Engineering Thermodynamics

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Week-09
Lecture-42
Gas Power Cycle

Welcome to the last lecture of the gas power cycle section 4. In this we will talk about Brayton cycle, which is a gas turbine related cycle. And you must have seen this especially in the engine or in big electric power plants. The process is very simple. It is Fresh air is initially taken which is gradually compressed. When it is compressed to a certain extent, then the fuel comes into it. Then it is compressed. When it is compressed, then at high temperature pressure, then the fuel, the mixture of air and fuel, goes into the turbine. because it is done at high pressure so this turbine is working this turbine through this shaft generates an electric work ok and rest when low pressure of course works rest of the fluid is done at low pressure it is done with exhaust gas so this cycle if you see it, it is open cycle because it will continuously input air flow and fuel intake and it will be removed by exhaust we will call it as your fresh air has been released from compressor on one and in one combustion chamber your fuel plus compressed air has been mixed here is the combustion and after that it has been released on high temperature pressure on turbine and from turbine it is filled with exhaust and the rest of the turbine generates a network. The network is taken in this because the compressor also has a W in. So, this has a W in and this W will be out here. So, W out minus Win will be your network. This is an open cycle. You can approximate this open cycle in closed cycle by idealization. Like we did in auto cycle and other cycles. We will do this in a closed cycle. And the easiest way is to replace the combustion process with constant pressure heat addition process. So, combustion is a kind of heat exchanger. Here, the heat is coming, and the compressed gas is more here. So, like this, the compressed gas is more in this heat exchanger, and it comes out at high temperature here. And the exhaust process, we will replace it with constant pressure at heat rejection. So, this is your exhaust, which you saw is exhaust. We are replacing this and replacing this. We are writing both things in this form. This is how your flow is continuous. This is not a fresh air flow. This system is a concept model which is an approximation of a gas turbine cycle. So, of course, this was developed in 1870. This was developed by George Brayton in 1870. And if you look at the big engines, General Electric for example, is a very big engine maker. So, you will find many examples of these engines, its principles and the conditions in which they bring in the gases and the intake. So, you can see. But here, particularly what we are talking about here is about thermodynamics and energy analysis. And later we will understand its inefficiency through the use of... It makes a difference on your doubloons for example.

So, let's move ahead. As we said, we will use four processes. Which will be an ideal Brayton cycle. Which will be a closed loop. What we did in this is that the combustion part, which is the process, we call it constant pressure heat addition. And the exhaust part, we have made it a constant pressure heat rejection. And the rest of the process is the compressor and turbine one.

We have already used this one. And all this will become isentropic. Meaning it is in constant isolation. It means that it is isentropic. You are in isolation, so it is isentropic. It will be adiabatic. Both things. Meaning your compressor. and your turbine so 1 and 2 are your part as isentropic and this part is isentropic. So, this is your compression, and this is isentropic expansion. So, what happens in the tub is that the fluid expands, and this is expansion. Take a compression. and this is your constant pressure heat addition, and this is the constant pressure heat rejection So we have written this here. 1, 2 isentropic compression, 2, 3 constant pressure heat addition, 3, 4 isentropic expansion, 4, 1 constant pressure heat rejection. And if you draw this in the PV diagram, you will get this. 1, 2 isentropic, 2, 3 constant pressure heat addition, 3, 4 Isentropic expansion of 41 constant pressure heat rejection You can also give it in the TS diagram 1 2 3 4 This is the difference 1 2 is your constant 3 4 is constant entropy 2 3 is constant pressure heat addition 4 1 is Constant pressure heat rejection If you notice, we started with the auto cycle, then the diesel cycle, then the diesel cycle, then the ideal Britain cycle. So, the auto cycle, ideal air cycle, ideal diesel cycle, ideal Britain cycle. If we talk about the pressure volume, So, notice how we did it. The heat addition was constant in the motorcycle. In all three cases, you will have to do expansion compression for the cycle. So, this is 1, 2, 3, 4. So, This was the constant volume. This was the auto cycle. Then comes the diesel engine. Both the combustion engine is in the engine. Talking about the cycle, we changed the combustion engine to constant pressure. So, this is 1, 2, 3, 4. And here, this is the diesel. And now in Brayton, this is 4, 1, here is 2. And here is 3 and here is 4. So, 4, 1 will also be at constant pressure. Here, in diesel, it was at constant volume. Heat rejection. Here you can see that the heat rejection is constant. It is pressure. So, this is the basic difference according to the PV diagram. Brayton cycle. So, both heat addition and rejection are at constant pressure. The rest of the compression and expansion is in the isentropic process. Now, let's do the thermodynamic analysis of this Brayton cycle. Assume that these processes are steady flow devices. And this is a steady flow process. Assume that the potential of the changes in the kinetic energy is negligible. Now if we are balancing the energy of any steady flow process, then we can write it as, that Q in plus Q out, and if we look at the unit plus W in and W out This will be your H exit which is the enthalpy changes in the exit and inlet which is the enthalpy changes There is no such thing in this, if you take any device, like this device, if you put it in steady flow, then naturally E in minus E out will come in your delta E system. If you re-enjoy this, you can also find this expression. You can find the expression Qin plus Win plus Hin, minus Qout plus the term of exit, you can find this expression. We are only interested in the expression Qin and Qout. Qin is between 3 and 2. So Q in will be H3 minus H2 and we will assume that this is the standard assumption so this is Cp T3 minus T2 Similarly, Q out is between 4 and 1 so this is H4 minus H1 this is also Cp T4 minus T1 Now if we talk about eta, then eta thermal if we do Brayton cycle then this Wnet will be divided by qin which is 1 minus qout by qin and here you can write 1 minus cp T4 minus T1 and here comes cpT3 minus T2 you can rearrange this also 1 minus t1 t4 by t1 minus 1 T2 by T3 by T2 minus 1.

$$\eta_{th,brayton} = \frac{W_{net}}{Q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$$

$$= 1 - \frac{T_1((\frac{T_4}{T_1}) - 1)}{T_2((\frac{T_3}{T_2}) - 1)}$$

$$\eta_{th,brayton} = 1 - \frac{1}{r_p^{\left(k-\frac{1}{k}\right)}} \; where \; r_p = \frac{P_2}{P_1}$$

Now, these processes are 1, 2, 3, 4 isentropic. The pressure is the same. So, in isentropic conditions, we can use air or idle gas in cold conditions. Or, in general, the expression we have taken is the same. The ratio of temperature T2 by T1. We can write it as P2 by P1. K minus 1 by K. or P3 by P4 because both are same this is k-1 by k this is T3 by T4 so this relation can be obtained so if you do this then all these expressions that you have taken out and plug in this expression and if you do this then you will get this expression eta Brayton 1minus 1 by rp K-1 by K in which Rp is P2 by P1 this is called pressure ratio So, note that if you look at the PV term, then this is your PV. 1, 2, 3, 4, and this is your P2, and this is your P1. Here is your heat addition and here is your heat addition and here is your heat addition. So P2 is the higher pressure, so P2 by P1 is the ratio, we call it pressure ratio. So, this is the pressure ratio. If you take out the plot of eta, then the eta plot depends on two things. Of course, it will depend on the rp and this range is typically between 5 to 20. So, P2 is around 20, 20 times P1 will remain. It goes to the maximum. And the second thing depends on this that K. It depends on K. thermal efficiency increases when R or K increases. You will notice that there are two major applications of this. First, it is used in propulsion of aircraft, this is a gas turbine engine. And second, it is used in electric power generation. So, these are the two main uses. Now let's talk about the back work ratio. The back work ratio is the total work of the turbine. Some of this work will be used to work on the compressor. So, this ratio is called back work. That is, how much work is used for the compressor. And this ratio is very high for back gas turbine. Almost 1 third of your turbine work output is used to drive the compressor. If the efficiency of your turbine or compressor is less, then you have to use it more. If you see the same thing in the steam power plant, then the back work ratio is very low because liquid is used there. and this work is proportional to your specific volume that's why your ratio is less because it is not compressed that much whereas compression is the highest in the gas now if you have more back work ratio then turbine is also higher so the more back work ratio, the bigger the turbine So, notice that the gas turbine power plant has more turbine than the steam power plant. If you consider the same net power output and keep it fixed, then the turbine size will have to be increased in the gas turbine power plant. Because its back work ratio is more. Now let's try to understand this concept through examples. So, this is your gas turbine power plant, which is working on the ideal Brayton cycle. Its pressure ratio is 8 and the gas temperature is 300 Kelvin, which is at the compressor inlet. And 1300 Kelvin is at the turbine inlet. So, let's tell it in the form of drawing. plot will come out like this. If we look at the TS diagram, okay, because the temperature is given, we look at the TS diagram. This is your 1,2, is your isentropic compression. Then comes your constant pressure, which is the inlet or addition of heat. Then you have turbine and then comes your heat rejection. So here your compressor is working, W compressor, W turbine, Q in and Q out. note that this pressure is constant P2 which is P2 by P1 This was 1, 2, this is 3 and this is 4. So, P2 by P1 Because in this condition, pressure P2 will come and P1 will come So, the ratio of this is Rp Now we have to take out the gas temperature at the exit of the compressor and turbine What does this mean? The exit of the compressor is So basically you have to find out T2 and T4. So, these are the questions. You have Let's start with process 1 and 2. So this is your process 1-2 So, what is this? This is isentropic compression. and you have T1 is 300 Kelvin T1 and T3 of inlet turbine is given T3 is also given 1300 Kelvin so now what is here this thing is directly information T1 you can also take from the table Because we have to consider the back-and-forth usage of the table. So, we will try this form without showing the table. And assume that you have seen the previous lectures on how to use the table. So, if T1 is given 300 Kelvin, then we can get H1 from here. Which you can get from the table. This comes out to be 300.19 kJ per kg. And then this also comes out, PR1 also comes out. Last time we talked about relative pressure. So, if you take the ratio of pressure, then the same will come out, the ratio of relative pressure will come out, the same will come out, the ratio of actual pressure. Because this is how your table is made. So, you can directly use the gas table to solve this problem. So, PR1 comes out like this. I have to find two options for T2 Either you find the property which is of air and you see from the table So it can be PR2 And if you know PR2 So I will go to your corresponding table I will check where PR2 lies and what is the corresponding temperature I will say that the temperature is T2 So how will you do it? You know that PR2 by PR1 is given, and this is PR2 by PR1 This means that I can get PR2 Which is 8 times PR1 So from here you get 11.0 Now I see the table What is the corresponding temperature of the air So air temperature is 540 K and enthalpy is 544.35 kJ. Again, we need to buy this table. You will get table A17 according to these tables. Now we will take the process.

Now this is also an isentropic process. This is the expansion of the turbine. We know T3 because T3 is the inlet condition of the turbine. According to the corresponding table, this is S3. So, all PR3 is this. Now we know that pr4 by pr3 is p4 by p3 But p3 by p4 p2 and p3 are constant, p4 and p1 are constant This means that p4 by p3 We can also call it p2 by p1 which is 1 by r Okay, so this means that to get PR4, we will put PR3 multiplied by 1 by r, r1,8, which will give you the value 41.36. And similarly, as we have taken out the rest, from here you will see again in the table, after checking the value in the table, the corresponding temperature will be taken out, 770 K, this is your turbine exit. And its value is 789.37 kJ of enthalpy. So, you have taken out the temperature values that you wanted. Now we have to take out the back work ratio. As I said, this is basically part B. So back work ratio... The fraction of the turbine is R. So, this is the fraction of the turbine work we have to use for the compressor. So, you will get this work. So, to get the work of the compressor, what is this compressor work? It is simple. The compressor is working. H2 minus H1. This is your compressor. H2 minus H1 and this is your enthalpy change. This will come out of the turbine. So, this is H2 minus H1. And this is your H3 minus H4. So, I have already taken out this value. Here we have written S3, S2, H1, H2, H3, H4. So, if we plug in this, then it comes out as 0.403. This means that the work of the turbine is 40.3% Compressor is more for compressor. Compressors are used for 40.3% turbine. This means that only 59.7% is actual work output. Now let's talk about thermal efficiency. What plugin did you use? that you know your Wnet and Wnet divided by Qin this is your 1 minus Qout divided by Qin and in this since you have calculated Wnet total of Wnet this can also be Wnet can also be taken like this Wout minus Wiin which you have done because you have taken out the turbine and then you took out the compressor which means that what you have taken out is W out this is Win so it is already calculated and you will do your Q in which is H3 minus H2 so plug in all the values so this will come out as 0.426 ok This will give you 42.6% heat. This is the thermal efficiency. You can also use the expression 1 by rp k-1 by k Now, what we did in this was not an assumption of cold air, but an air standard assumption but variable, it was not written that variable heat capacity or variable specific heat is to be used But this is an assumption of cold air. Cold air is when you can tie a constant specific heat. So, cold air standard assumption. You are saying that the constant specific heat. If you agree with this, then you can easily take out this eta and 1.4 minus 1 by 1.4 This is 44.8. This means that it is very close. And our assumption is that we can ignore the changes in the specific heat from the temperature. And we can use this for the Britten cycle.

Let's move forward, but if you have the turbine or compressor that you are using, if there is inefficiency or irreversibility in it, then you will not have 100% efficiency, then you will have to

use the isentropic efficiency. In such a case, Temperature vs entropy plot is 1 to 2 So this vertical line is constant entropy i.e. in ideal condition Here 2a will come to the point where you have to work more because its entropy will increase here that's why 2a will come here and the second expansion process this is your compression this is also the expansion process if there is a reversibility in this then 3 to 4 There will be no vertical drop in the entropy plot. So, this entropy cross will not be constant. In this case, your 3-4A will show like this. This is your constant pressure line. and this 4a will come on higher entropy. But normally, pressure drops on such processes. That's why we are showing the dashed line. We will assume that it is a constant pressure point, but it also drops the pressure to some extent. So, we are illustrating it, telling it and showing it in this way. But in this lecture or in general, we will ignore the problems we will solve. So, the compressor of eta will be like this. Ws is isentropic work by Wa and we will approximate it as h2s minus h1 divided by h2a which is actual minus h1 so S means isentropic and in the same way you will call it Wta where Wa will be actual work output divided by Ws because note that we use this ratio in compressors and turbines in reverse because eta is less than 1 and this will come out we are approximating delta H3 minus H4A divided by H3 minus H4S
So, now you can use this to solve the problem we did before let's assume that the compressor's efficiency is not 100% now it is 80% and turbine's efficiency is 85% Now what will happen in the back wall work ratio? Will we have to do more work, more fractions of the turbine? And if we have to do it, then how much will we have to do? I mean, how much actual work will be done by the turbine? And in the same way, what will be the change in thermal efficiency? What will be the change in turbine exit temperature? Let's solve this problem. So, the compressor is given to us as eta. If the value is 80% then it means that the W compressor in is WS by eta C. We did not take out the value of WS here. But we did not take it out. So, this WS compressor in was 244.16 kJ per kg. Similarly, eta was for turbine or compressor, which was 66.60 kJ per kg. So, we use this value in the next problem. Note here that WS is written here. W comp in is equal to WS divided by eta c. Here we will write 244.16 kJ per kg, which we had taken out in the previous problem. which will be simply H2-H1 and this is the eta which is the point H so from here your actual compressor will work which will be more than the ideal condition similarly turbine will be turbine out This will be eta TWS Here will be 0.8 and ideal The work that is done in turbine in isentropic condition is 6 The work that is done in turbine The output that is given is 606.60 kJ per kg Okay So this is 1515.61 kJ Now this means that our actual work in is done with the compressor and the other one is done with the turbine out. So, the back work ratio is the ratio of let's say bug which is called RBW. So, this is WComp in and W turbine out This comes out, use it So this is 305.20 divided by 515.61 This is 0.592 Okay So Earlier we had 40 something Here it is 59.2% Which will have to be used again and 59.2% of the turbine work will have to be used for the compressor. So, efficiency has increased a lot. We reduced it by 20% so that we will have to use our work again. So, overall, our work output has decreased. So, naturally, the thermal efficiency will decrease. We will take it out. How? So, now the question arises that to take out the thermal efficiency, we need the Wnet. Divide by Q in. So, naturally if we look at this expression, the temperature now the compressor is exited at higher temperature. Because 2A is at a higher temperature. Note this. So, some parts will change in enthalpy. So, we can determine this. so, to remove Qin You have to see that Qin will go here. Qin will go from here. So, Qin will be H3 minus H2A. So, Qin will go from here to H3 minus H2A. Now, to remove H2A, The work that we have done, has effectively reached from 1 to 2A in the work. The compressor that we have done. So, we can balance it. The energy balance that we have done will be H2A minus H1. This means that H2A is H1 plus W comp in. So now we know that this is already 305. We have

already taken out H1, H2, Here you will use table fee and you will get 2A which is 598 Kelvin So you will get S2A Similarly you can get Qin is S3 You already know S3 This is given in the previous video because the inlet condition is same At the same temperature which is 1300 Kelvin So you know S3 So, Qin is S3 minus S2A So, we have taken out this first Minus S2A 605.39 So, this comes out as 790.58 KJ per kg So, now we have to take out Wnet is W out Minus W in is the same as the previous one, 500.61 minus 305.4 kJ So this is 210.41 kJ per kg same units 0.266 Means this is 26.6 if you notice what we did before, so in this 42.6 came notice 42.6 Your efficiency is the efficiency of its turbine 26.6 went down so much thermal efficiency dropped Inefficiency so you can understand what is the issue And after this To measure the temperature, you need to use H3 minus H4A, H4A is H3 minus W turbine out which is 515.61 H3 is already known it was 95.97 So it comes out as 880.36 kJ per kg. You will take it out from here. Look at the table. You will take it out from here. T4A which was called 853. So, notice that your temperature is also considerably higher than the compressor which exists. So, this is understood that because the temperature is also very high. Now to bring it back to the compressor, the compressor's exit normally suggests that the temperature exit can also be used in the compressor so that the temperature can increase. So, this concept is called regeneration, which people use in the industry. And what happens in this is that the temperature at which the compressor came out. The input is the air, here it is compressed, the temperature is increased a little. but it is increased by the region essentially, which is coming out of the turbine exit. As we said that the turbine exits of 4, we just saw in the example, that the temperature of the exit of 4 is high. So, we use this only, we use this only, using its heat transfer, heat exchanger. So, from here heat transfer is done and the temperature is increased to 2. So, from 2 to 5. So, we have to reduce the additional energy of combustion. So, this concept is that to increase the temperature of the compressor's gas outlet, we are using the turbine exit and this concept is called regeneration. your thermal efficiency increases in the Britain cycle. So, we use this concept in the regeneration cycle. We will not discuss much about this. If you want, you can learn more about this. You can read about it in your books. There is a lot of literature about it. But we wanted to explain how the concept of sustainability Optimization is very important in this process. Nothing should be wasted. How to use the exergy of the thing at a high temperature. And in this process, the process should be made efficient. So that it can increase its efficiency. So, I hope I have explained to you. You understood this whole concept. How the reciprocating engine works. There are two types of it, one is Spark ignition, one is Compression ignition, and the third one is Gas turbine, which works like a separate power plant or works in your propulsion system, which we call Brayton cycle. So, after that, what else can we complicate in Brayton cycle and to make it efficient, in which inter-cooling, reheating, regeneration, all these concepts come, which you can read separately. I hope you understood it. Now we will pick the next topic in the next lecture. Till then, I bid you farewell.