Concepts of Thermodynamics
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Lecture – 62
Brayton Cycle

In the previous lectures, we were concerned about 2 very important air standard cycles the Otto cycle and the diesel cycle. We will consider a third example of a air standard cycle, which in practice represent something which is not a construct constant mask control system, but a steady state steady flow process in a control volume framework. So, that cycle is known as Brayton cycle or Joule cycle.

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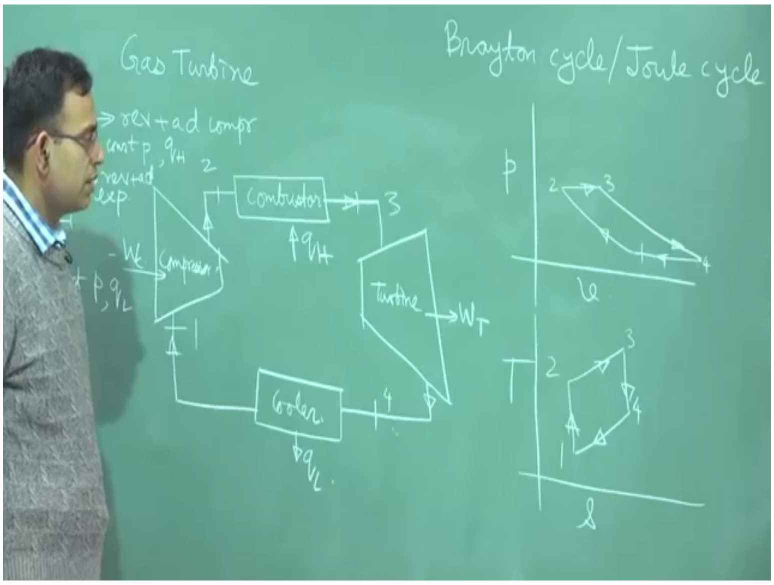

So, just like the Otto cycle and diesel cycle they have practical motivations, this Brayton cycle or Joule cycle it has it’s own practical motivation and that is associated with a type of power plant known as gas turbine power plant. So, the Otto cycle and diesel cycle we related those to a type of engine called as internal combustion engine because the combustion process takes place within the in system itself.

So, it is internal to the process, but there are other scenarios of power generation where the power generation is governed by heat transfer taking place from locations which are external to the system. So, from outside heat source the heat source maybe combustion of a fuel, the heat is transferred to the working fluid and these are called as external combustion engines.

So, because the combustion process does not take place as a part of the system it is a much, it offers with the much cleaner way of cycling the working fluid not only that because the fuel is not an integral part of the system you can use cheaper fuels and therefore, if you run an engine you could attend very high speeds because you could go to very high values of pressure. So, once you go to very high values of pressure, the and the high value of pressure can be sustained in a flow process rather than a momentary high value of pressure which you get in an internal combustion engine.

So, all these things make this device based on external combustion likely to generate high values of power, but the problem is that these are not self starting not only that you require a huge amount of you know reducing air to have reduce speeds, otherwise these are very high speed engines. So, for ground transportation these are not commonly used, but for aircraft transport where high speed movement is required these may be used.

One of the advantages is using a cheaper fuel for gas turbines as compared to internal combustion engine but that is offside by the face that because the highest temperature in this gas turbine is quite high. So, the turbine blades have to be designed with a very high quality material to which stand that temperature. In internal combustion engine also high temperature and high temperature attain, but that is momentarily during the cycle, but in a gas turbine there is sustained high pressure and high temperature and the material of the gas turbine blades should be sophisticated enough, capable enough to which stand that high temperature.

So, those costs those initial costs are quite high, but the operating cost due to use of cheaper fuels may be low, but irrespective of the cost because of the high speed issue it is not possible to use this for ground transportation and it will also be a much bulkier system as compared to a system, where combustion takes place within the system itself. So, such a bulky system cannot be used for ground transportation.

So, what is essentially the part of a gas turbine? So, you have a compressor and then you have a combustor. So, this compressor compresses air right, this air is not mixed with the fuel if you consider a perfect thermodynamic cycle right you cannot consider that. So, this air, so instead of a low pressure low temperature, air it is a high pressure high temperature air and then heat is transferred through combustion of the fuel.

Then despite what is the reality? The model cycle will consider only the air with the high pressure and temperature, in reality it could be air fuel mixture. So, then this is expanded in a turbine and then heat is thrown away to the ambient, but you know to come, so this is a compressor, this is a turbine and the working fluid is air. So, instead of considering an open cycle and open process like this.

So, it is not a cycle open an cycle is a misnomer you know, it is like a you know brick made of gold something like that when it is open it is not a cycle, but I mean people usually call it open cycle, but actually to make it a cycle you imagine that, there is a heat rejection across a device which is a is just a cooler or a heat rejection device this is a conceptualization of the reality that is taking place remember this is not exactly the reality this is a conceptualization or modelling of the reality that takes place in a gas turbine cycle.

So, we identify the state point 1 to 2, 2 to 3, 3 to 4 and 4 to 1. So, here you have q H here you have q L here you have W turbine and you have a compressor work that is input. So, the net work is the balance between the turbine work output and compressor work input which is same as q H minus q L to complete the cycle. So, we will draw this cycle in p v and T s diagram.

So, 1 to 2 see this is also under air standard cycle per view, so all processes are considered to be internally reversible 1 to 2 we will assume reversible adiabatic compression, this is the flow process right this is not a control mass system. So, 1 to 2 reversible adiabatic compression looks like the same 1 to 2 in the p v diagram as we represented in the Otto cycle or diesel cycle, but conceptually there is a difference that was a control system and it is a flow process.

So, reversible adiabatic compression, then 2 to 3 you have a constant pressure heat addition, the combustion process is modelled as a constant pressure heat addition. So, let me write this 1 to 2 reversible plus adiabatic compression, 2 to 3 constant pressure q H, 3 to 4 reversible plus adiabatic expansion and 4 to 1 constant pressure heat rejection.

So, when you have these let us plot these in the p v diagram first. So, here constant pressure heat rejection is why? Because here it is not a piston cylinder arrangement that is taking care of the physical device. So, the difference between 4 to 2 is not related to any physical volume of the size constraint of the device. So, it is just the physical nature of the process which is a constant pressure process that is modelled here.

So, 1 to 2 then from 2 to 3 in the T s diagram we have constant pressure process. So, this is T s diagram. So, the next job will be to calculate the efficiency of this cycle.

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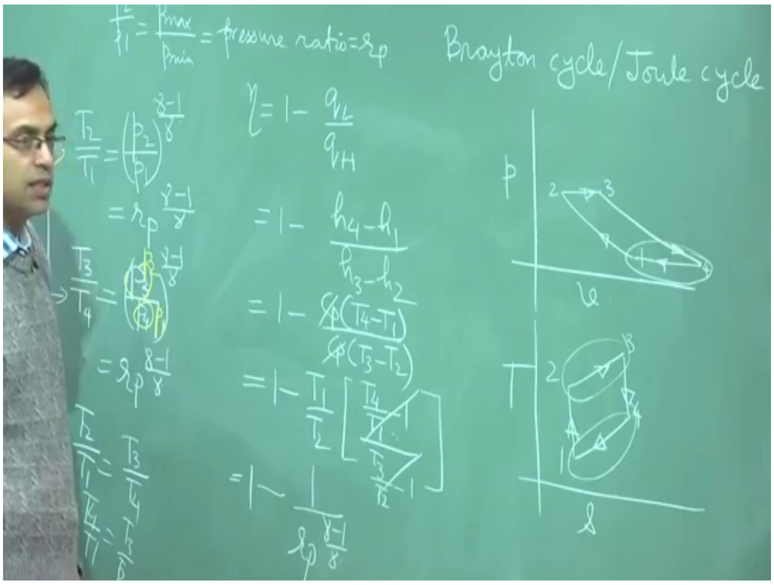

So, what is q L? q L is the steady state steady flow process across the cooler. So, q L is basically the difference in enthalpy between the state points 4 and 1 this one right. So, q L is h 4 is a steady state it’s a flow process right.

So, fundamentally if you apply the first law of thermodynamics for a steady state steady flow process across the cooler you will get this as q L. So, do not learn it like a formula, apply the first law for getting the expressions for the heat transfer and the work done and remember this you are writing as a magnitude and not with sign. What is q H? q H is similarly h 3 minus h 2. So, had it not been constant C p C v still we could write this is very general.

Now, because of the air standard cycle assumption air is treated as an ideal gas with constant C P and C v. So, this is C P into T 4 minus T 1 divided by C P into T 3 minus T

2. So, we write this as one minus T 1 by T 2. So, now, we can write from 1 to 2 you have T v to the power gamma minus 1 or in terms of pressure T 2 by T 1 is equal to p 2 by p 1 to the power gamma minus 1 by gamma right.

It is equivalent to p v to the power gamma equal to constant and T v to the power gamma minus 1 equal to constant, you can eliminate v by writing p v equal to r T and get T in terms of p. So, p 2 by p 1 is the ratio of the maximum pressure to minimum pressure of the cycle and this is called as pressure ratio this is p max by p v this is called as pressure ratio.

So, this is r p to the power gamma minus 1 by gamma and similarly T 3 by T 4 is equal to p 3 by p 4 to the power gamma minus 1 by gamma right and p 3 is same as p 2 and p 4 is same as p 1. So, this is r p to the power gamma minus 1 by gamma therefore, from this 2 we can write T 2 by T 1 is equal to T 3 by T 4 right that means, T 4 by T 1 is equal to T 3 by T 2, so this gets cancelled.

So, this is 1 minus T 1 by T 2 and T 1 by T 2 is 1 by r p to the power gamma minus 1 by gamma, so this is the expression for efficiency of the cycle. Now the question is given this efficiency, how do you get an expression? That finds out what is the maximum work that you can get out of this, maximum efficiency and maximum work are 2 different things.

So, given, so what are given? Given T 1 and T 3 the minimum temperature and the maximum temperature, what is the maximum work that you would get out of this? So, let us try to do that.

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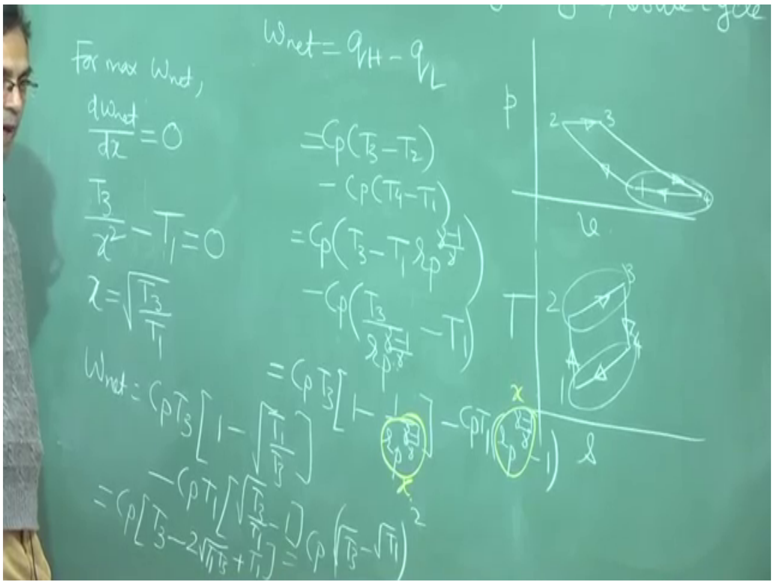

So, w net that is q H minus q L I am telling you again that instead of calculating the work done in this case if you wanted to calculate the work done it would not be integral PDP, but it would be VDP, but again because the temperatures are known and heat transfers are sole function of enthalpies, which are internal functions of temperature and temperatures are easily obtainable from the state point diagram through equations of state and process equations.

It is much more convenient for air standard cycles at least to calculate the heat transfer rather than to calculate the work done. So, for calculating the work done we go through the heat transfer route. So, q H what is q H? q H is C P into T 3 minus T 2 minus C P into T 4 minus T 1. So, what we have fixed is T 1 and T 3, so if you fixed if you have fixed up T T 1 and T 3.

Now what is T 2? T 2 is T one into r p to the power gamma minus 1 by gamma. So, C P into right and what is T 4? T 4 is T 3 by r P to the power gamma minus 1 by gamma right T 4 is T 3 by r p to the power gamma minus 1 by gamma minus T 1. So, you can little bit rearrange this C P into T 3 into 1 minus one by r P to the power gamma minus 1 by gamma minus C P into T 1 r P to the power gamma minus 1 by gamma minus 1 right.

So, we want to derive a condition under which the, this work output is maximum. So, just for simplicity, so this same variable is appearing r P to the power gamma minus 1 by gamma let us say this is x. So, w net is a function of x, so for maximum w net d w net d x must be equal to 0. So, you can write T 3 by, so 1 by x will become minus 1 by x square minus T 1 is equal to 0 right.

So, x will be square root of T 3 by T 1 right. So, the efficiency in this case, so you can find out the work done by substituting this here. So, w net will be C P T 3 into 1 minus root over T 1 by T 3 minus C P T 1 into root over T 3 by T 1 minus 1 right. So, this is C p T 3 if you take C p C p common T 3 minus 2 square root of T 1 T 3 plus T 1.

So; that means, C P into square root of T 3 minus square root of T 1 whole square right, square root of T 3 minus square root of T 1 whole square is not it and efficiency is 1 minus 1 by r P to the power gamma minus 1 by gamma, so minus 1 by x right. So, 1 minus square root of T 1 by T 3.

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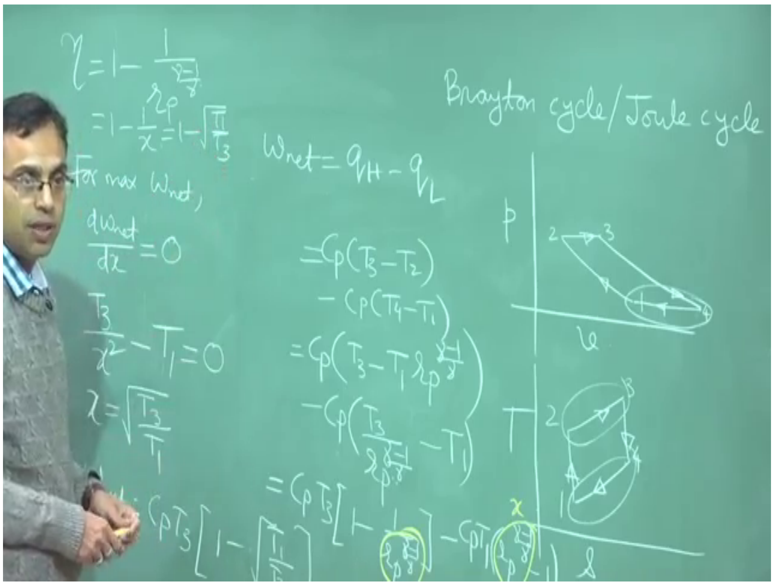

So, given maximum temperature and minimum temperature, if you want to derive the maximum work you can always fix up a pressure ratio and then for that pressure ratio your maximum work is this one and the maximum efficiency is just a function of the temperatures.

So, we will quickly work out a problem on the Brayton cycle to wind up what we have discussed today and that problem is problem number 9.3.

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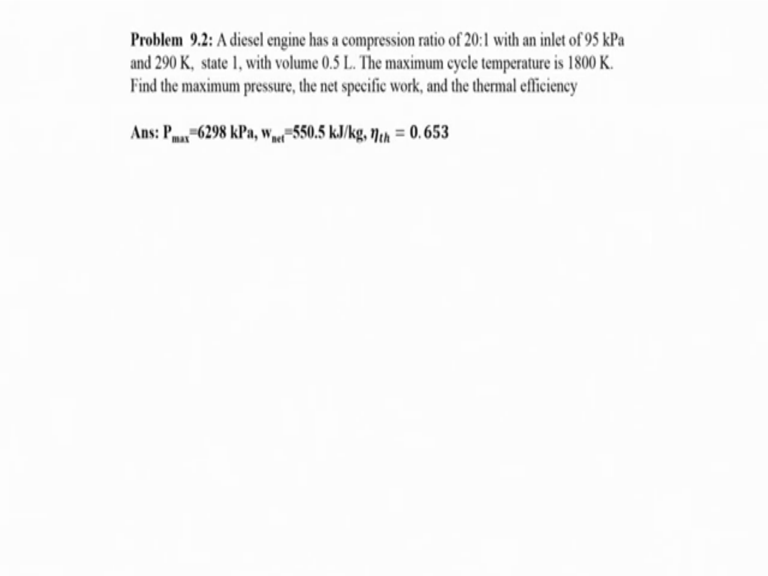

Problem 9.2: A diesel engine has a compression ratio of 20:1 with an inlet of 95 kPa and 290 K, state 1, with volume 0.5 L. The maximum cycle temperature is 1800 K. Find the maximum pressure, the net specific work, and the thermal efficiency

Ans: P_{max}=6298 kPa, w_{net}=550.5 kJ/kg, $\eta_{th} = 0.653$

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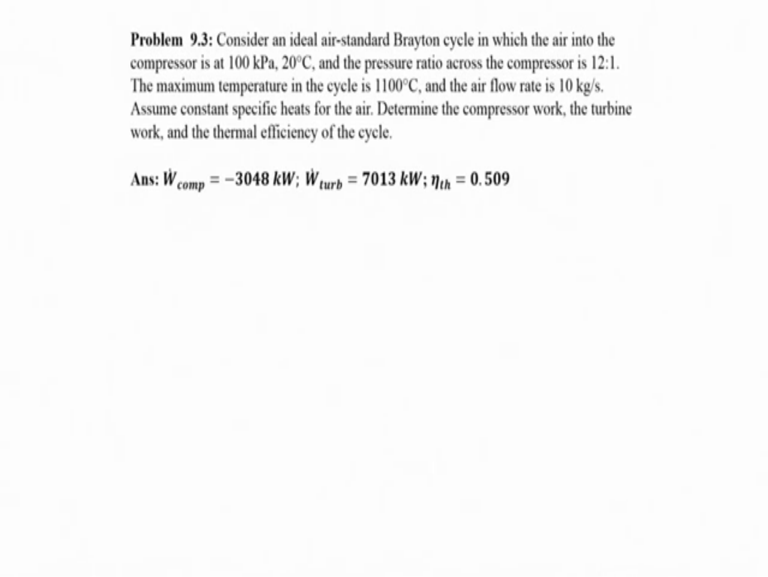

Problem 9.3: Consider an ideal air-standard Brayton cycle in which the air into the compressor is at 100 kPa, 20°C, and the pressure ratio across the compressor is 12:1. The maximum temperature in the cycle is 1100°C, and the air flow rate is 10 kg/s. Assume constant specific heats for the air. Determine the compressor work, the turbine work, and the thermal efficiency of the cycle.

Ans: $\dot{W}_{comp} = -3048\ kW$; $\dot{W}_{turb} = 7013\ kW$; $\eta_{th} = 0.509$

Consider an ideal air standard Brayton cycle in which air into the compressor is 100 kilo Pascal 20 degree centigrade, pressure ratio across the compressor is 12 is to 1 and maximum temperature of the cycle is 1100 degree centigrade, air flow rate is 10 kg per second. Assume constant specific heats for the air determine the compressor work turbine work and thermal efficiency of the cycle.

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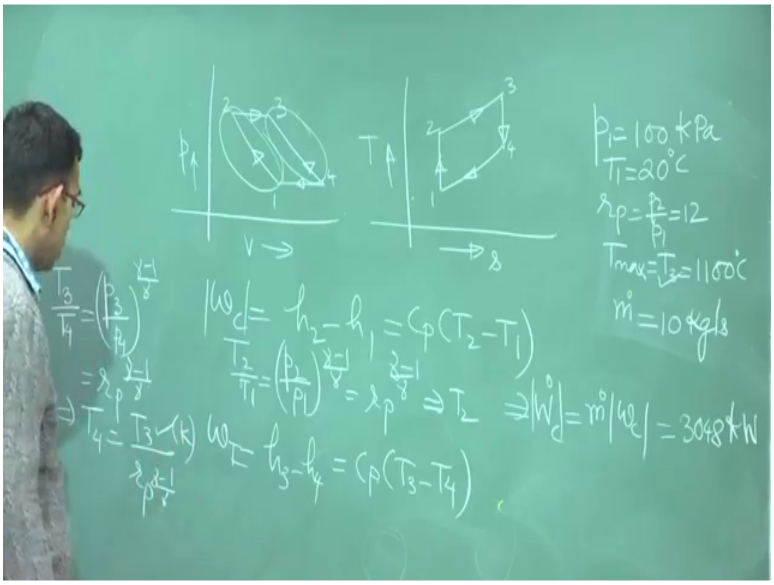

So, let us quickly do the analysis this is very straight forward, but we need to do it meticulously. So, p 1 is 100 kilo Pascal, T 1 is 20 degree centigrade r P is P 2 by P 1 which is 12, T max which is T 3 this is 1100 degree centigrade and m dot is 10 kg per second. So, first part is find out the compressor work. What is the compressor work? Which part is the compression? The compression is 1 to 2 right first law steady state steady flow.

If you apply to the compressor work will be h 2 minus h 1, first law steady state steady flow to the compressor. So, this is C P into T 2 minus T 1. So, T 2 you have to find out, so T 2 by T 1 is P 2 by P 1 to the power gamma minus 1 by gamma, so this is r P to the power gamma minus 1 by gamma, so that will give you what is T 2. So, if you substitute that here you will get the compressor work, this is per unit mass, so total rate of compressor work is m dot.

So, this is magnitude of the compressor work actually the compressor there is work input and not output. So, this is magnitude, so this is m dot into m dot is 10 kg per second, so compressor work is 3048 kilowatt Next part is what is the turbine work? Turbine work is output. So, work what is the process is this is the turbine process. So, that is h 3 minus h 4. So, this is C P into T 3 minus T 4 again you can get this by applying steady state steady flow energy analysis for the turbine.

So, T 3 is already given and you can get T 4 by noting that T 3 by T 4 is same as p 3 by p 4 to the power gamma minus 1 by gamma, so this is r P to the power gamma minus 1 by gamma. So, T 4 is T 3 divided by r P to the power gamma minus 1 by gamma, remember it has to be in Kelvin.

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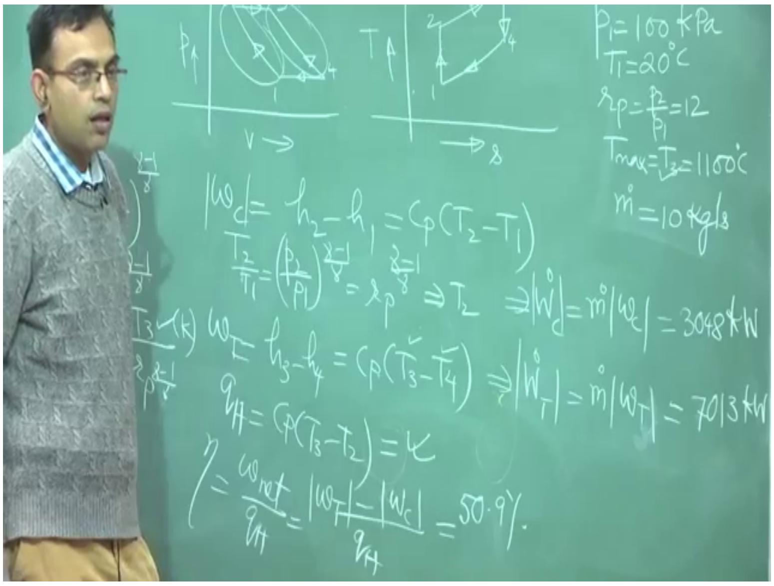

So, this will give you what is T 4 T 3 is known, so you know per unit mass what is the turbine work. So, this is m dot into w T this is here the mod and actual there are both positive here actual is negative, but mod is always positive. So, this is 701.3 kilo joule per kg.

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Sorry kilo joule per kg second sorry 701 sorry not this is 701.3 kilo joule per kg, but there is also ten kg per second, so it is 7013 kilowatt. And then you have to find out the efficiency, so you have the net work output already you have got that is w turbine minus w compressor and what is q H? q H is C P into T 3 minus T 2.

So, you have T 3 already there and T 2 also you have calculated, so you can calculate q H from here. So, efficiency is w net by q H, so this is mod of w turbine minus mod of w compressor by q H and this is 50.9 percent ok.

So, today we have discussed about the Brayton cycle which is one of the very important air standard cycles used to ideally model the gas turbine thermal power plant process. We have seen how to analyse this cycle and how to calculate the thermal efficiency, we will continue with more cycles and cycle analysis in our subsequent lectures.

Thank you.