**MARINE ENGINEERING**

**By**

**Prof. Abdus Samad**

**IIT Madras**

**Lecture51**

## Gas turbine: Regeneration, Reheat, Intercooling

Good morning everybody. We started already gas turbine systems. Gas turbine we have discussed and we learned that there are different components in gas turbine. One is your compressor, then compressor will be connected to your turbine and compressor and turbine in between there will be one combustion chamber or combustor. So, this one we have seen.

compressor, turbine, this one combustion chamber or combustor. So, this way your gas turbine system will be working. Now, we will try to discuss about regenerator. What is regenerator? Regenerator means you are using exhaust heat to improve system performance.

how does it work? Let us first draw a line diagram, compressor connected to one turbine. So, then compressor will have inlet air 1, from inlet air it will go to one heat exchanger then another then it will go to turbine and this is power output W turbine this is turbine and from turbine the exhaust gas will come and it will be exchanging heat here, then it will go to here and like this.

So, this one I will be making one block, this one another block. 1 to 2 it will go, 2 to 3 it will go, 3 to 4 it will go, 4 to 5 it will go, 5 to 6 it will go, 6 to 1. Now, this one is regenerator. I will explain later. first you draw the figure, heat rejection is happening Q2 here and heat input is happening here.

this is Q1. Now, you draw this one in TS diagram. TS diagram, TS. TS diagram, it will be looking like this. First, you have to draw this pressure line, constant pressure 1 to 2, you can see your compressor is working at 1 to 2 in between, then it will be going to 0.3, then 4, you can see 4 is before turbine, so 4 to 5, 4 to 5, your expansion is happening, we are assuming isentropic expansion.

now 5 to 6, what is happening? 5 to 6 heat exchange is happening. So some heat will be lost or it will be given to your compressed air. So you can see this 2 to 3 and 5 to 6, it is having one regenerator. What is happening?

the exhaust gas from turbine whatever gas coming after turbine so the gas will be used to heat your inlet air inlet air means after compression the air is going to combustion chamber so that air will be heated up so waste it the turbine exhaust is having lots of energy it's very high temperature actually 400 500 degrees still temperature will be there So that temperature or the heat will be used to increase your compressed air temperature after compression the air is compressed so that air temperature will be further increased and it will be injected into your combustion chamber so why does this increase if you increase your combustion chamber will be requiring less amount of heat to give to air now or the Mass fuel plus air mixture okay so that is why you are using certain amount of heat from the exhaust gas to increase your compressed air temperature okay so now the process is happening one to two is your compression two to three is your regenerator or regenerator is giving a certain amount of the exhaust gas is giving a certain amount of heat to your compressed gas so but processes i say isobaric process two to four you can see this is isobaric process so process happening two to three temperature increased and three to four what is happening three to four actually your heat addition happening so instead of giving heat two to four you are giving heat three to four so actually you save certain amount of heat or energy now four to five Your expansion process happening W turbine and 2 to 3 actually W compressor and 5 to 6 you can see 5 to 6 actually the heat given to your compressed air.

So, that compressed air means 2 to 3 is the process you can see in the figure, 2 to 3 taking heat and 5 to 6 giving heat.  5 to 6 also constant pressure process, 5 to 1 actually, 5 to 1 constant pressure process and in between 5 to 6 process happening. So, there your heat rejection happening. So, that heat is going to 2 to 3 process. I am drawing one arrow symbol you can see 5 to 6 the process that the amount of heat is going to 2 to 3.

Now, 6 to 1, what is happening? 6 to 1, heat rejection happening. normally the combustion mixture will go to atmosphere. So, to make this closed cycle, 6 to 1 is drawn as a continuous line. So, this is called regeneration.

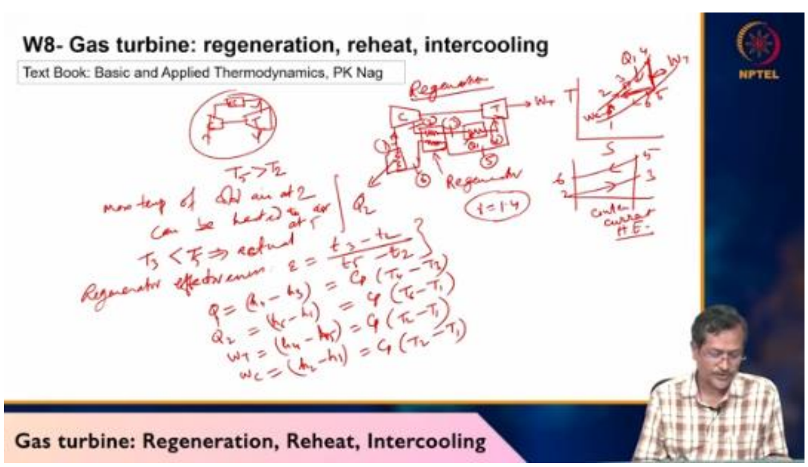
So, regeneration. Now, T5. temperature at 5 must be greater than T2. So, why T5 must be greater than 2? If T5 is not greater than 2, then heat will not be flowing to your compressed air.

From exhaust gas, heat must be flowing to compressed air. exhaust gas temperature must be higher than that. Now, maximum temperature of cold air, max temperature of cold air. air at 2 can be heated in temperature of air at 5, can be heated to air at 5, similar to air, I mean same temperature you can reach actually if it is ideal condition, but practically it is not possible. So, the actual case is T3 less than T5.

actual case. T3 will be less than T5 because when 5 to 6, 5 temperature higher, 6 temperature lower, this is and 2 to 3, 2 temperature lower, 3 temperature higher. So, 5 means here 6, 2, 3, you can see this counter current heat exchanger actually, we are assuming counter current heat exchanger. You can see this 6 to, 5 to 6 fluid is releasing heat and 2 to 3 it is accepting heat. Now, regenerative effectiveness,

generator effectiveness equals T3 minus T2, T5 minus T2, this formula you should remember. Now, heat given to the system Q1 equals H4 minus H3 equals Cp T4 minus T3, Q1, Q2 h6 minus h1 you can see this heat rejection h6 minus h1 equals cp again constant pressure process so t6 minus t1 now turbine work wt equals h4 minus h5 okay so again cp t2 minus t1 okay approximately you can assume constant Cp. for approximation purpose, normally we assume Cp and Cp are constant and normally the gas gamma value will be 1.4.

If no value is given, gamma value of Cp, Cp, so you can assume gamma value 1.1, 1.4. So, W compressor, how much power you are giving to compressor? H2 minus H1, again Cp T2 minus T1. now eta equals 1 minus Q2 by Q1 because 1 minus T6 minus T1, T4 minus T3. So, from there you can calculate your efficiency, your power output, your heat input, and your heat rejection.



Now, we have seen area heating and intercooling happen between two compressors. Let us say compressor 1 and compressor 2, C1, C2, in between there will be intercooling. C1, I will write properly C1. okay so you can see this c1 c2 c1 compressing certain amount of air then when it is compressing because of charles law you can see you can remember the charles law says like if you are compressing temperature will be going up so after c1 temperature will be going up so if you reduce temperature then again volume will be dropping because you reduced heat then again you put low volume air into c then C will be compressing further.

So, that C compressed air, C2 compressed air, that will be going to your combustion chamber. Then you will have one turbine or one turbine or main turbines. And those turbines will be connected to the compressors. Now, what happens, is the intercooler, in between these two compressors, the cooling is happening, this is called intercooler. during our pumps and compressor section also we have discussed intercooler intercooler means you are reducing temperature so that your compressor performance increases or efficiency of performance increases so input work will be lower if you are using intercooler okay so here in actual system in gastronomy system normally we use actual compressor maybe actual and sometimes centrifugal compressor also may be there but no normally first stage will be actual compressor definitely

then you reduce volume, then you can use centrifugal compressor. Turbine, normally will be an axial turbine. Now, how this whole system will be working? So, we can assume there is your condenser here. Now, I want to draw this one on the TS diagram.

TS diagram again when you are drawing TS diagram you have to draw pressure line first then you have to put number 1 and then after compressor 1 you are giving 2 after intercooler you are giving 3 then after compressor 2 you are giving 4 then combustion chamber after 5 after turbine you are giving 6 6 then your heat rejection So, Q2 here, Q1 here and turbine work Wt minus Wc equals W net, net work output you are getting W turbine minus W compressor. Now, in TS diagram 3 to 4, you can see 3 to 4, first 1 to 2 compression will be happening 1, 2, 2 compression happened, then after 2 intercooling happening, intercooling happening means pressure you are not changing rather you are changing temperature. what will happen?

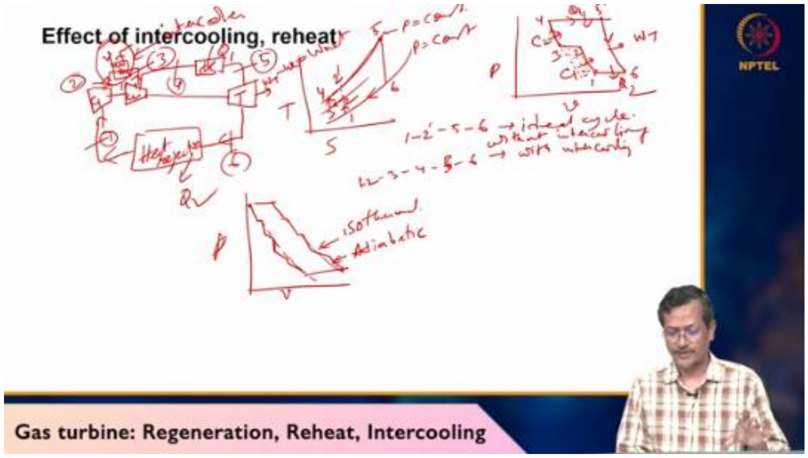
Your process will be downwards towards T, then 3, 2, 4 again compression happening, so temperature going up. So, 2, 2, 3, 3, 2, 4 happened, Now, 4 to 5, 4 to 5 means you are adding heat. So, 4 to 5 means the whole process is like this, then 5 you reached. 5 to 6, your isentropic turbine expansion.

So, 6 to 1, again your heat rejection process or constant pressure process. So, this line P equals constant, this is also P equals constant.  now if i draw this on a pv diagram so it will be like this six to one six to one is a constant pressure process but it is near to atmospheric pressure right so six to one so one two two what is happening compression happening so one two two compression happening then two to three two to three actually your pressure not changing rather heat rejection happening so volume will be reduced so volume reduced now three to four three to four again your compression happening so compression adiabatic compression so it will be like curved so one two three to four four to five what is happening you see four to five actually constant pressure process because inside combustion happening but pressure four to five will be same so four to five year compression process okay now five to six turbine expansion so it will be adiabatic process so it will be curved line actually okay so turbine expansion process w turbine and compression happening here one time your compression happening another one time corporation like c1 c2 we can say

four to five your heat addition process so here i can write q1 and six to one heat rejection process so i can write q2 okay so because of intercooling you can see certain amount of energy is saved actually this dotted line i'm making this lots of dot i'm putting there this part actually energy saved because you reduce temperature okay so one two dash uh i can put here one two dash in TS diagram I put 1, 2 dash, 1, 2 dash, 5, 6 ideal cycle without intercooling, without intercooling, but 1, 2, 3, 4, 6, 1, 2, 3, 4, 5, 6, 4, 5, 6, so that will be with intercooling. So, when we are going to with, without intercooling, we are having more, we are using more energy to get certain amount of power. Now, what is the purpose of intercooling?

If I draw, if I have let us say multiple stages of compressor, compressor 1, compressor 2, compressor 3, compressor 4, many compressors are there.  if we have many compressors actually we will be trying to achieve our isothermal condition. If we have isothermal system that will be having the best efficiency, the whole system. P, V and let us say this one my system actually this is isothermal dotted line this is adiabatic okay so if certain process is adiabatic in our system so that system will be taking more energy so performance will lower but if i can achieve isothermal system then my system will performance will be better

actually intercooling will try to match towards isothermal condition. but in practical situation, we cannot make many compressor 1, C1, C2, C3, C4 like this. So, maybe 2, 3 stages we can limit and we can get some optimal performance. But if we can make let us say 100, 200 stages like C1, C2, C3, C100, then actually we will be achieving almost isothermal condition. So, reheat with intercooler how to look like?




I have one compressor, I have another compressor, connected, connected, turbine, turbine. Now, compressor 1 is having input here 1, 2, 2 to 3 you have intercooler, then 3 to 4 you have combustion chamber, Q1 coming, 3 to 4, 4 to 5 is your heat addition process, 5 to 6 again reheating process happening. it will take heat again it will go to turbine two turbine two c one c two t two then going like this then going coming here then coming out five to six six to seven seven two heat rejection heat rejection it is going to again 1, 7 to 1.

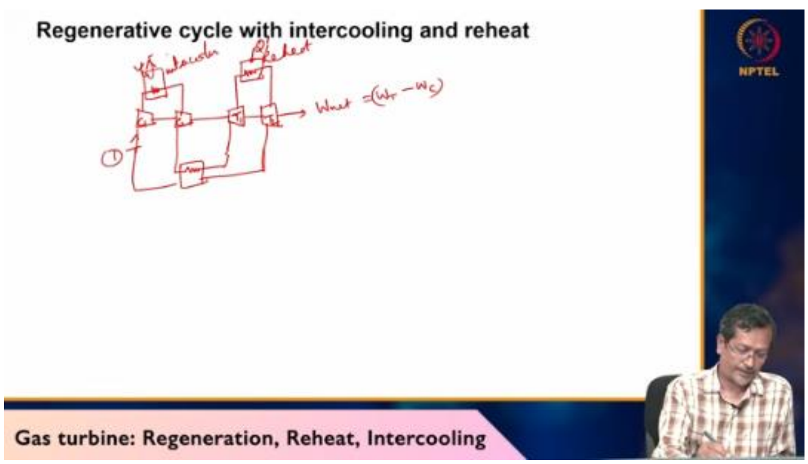
Now, if I draw this one in TS diagram, first I have to draw the pressure lines. So, 1 is here, 1 to 2 compression happened, so vertical line because we are assuming ideal cycle, isentropic cycle. ah then two two two three three two to three what is happening uh heat rejection happening so that's why temperature going down three to four compression happening four to five heat addition happening four to five heat addition happened five to six turbine took certain amount of power five to six will be here not here six seven it will be eight okay five to six will be turbine will be giving some power then six to seven actually again temperature increasing but constant pressure then again your expansion happening seven eight okay not this one, this will be opposite way, this one, this one, this one.

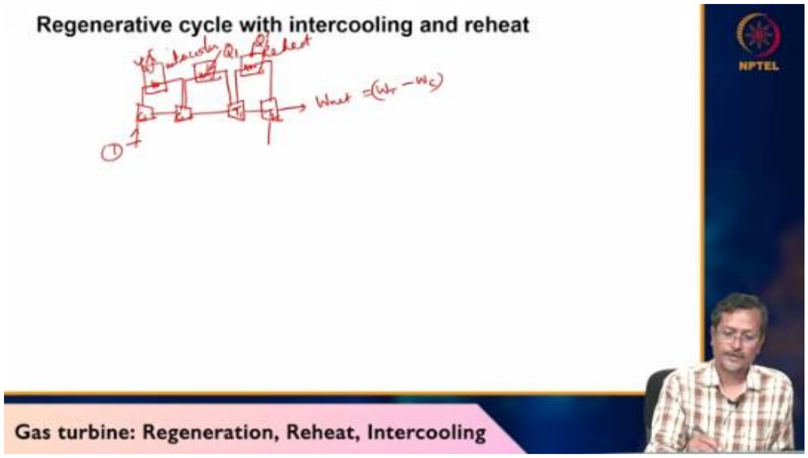
Now, you can see 1, 2, 2 compression happening. So, this is C1 process, 3 to 4 C2 process, 4 to 5 heat addition process, 5, 8 to 1 your heat rejection process, 6 to 7 reheat cycle, reheat and 2 to 3 your intercooler. So, intercooler and reheat cycle in one figure in TS diagram you can see there. Now, if we consider one regenerative cycle with reheat and intercooler, how it will look like?

Again, you draw compressor 1, compressor 2, it will be connected to turbine, expansion. Now, C1, C2, T1, T2, W net equals to W turbine minus W compressor. Now, C1 getting air 1, C1 to C2 there will be intercooler. So, I will be drawing one box here, one coming like this, going like this. So, this is intercooler.

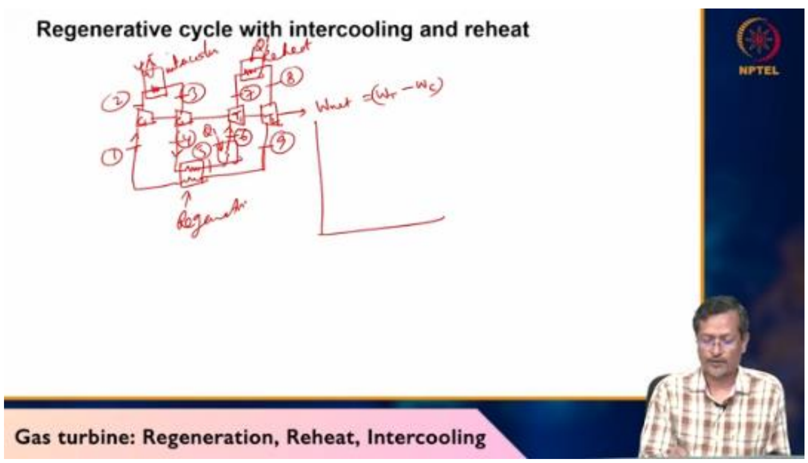
Now, C2 to T1 there will be one heat addition process, the combustion chamber or combustor So, combustor to turbine 1, turbine 1 to turbine 2, there will be reheat process. I can make another reheat process, reheat. So, reheat may be Q1 dash. Now, Q1 dash to T2 it is going.

So, T2 i'll change something here this line i'll draw opposite way a little bit more clear then okay so t2 to coming here from here to one okay Now, it will be clearer, 1 to 2, it is going compressing, 2 to 3, 1 intercooling happening, 3 to 4, your compression again happening, 4 to 5, what is happening here, regenerator. So, the regenerator is giving heat to your compressed air.  so after compression your heat addition will be happening so q1 you are giving heat here so then four to five five to six see five to six actually your combustor six to seven your turbine one expansion process seven to eight your reheat process eight to nine your again expansion process nine





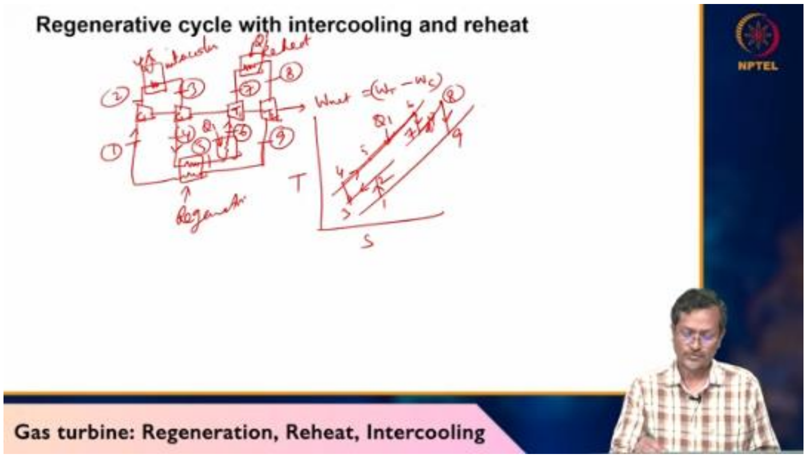

to 1, the regenerator is happening. Now, the whole thing I want to put in TS diagram. How does it look like? First you draw main pressure line. So, 1 to 2 compression happening, 1 to 2, 2 to 3 some heat rejection happen, 3 to 4 again compression happen, 4 to 5 what is happening?




4 to 5 some heat addition happened okay so four to five heat addition happened then five to six your combustion chamber worked then six to seven expansion worked okay seven seven to eight again reheating happening okay seven to eight reheating happening then eight to nine again expansion happening okay now you see the process So, 1 to 2, compression happened. 2 to 3, intercooling or heat rejection happened. 3 to 4, again compression happened.

4 to 5, your compressed air got certain amount of heat from your exhaust gas. 5 to 6, your combustion chamber is working. 6 to 7, turbine worked. 7 to 8, your reheat worked. So, this is Q1 dash, some heat you have given.

8 to 9, your turbine to work. So, this is T1, this is T2, this is C2, this is C1. This way you can draw your TS diagram. regenerative effectiveness, regenerative effectiveness equals actual temperature rise, temperature rise divided by maximum possible rise.




T5 minus T4 divided by T9 minus T4.