour of the ideal fluid why? Because we know that it is difficult to maintain a process to be ideal process in real practice. Even though we need to study that and studying that we need to calculate the ideal cycle efficiency. And not only that by knowing this we are also introducing this word that is relative efficiency or efficiency ratio. Objective is this particular relative efficiency of the plant or efficiency ratio of the plant is used as the measure of the perfections of the actual cycle which are, there in the real applications.

So, this efficiency ratio is used as the measure of perfections achieved in actual cycles. So basically, this cycle efficiency is the ideal one but in reality will be getting actual one. Our objective should be to go for improvement of the actual cycle to achieve the ideal one. So our objective should be not to reach at efficiency is equal to 1 as that is not possible at all, but closer to 1. So that is why we study this.

So, we have understood that though it is very difficult to achieve a cycle to be ideal cycle in practice but still we need to study it, why? Only to measure the perfections that will be achieved in real cycle.

You know that among the ideal cycles, the Carnot cycle is considered first that you have started in thermodynamics. I am not going to discuss about all those part but among the ideal cycles, Carnot cycle is considered first and subsequently all actual cycles are considered. So, accordingly, the ideal vapour cycle that is what we are going to discuss today, should be the Carnot vapour cycle.

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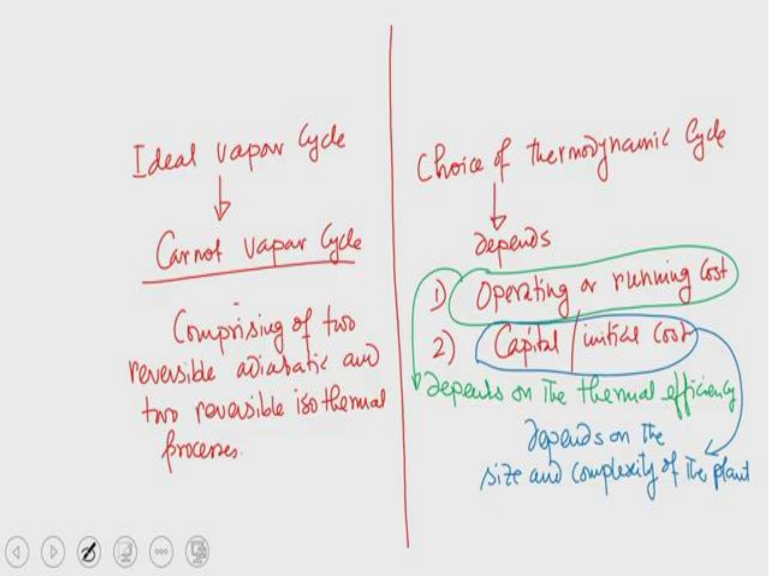

Ideal vapour cycle → Carnot vapour cycle

So, this Carnot vapour cycle that you have studied in thermodynamics, is comprising of two isothermal and two adiabatic processes. We shall be discussing those part. But before I go to discuss, I would like to discuss about a few important thermodynamic aspects like, what do you mean by work ratio? What do you mean by back work ratio etcetera?

So, this Carnot vapour cycle which comprising of two reversible adiabatic and two isothermal processes. We shall be discussing this particular cycle, but as I have mentioned just now that we shall be discussing a few thermodynamic aspects before we go to discuss about this. What are those? You know that till now we have introduced about this ideal cycle actual cycle. But it is not possible to have any cycle to be ideal cycle. So, we need to consider the actual cycle. So which cycle should be considered to represent the processes which are there in a power plant? I mean the processes which are there in a power plant should be mapped following a thermodynamic cycles, so which cycles should be considered?

So, the choice of any particular thermodynamic cycle depends on two important quantities. One is the operating or the running cost of the cycle or plant and number two is the capital cost or sometime it is known as initial cost. So, whether any particular cycle should be considered or selected that largely based on the consideration of the operating or running cost and the capital cost.

Operating on running cost depends on the thermal efficiency of the plant, while the capital cost or initial cost depends on the size as well as complexity of the plant. So, I am discussing this because again the name of the course is thermal engineering basic and applied, so these points you should know.

So, any particular thermodynamic cycle that should be considered to compare the processes of a real power plant will be selected based on these two important points. One is operating and running cost other is capital cost. So next, I am coming to discuss about two important performance measuring parameters, thermodynamic aspects.

So, if we can represent all the processes in the thermodynamic planes or ordinate diagram and then also we can compare them with any thermodynamic cycle. But eventually what we need to do next? Basically, you need to measure the performance. So, when you are trying to measure the performance, which particular index will be used to compare that? Let me repeat it.

So, we know that efficiency ratio or relative efficiency = 1 is very good, for the maximum work output, maximum performance or the best performance of the plant. But it is very much unlikely that the efficiency ratio will be 1 but our target should be to get closer to 1. Now, when we come to know that the performance of this particular cycle because the cycle should be the actual cycle. So, when we are trying to compare different actual cycles, we need to define the performance measuring parameter which should be used to compare the performance of different actual cycles.

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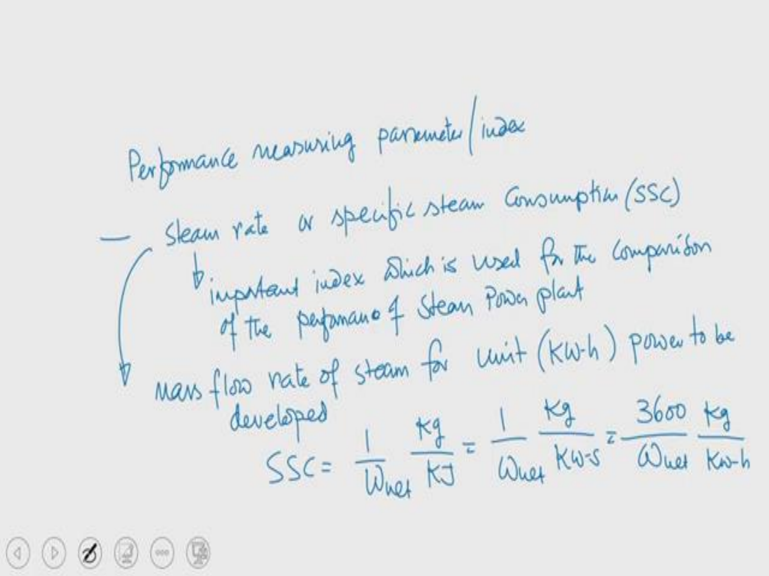

Performance measuring parameter or index

One such parameter is known as steam rate or specific steam consumption that is SSC-specific steam consumption. What is that? So, steam rate or specific steam consumption is one of the one important index which is used for the comparison of the performance of the steam power plant. So, this is an important index.

What is that? So basically, steam rate or specific steam consumption is defined as the mass flow rate of steam required for unit kilowatt power to be developed.

$$SSC = \frac{1}{W_{net}} \frac{kg}{kJ} = \frac{1}{W_{net}} \frac{kg}{kW.s} = \frac{3600}{W_{net}} \frac{kg}{kW.h}$$

So, now I have introduced another term that is W_{net}. It is the net work we are getting from the power plant. So the specific steam consumption is nothing but the mass flow rate of steam per kg for unit power to be developed. So, if you would like to develop 1 kilowatt hour power, the requirement of the mass flow rate of steam for that is this specific steam consumption rate.

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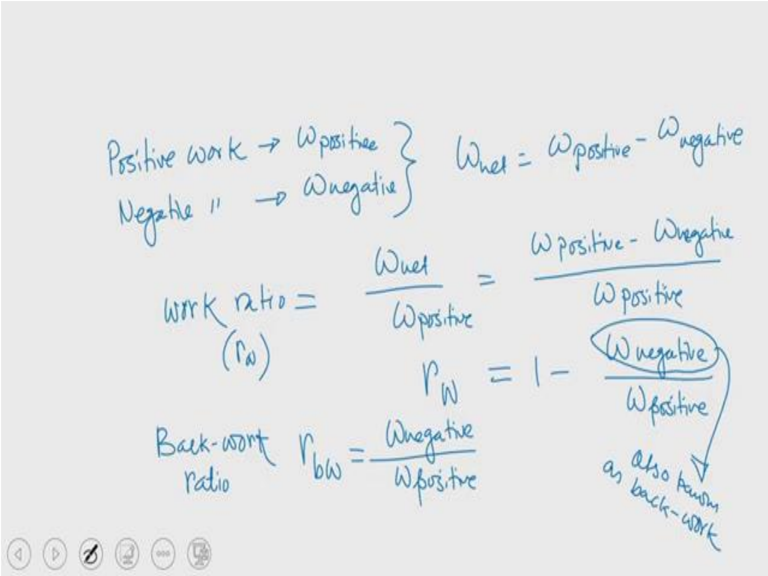

I will come to this particular point again but before that since we can see that this SSC is related with this W_{net}, so what do you mean by W_{net}? For that let me define a few things like positive work that is $W_{positive}$ and negative work that is $W_{negative}$.

$$\text{Net Work}, W_{net} = W_{positive} - W_{negative}$$

So, what is $W_{negative}$? If we go to the first slide, wherein we have drawn the schematic depiction of the plant, you know that we are getting this amount of work from this plant but a small or a certain fraction of this work should be supplied to pump for it is operation.

So, we are supplying heat, at the cost of this input energy, we are getting some amount of energy in the form of work but a certain fraction of this output work or output energy must be supplied in the form of work to the pump for it is operation. So, if you try to look, as if this W_{in} to the pump appears to be the negative work, while W_{out} that is the work is coming out from the turbine is the positive work. So basically, W_{out} is the positive work that we are getting out from the system, while W_{in} is the negative work that we are supplying to the system. So, eventually the net work should be

$$W_{net} = W_{out} - W_{in}$$

Because certain fraction of this work should be supplied to the pump. Now, the ratio of this net work to positive work is known as work ratio.

$$\text{Net Work}, W_{net} = W_{positive} - W_{negative}$$

$$\Rightarrow W_{net} = W_{Turbine} - W_{Pump}$$

$$\text{Now Work Ratio}, r_w = \frac{W_{net}}{W_{positive}} = \frac{W_{positive} - W_{negative}}{W_{positive}}$$

$$\Rightarrow r_w = 1 - \frac{W_{negative}}{W_{positive}}$$

What we can see that our object should be to get high work ratio. Because we are getting positive work from the turbine, but this is not the net work. So, net work we are getting is W_{net}. So, our objective should be to increase W_{net}, so, the work ratio should be high.

What we can say from the mathematical expression is that if you would like to get higher $r_{w,}$ then the negative work should be less. So, the negative work that is work supplied to the pump should be less. If negative work is high then r_w will be less and efficiency of the plant will be less. So, this is very important that if negative work that means the work required to be supplied for the operation of the pump is a significant fraction of the positive work, then r_w will be less and thermal efficiency of the plant will be less. And here you know that negative work is also referred as back work.

$$\text{Back Work ratio}, r_{bw} = \frac{W_{negative}}{W_{positive}}$$

I will be discussing again another important critical point from this particular definition. But if you would like to discuss that we need low back work ratio, high work ratio. So, low back work ratio means $W_{negative}$ should not be very high. If $W_{negative}$ is not very high, back work ratio will be less while if $W_{negative}$ is less then r_w that is work ratio will be high. So that is the proper combination for the higher thermal efficiency or performance of the power plant.

So, if you like to summarize today's discussion, starting from the block diagram of the power plant, we have discussed about several thermodynamic issues. Then we have discussed about the need of studying ideal power cycle. And then we have discussed that among the ideal cycles, the Carnot cycle is the first one. So, the ideal vapour cycle should be the Carnot vapour cycle. We have discussed that the Carnot cycle comprised of two processes, reversible isothermal and reversible adiabatic processes. We shall be discussing the analysis of this Carnot cycle in the next class but before that we have discussed about a few issues related to the performance of the power plant. I mean when we are trying to compare the performance of different actual cycle, what should be the basis of the comparison rather, what would be the performance measuring parameters? To this end, we have discussed about one important index that is specific steam consumption and then specific steam consumption also related to W_{net} that is the net work. Also, we have discussed about the, what we mean by net work and from there we have defined the work ratio and back work ratio.

With this I stop here today and in the next class we shall discuss about the analysis of the ideal power cycle. Thank you.