Steam and Gas Power Systems
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Module No # 07
Lecture No # 32
Gas Turbine Cycle Performance Evaluations

Hello I welcome you all in this course on steam and gas power systems today we will discuss on gas turbine cycle performance evaluation. The performance of any machine is important evaluation is very important for any machine in the gas turbines.

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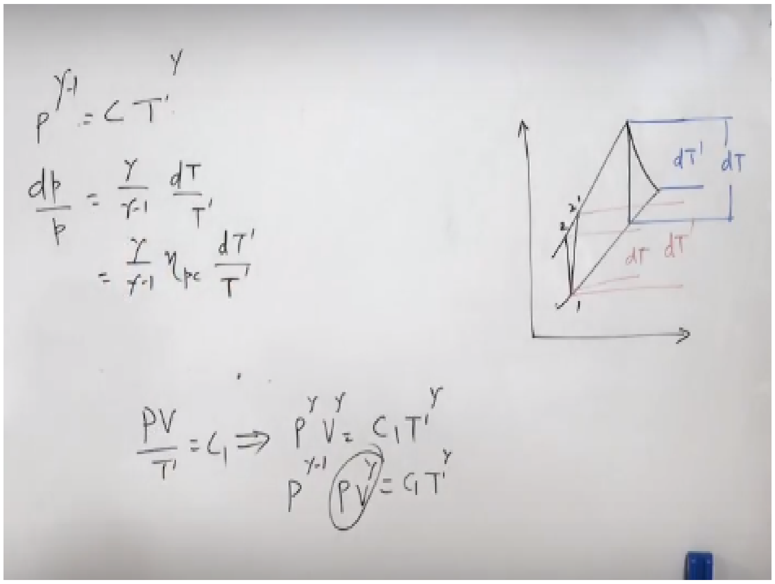

The performance evaluation is done with the help of thermal efficiency isentropic efficiency of compressor isentropic efficiency of turbine right. So in the compressor when the compression takes place from state 1 to state 2 in the gas turbine from state 1 to state 2 it is isentropic temperature in this compression the power consumed it minimum. But in actual practice this point two is shifted to two dash right.

So isentropic efficiency comes into picture so isentropic efficiency of the efficiency of the compressor is T2 - T1 divide by T2 dash - T1. Now suppose I change the compressor ratio suppose for this compressor the compression ratio is four I take another ratio another compressor which is another compression ratio is 6 and then if I compare if the efficiency but it what happens this isentropic efficiency varies big pressure ratio.

So it becomes very difficult to compare the performance of different compressors so in order to cope with this polytrophic efficiency has come into picture. Polytrophic or small stage efficiency now polytrophic or small stage efficiency is for differential rise in pressure what is the actual power consumption? So the pressure is saying but there is a difference raise in pressure or differential raise in temperature or polytrophic efficiency of the compression can be two dash.

DT over DT dash this is DT and this is DT dash right and this ratio is and once we have polytrophic efficiency we can compare the performance for different compression ratio right. Similarly for the turbines again expansion takes place like this so in turbines this is DT dash and this is DT. So in polytrophic efficiency of the turbine this is compressor polytrophic efficiency of the turbine is going to be DT dash by DT reverse of this okay

We know that PV by T dash = constant right and PT power gamma VT power gamma is equal to let us say C1 T dash to power gamma or P raise to power gamma - 1 P V raise to gamma = C1 T1 dash raise to power gamma. This is also constant so we get P raise to power gamma is equal to some constant C T dash raise to power sorry this is gamma - 1 = T raise to power gamma or we can always write DP by P in differential form is equal to gamma over gamma - 1 DT over DT dash.

Now we have taken DT so DT can always be replace by efficiency polytrophic efficiency so gamma over gamma - 1 polytrophic efficiency of compressor DT dash by sorry DT dash T T dash is going to be T dash DT by DT dash, DT dash by DT dash.

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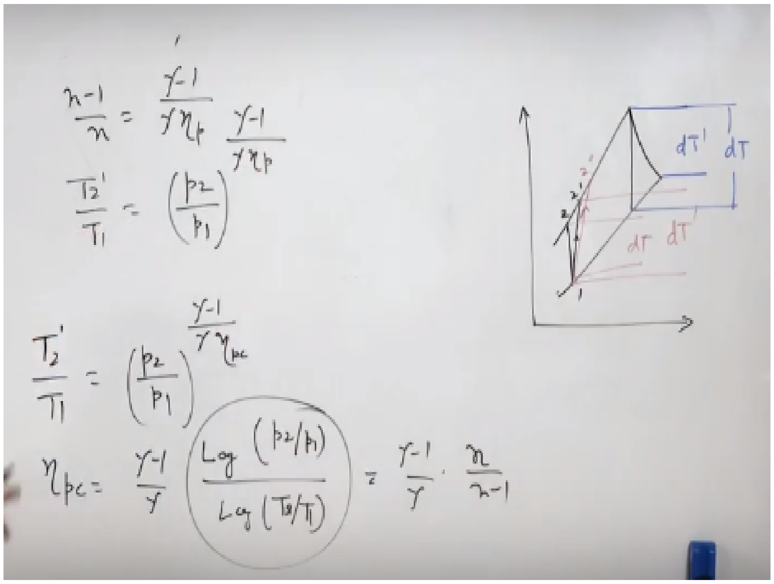

Now again we get if we integrate this right if we integrate this so you will get from 1 to 2 integrate from 1 to 2 now we will go for a fully stage we are taken for a smalls stage now we will integrate this now if we integrate a T2 dash by T1 starting from T1 to T2 dash is going to = P2 by P1 gamma - 1 over gamma.

This is small stage efficiency right or we can say that hmm if you want to take polytrophic efficiency from here it is going to be gamma - 1 over gamma log or natural log let us state log P2 y P1 divided by log T2 by T1 right. And this will give this will give gamma - 1 over gamma into N over N - 1 for this process 2 to 2 dash right and once we get this we can say that N – 1 upon N = gamma - 1 upon gamma polytrophic efficiency of the compressor right.

So now instead of putting say T2 dash will not during this process exponent is not gamma during this process only the exponent is gamma but if we know the polytrophic efficiency we can always use gamma we do not want to use suppose for another compressor for another compressor the compression is like this two double dash right. So here we can have the pressure ratio as T2 dash by T1 = P2 by P1 raise to power gamma - 1 over gamma polytrophic efficiency.

Similarly for the turbine for turbine we can write T suppose this is 3 and 4 and 4 dash right. So 3, 4 dash by T3 is P4 by P3 gamma - 1 over gamma here it will multiplied not to be divided. So that is the benefit of small scale sorry small stage efficiency this efficiency this small stage efficiency is used for comparing the performance for the different compressor.

Now we will try to find optimum pressure ratio for maximum power what should be the optimum pressure ratio for some specific output in a gas turbine right.

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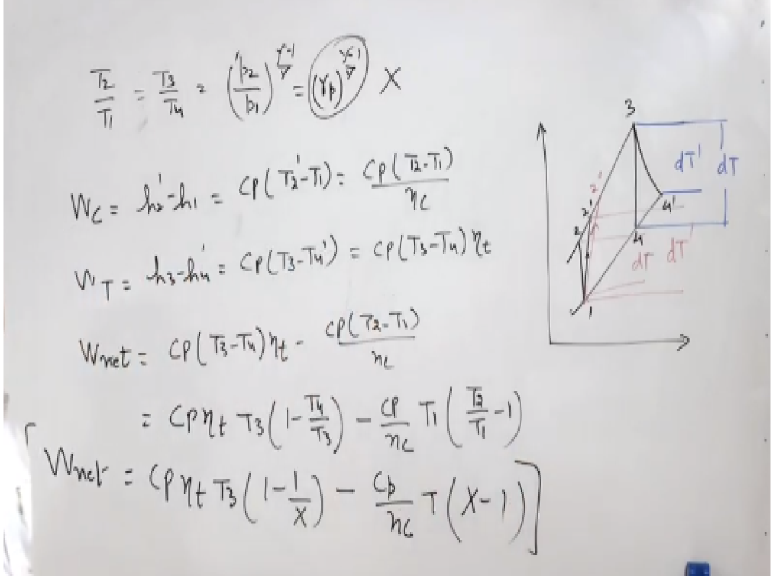

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \boxed{(r_p)^{\frac{\gamma-1}{\gamma}}}\ X$$

$$W_C = h_2' - h_1 = C_p(T_2' - T_1) = \frac{C_p(T_2 - T_1)}{\eta_c}$$

$$W_T = h_3 - h_4' = C_p(T_3 - T_4') = C_p(T_3 - T_4)\eta_t$$

$$W_{net} = C_p(T_3 - T_4)\eta_t - \frac{C_p(T_2 - T_1)}{\eta_c}$$

$$= C_p\eta_t T_3\left(1 - \frac{T_4}{T_3}\right) - \frac{C_p}{\eta_c} T_1\left(\frac{T_2}{T_1} - 1\right)$$

$$\left[W_{net} = C_p\eta_t T_3\left(1 - \frac{1}{X}\right) - \frac{C_p}{\eta_c} T\left(X - 1\right)\right]$$

Now T2 by T1 next one is optimum pressure ratio for specific output so T2 by T1 = T3 by T4 = P2 by P1 raise to power gamma - 1 over gamma it is well known for a adiabatic process 1 to 2 and 3 to 4. Now P2 by P1 is pressure ratio and this is gamma - 1 over gamma fine.

Now work of the compressor = H2 dash - H1 and that = CP T2 dash - T1 or it is = CP T2 - T1 efficiency of the compressor. Work of the turbine = H3 - H4 dash = CP T3 - T4 dash = CP T3 - T4 efficiency of the turbine it will multiply. Network is going to be CP efficiency of the turbine - CP T2 - T1 efficiency of the compressor that is the net worth.

Or we can say it is CP efficiency of the turbine T3 1 - T4 by T3 - CP divide by efficiency of the compressor T1 T2 by T1 - right now this is X this is X suppose this is X. So T4 by T3 is 1 by X so = TP efficiency of the turbine T3 1 - 1 by X right. -CP efficiency of the compressor T1 T2 by T1 it is X right. It is X - 1 this is net now we will differentiate this with respect to X and I will put it zero as usual practice and then will find the value of X.

So when we differentiate this DW by DX it is 0 = CP and T T3 and this is 1 by X square this is X - 1 so 1 by X + X square this is T1 - CP efficiency of the compressor T1 and this is 1 derivative of this is 1. So X = under root efficiency of the compressor or efficiency of the turbine T3 by T1 right. X is pressure ratio raise to power gamma - 1 over gamma.

So X is pressure ratio raise to power gamma - 1 over gamma now from here we can find the optimum pressure ratio and that is going to be equal to efficiency of the compressor efficiency of the turbine T3 by T1 raise to power gamma over 2 gamma - 1. So when a turbine is working between because normally the extreme temperatures are given T1 and T3 are given and we know the polytrophic efficiency of the compressors and the turbine and gamma if working fluid is air right.

Then we can always find the optimum value of pressure ratio for maximum output because if you increase the pressure ratio the compressor work consumed by the compressor will increase at the same time output will also increase or if reduce the pressure ratio the work consumed by the compressor will reduce at the same time output will also reduce. So we have to strike the optimum value between this and this is the optimum value for pressure ratio between the temperature range of T3 and T1 right.

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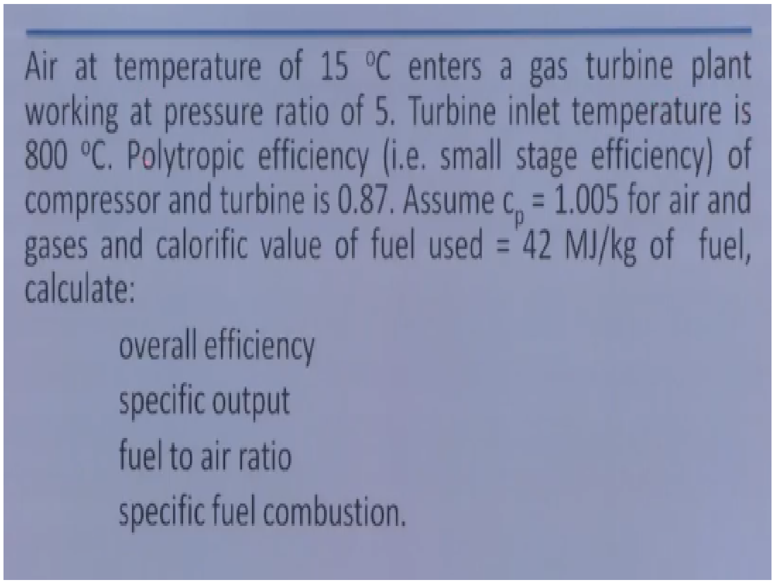

Air at temperature of 15 °C enters a gas turbine plant working at pressure ratio of 5. Turbine inlet temperature is 800 °C. Polytropic efficiency (i.e. small stage efficiency) of compressor and turbine is 0.87. Assume $c_p = 1.005$ for air and gases and calorific value of fuel used = 42 MJ/kg of fuel, calculate:

- overall efficiency
- specific output
- fuel to air ratio
- specific fuel combustion.

Now after this we will solve one example on gas turbine performance and this is about air at temperature 15 degree centigrade enters the gas turbine plant working at pressure ratio 5.

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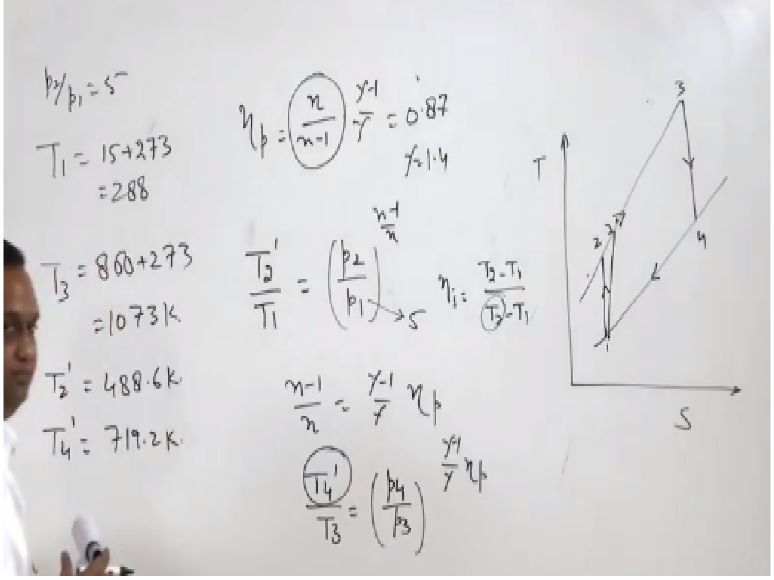

So P2 by P1 is 5 we will note down values here first so P2 by P1 = 5 and P1 is 15 + 273 = 278. Actually it is 273.15 but we normally neglect one five because if we neglect it will have very small barring on negligible barring on the results. So T1 is ok turbine inlet temperature is ok a turbine inlet temperature is 800 degree centigrade so T3.

Let us draw the temperature entropy diagram also four so T3 is are 800 degree centigrade so 800 + 273 = 1073 kelvin and polytrophic efficiencies small stage efficiency we have already derived a derivation on that of compressor and turbine are .87 small stage efficiency assume CP 1.005 for air and gases.

And calorific value of fuel is 42 mega joules per KG of fuel calculate overall efficiency, specific output, fuel of air ratio and specific fuel combustion. So P2 by P1 is given here polytrophic efficiency is N upon N - 1 gamma - 1 upon gamma from here we will get the value of N upon N - 1 because polytrophic efficiency is given 0.87 and gamma = 1.7 for air.

So we will get the polytrophic efficiency once we have the polytrophic efficiency then we can get T2 dash by T1 = P2 by P1 raise to power N - 1 upon N that's it. That is the benefit of having polytrophic efficiency. We do not have to do otherwise stage efficiency than first of all you are calculating T2 and then with the help of this isentropic efficiency we are calculating T2 dash normal process was this is T2 dash that isentropic efficiency is T2 - T1 divided T2 dash - T1.

So first calculate T2 and then from this equation calculate T2 dash then with this smaller stage efficiency we can directly calculate the value of T2 dash. Now T2 by T1 is already five it is given five T1 is already given 288 and this will give the value of T2 dash as 488 point as kelvin right. For expansion process for expansion and minus one upon N = gamma -1 upon gamma polytrophic efficiency for turbines right and for turbines also T4 by dash by T3 = P4 by P3 raise to power gamma - 1 over gamma polytrophic efficiency.

From here P4 by P3 also known to us that is 1 by 5 right from here we will get the value of P4 dash and T4 dash is 719.2 kelvin. Now we have the T3 we do not need P4 so we have T4 dash so we have the value of T1, T2 dash, T3 and T4 dash right.

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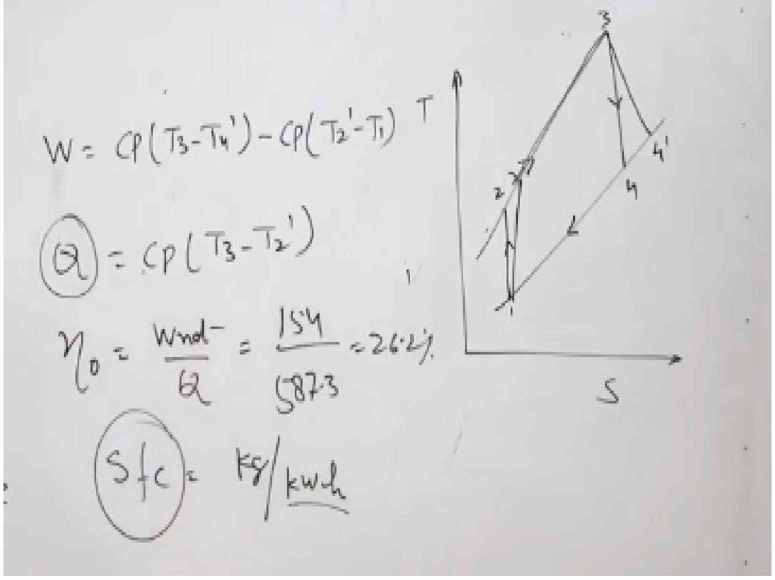

$W = C_P(T_3 - T_4') - C_P(T_2' - T_1)$

$Q = C_P(T_3 - T_2')$

$\eta_0 = \frac{W_{net}}{Q} = \frac{154}{587.3} = 26.2\%$

$Sfc = kg/\underline{kwh}$

Now we can find easily calculate the network is network is CP T3 by T4 dash - CP T2 dash by T1 and we have all these values T3 T4 dash T2 dash T1 CP given and this will give the network as 154 kilo joules per KG. Similarly we can find the Q also CP T3 - T2 dash right if we take this ratio that will give the efficiency that is work net divide by Q right and this is nothing but 154587.5 it is 26.27.

A specific output per KG of now specific fuel consumption fulfill consumption per kilowatt hour and here per KG this much of heat is required we know that Q and this Q will come from how much of fuel and how much energy is generated in kilowatt output is in kilowatt. So specify consumption is kilogram of fuel consumption per Kilowatt hour of power generation right. This is how we can calculate the specific fuel consumption in this case.

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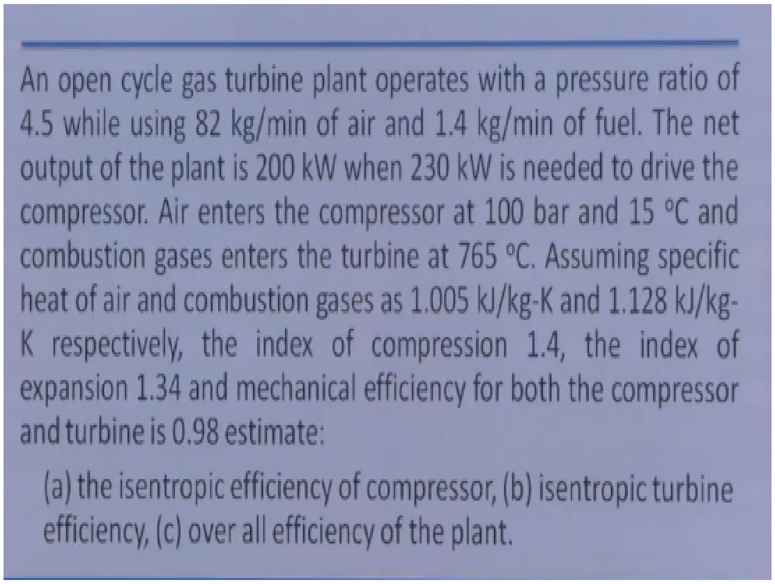

An open cycle gas turbine plant operates with a pressure ratio of 4.5 while using 82 kg/min of air and 1.4 kg/min of fuel. The net output of the plant is 200 kW when 230 kW is needed to drive the compressor. Air enters the compressor at 100 bar and 15 °C and combustion gases enters the turbine at 765 °C. Assuming specific heat of air and combustion gases as 1.005 kJ/kg-K and 1.128 kJ/kg-K respectively, the index of compression 1.4, the index of expansion 1.34 and mechanical efficiency for both the compressor and turbine is 0.98 estimate:

(a) the isentropic efficiency of compressor, (b) isentropic turbine efficiency, (c) over all efficiency of the plant.

Now we will take another problem on the gas turbines that is an open cycle gas turbines plant operate with the pressure ratio on of 4.5. We will quickly solve this problem an open cycle gas turbine plant operates to the pressure ratio of 4.5 while using 82 KG per minute of air and 1 KG per minute of fuel right.

So flue gases will be sum of this 83.4 the net output of the plant is 200 kilowatt when 230 kilowatt is needed to drive the compressor air enters the compressor.

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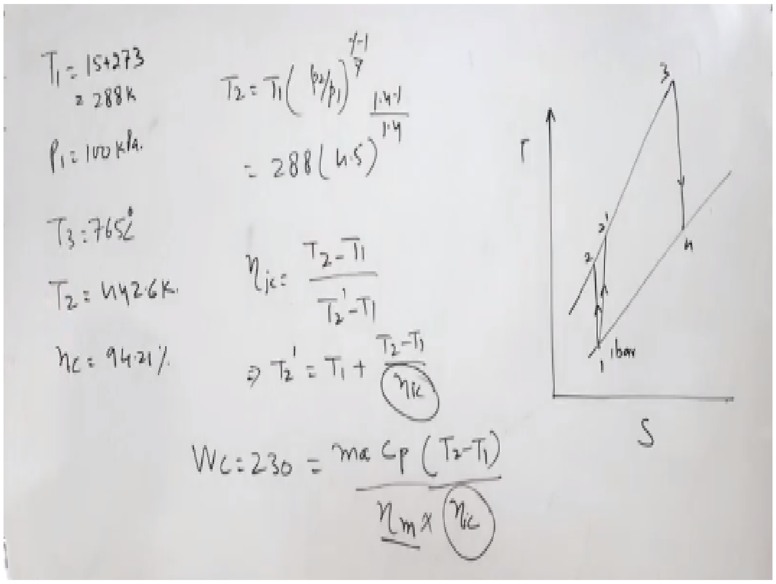

So let us first draw the cycle on temperature entropy diagram air enters the compressor at 100 bar and 15 degree centigrade. So T1 is 50 + 273 = 288 kelvin and P1 is 100 bar. So there is a small correction the pressure is not 100 bar it is 1 bar so I made necessary correction the pressure is it is close to atmospheric pressure.

So the air enters compressor one bar this is 1 bar so P1 = hundred kilopascal ok and air and the gases enters the turbine at 765 so T3 is 765 degree centigrade. So first of all will calculate T2 = T1 P2 by p1 raise to power gamma - 1 over gamma and the pressure ratio is 4.5. So T1 is 2884.5, 1.4 - 1 divided by 1.4 and this T2 is 442.6 kelvin.

Now once we have T2 we can calculate the value of T2 dash that is isentropic efficiency of compressor is this is T2 dash T2 - T1 divided by T2 dash - T1 or T2 dash = T1 plus T2 - T1 divide by isentropic efficiency of the compressor. Now we have the value of T1 and T2 and this will give us the value of T2 as now but we do not have compressor efficiency.

Now so P2 calculate the isentropic efficiency of the compressor we do not have isentropic efficiency of the compressor. Now this can be I will found out by taking work by the compressor work of the compressor is 230 kilowatt and that is equal to mass of the air specific heat of the air T2 - T1 divided by efficiency of the compressor and mechanical efficiency of the compressor because mechanical efficiency is also given the mechanical efficiency of both compressor and turbine are 0.9.

This mechanical efficiency is not isentropic efficiency so we should not get confused this mechanical efficiency with isentropic efficiency. So this is going to be expression for power in the compressor this is mass of the air specific heat ideal temperature raise divided by from here we will get efficiency of the isentropic efficiency of the compressor right. Mechanical efficiency is given here .98 so from here we will get isentropic efficiency of the compressor.

And this is going to be 94.21% right. Now first part we have completed isentropic efficiency of the compressor now we have to have to find isentropic efficiency of the turbine.

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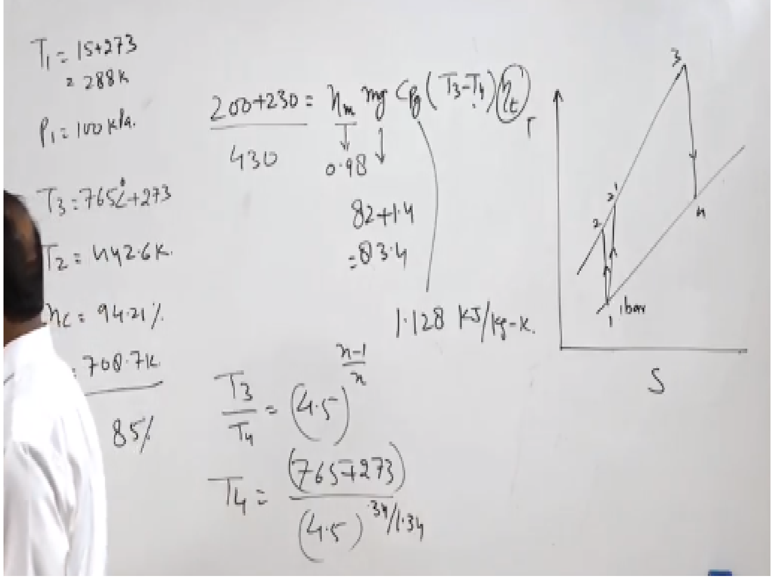

Now for the turbine output turbine output is 200 + 230 right and this is equal to mechanical efficiency mass of the gas specific heat of the gas T3 - T4 isentropic efficiency of the turbine right and this is 430 mechanical efficiency 98 percent is given mass of the gas is 82 + 1.4. So 82 + 1.4 this is 83.4 KG right and specific heat of the gas is also given 1.12, 81.128 Kilo joules per KG kelvin.

T3 and T4 we have already calculated T4 we have not calculated so T4 is going to be T3 or raise to power N upon value of N is given here. So T3 by T4 = pressure ratio is 4.5 and N 1 - upon N right. So T4 is T3 is 765 divide by 4.5 raise to power N -1 N is 1.34. So .34 divide by 1.34 this will give the T4 as 708.7 kelvin.

This is 765 + 273 this is 765 degree centigrade ok 273 right. And this will give T4 as 708.7 kelvin now T3 by T4 now once we have value of T4 right. We can get the value of efficiency of the turbine from this equation now efficiency of the turbine is here is 85%.

So isentropic efficiency of the compressor is there and isentropic turbine efficiency are calculated now overall efficiency of the plant for overall efficiency output is with us we need to know the input.

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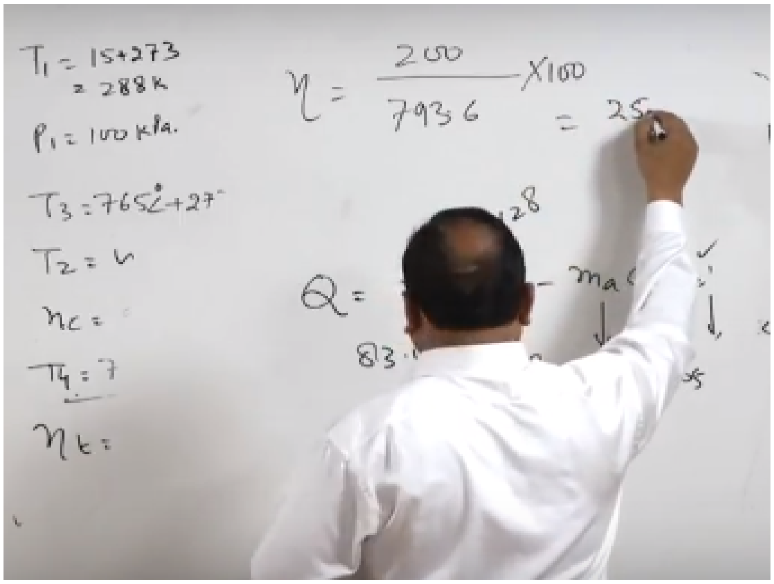

Now input is Q = NCP GT3 - NA CP A T2 dash right CPG is given in the numerical that is 1.128. Mass of gas is 83.4 T3 we can take from here 765 + 27300 and 38 mass of the air 862 CP A is 1.005 and T2 dash is so T2 dash we have already calculated this will give Q = 793.6 kilo watt right.

In order to find the overall efficiency the net output net output is 200 kilowatt divided by the heat supplied 793.6 kilowatt multiplied by 100 and this will give the overall efficiency as 25.2% that is all for today from next class we will continue with the modification in gas turbine.