IC Engines and Gas Turbines

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Lecture – 40
Some Aspects of the Cycle

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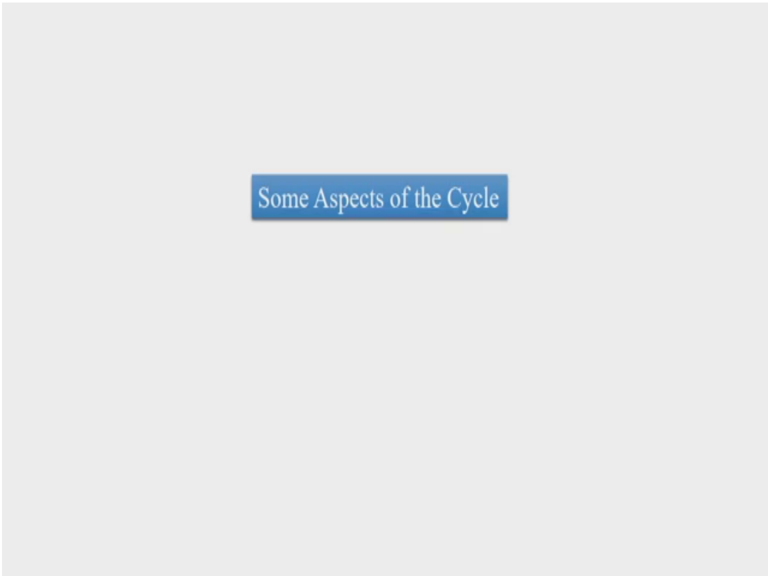

Ok, welcome to the today's class. We have covered the portion till time was about the different attachments to the cycle and working with the examples associated with those ideal or non-ideal components. Now, in today's class, we are going to see Some Aspects of the Cycle. What aspects we have seen till time, the aspect what we have seen was that what is the Brayton cycle upon which we can have our power plant running.

And then we have seen that if this Brayton cycle operates, then what are the governing parameters of that Brayton cycle means, how the performance of the given Brayton cycle gets altered. So, we have seen that performance of the Brayton cycle gets affected by working medium gets affected by pressure ratio. So, these are the two important things which are there for the ideal cycle also.

Further, there is performance alteration with other attachments. Like if we have heat exchanger, if we have re heater, and if we have the intercooler, so these things will alter the performance. What do we mean here by performance? Here performance by the meaning of hours is related with the efficiency of the plant. And it then the efficiency, what did we talk about was the thermal efficiency of the power plant, which is network upon q in which is rather q out minus upon q in that was the overall efficiency rather that was the thermal efficiency of the power plant that is what we had seen.

So, the point is for the other component for the components like re heater, we have considered that was not just not rather mainly for increasing the efficiency, but that was for increasing the power output of power plant. And then we have considered exclusively the heat exchanger for the concept of increasing the efficiency. So, these are the things, what we have already thought about.

But, then what we had thought was that if these components are non-ideal, then there are isentropic efficiencies associated with turbine, associated with compressor, then there is heat loss with the heat exchanger, and all these losses would lead to different efficiency than the efficiency which we have calculated, otherwise considering everything to be ideal.

So, the performance of the cycle gets altered by pressure ratio, and by gamma in case of a ideal cycle. And performance of the cycle gets altered by same r p, same gamma, but along with the compressor efficient isentropic efficiency of compressor, isentropic efficiency of turbine, and then the losses in the heat exchanger combustion chamber. So, these are the thing which we have seen.

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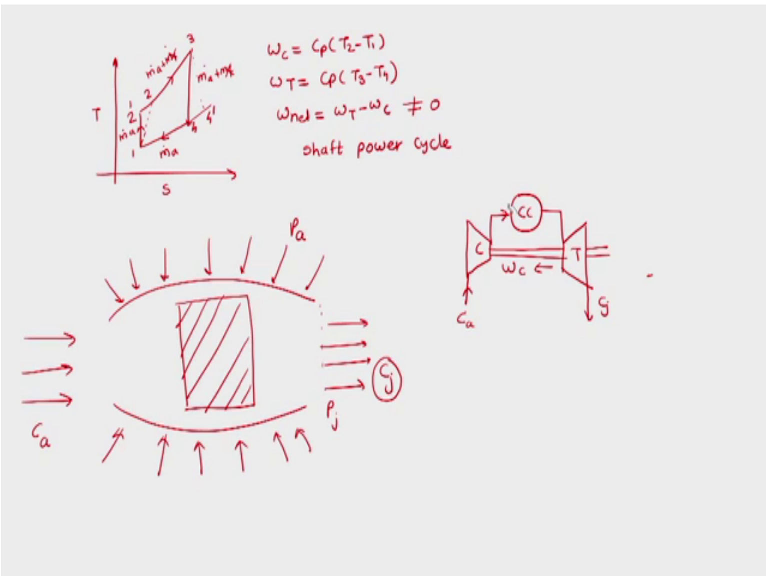

But, all these things whatever we have seen were related with the shaft work output which is w net. So, what we have said that there is a Brayton cycle, and then this is T S diagram for the Brayton cycle. And then in this T S diagram, this is 1 to 2 which is compressor, then 2 to 3 which is 2 to 3, which is heat addition in the combustion chamber. And then 3 to 4 is 3 to 4 is the turbine, and then 4 to 1.

And then we have 2 here, then it becomes 2 dash. And then we have 3 here, 4 here, then it becomes 4 dash, this is what we have seen. So, this we said that w c is the compressor work which is c p into T 2 minus T 1. And w T is the turbine work which is c p into T 3 minus T 4 this is what we have seen. So, we said that w net is w T minus w c. But, then that means, that we are interested in the w net which is a non-zero number. Since, this is a non-zero number, we are interested in w net, this whole cycle is called as the shaft power cycle shaft power cycle.

Here our interest was to get the shaft our interest was mainly to get w net which is a non-zero thing. And then that shaft power, obviously would be connected to a or given to a generator which will produce electricity. So, till time what we worked was mainly for electricity generation like power plant like cases. But, with the lecture of today, where we are going to concentrate on other aspects of the cycle, we mean here that we are interested in the Brayton cycle based power plant, but not for electricity generation, but for propulsion, but for transportation.

So, in this case, w net is not our interest or w net is rather 0. We are not going to have any w net, since we are interested in the propulsion system. So, in that case, we will have suppose gas turbine power plant, where it is inside a control volume for us. This is gas turbine power plant in which air is coming with velocity c a in which air is leaving with velocity c j. Then there is pressure acting on this surface of the gas turbine, which is atmospheric pressure. So, let us call it as p a, and then this jet over here has pressure p j. So, what we are talking about is the propulsion based understanding for the Brayton cycle.

So, propulsion based understanding for the Brayton cycle, we know that we have seen earlier that there is a compressor in which air will come, then it will go into the combustion chamber. And then from the combustion chamber, it will go to the turbine ok. This turbine was running the this turbine was running the compressor. But, here we were having turbine to be connected to the generator also earlier. So, there was w net given to the generator, w c was given to the compressor by the turbine, obviously there would be some transmission losses, then in both the sides it has to be more. So, turbine has to be more work than w c to the compressor, and more work than the rest of the work, it will obviously give to the generator.

So, the point is here we are going getting the velocity, which is almost the velocity which is coming at the inlet to the compressor. Since, the cycle over here whatever we have drawn is drawn for the constant mass case. So, everywhere we are having same mass, obviously we will add fuel, and then the mass of fuel is neglected. Otherwise, here we have mass of air, here we have mass of air plus mass of fuel, here we have mass of air plus mass of fuel, and here we have obviously in case of open cycle, we do not have anything, but we will again take air which is mass of air at one.

But, if we have an closed cycle plant, then we will not have mass of fuel we will not have mass of fuel, then it becomes mass of air everywhere. So, whenever we draw a TS diagram, we draw for a constant mass flow rate or a constant mass current case. So, here the point is that we are going to leave this air. So, the velocity which is coming out from the turbine is almost equal to the velocity of the inlet to the counter by compressor.

So, the point is now, we are interested in having a propulsion system. Since, we are interested in propulsion system; we want c j to be the velocity of the jet to be coming out of the turbine. So, we have c a here, and we have c g. So, now it is going with higher kinetic energy as compared with the inlet kinetic energy. So, this change in kinetic energy or change in momentum would lead to thrust to the power plant or to the aircraft. So, we are interested in generating the thrust in case of power plant, which are used for transportation applications.

Obviously, these things would actually power plant would have many components than this, it would have multiple compressors, it would have intake, and then (Refer Time: 10:16) of the turbine, there are maybe there are many passages of the turbine in there might be afterburner in case of the turbine, but at gross it would be like c a like here, then c j like here. So, the performance cannot be judged here based upon the efficiency, what we have talked about double unit upon q in.

So, thermal efficiency of the Brayton cycle is not applicable, if we are going to go with the plant which is going to be used for transportation application. So, having said this, we need to make the new arrangement or new performance parameter for the transportation application based thermal power plant or Brayton cycle based power plant.

In this case, we have actually major objectives many objective to decide or design a thermal power plant. In Brayton cycle based (Refer Time: 11:19) power plant. So, in that case we might have an objective to work upon maximum thrust, we might have to optimum upon maxi we have we might have to work up on optimum economy in case of cruise or in case of steady flight. So, these objectives need to be thought for, and then these objectives would have certain quantifications. And those quantifications need to be assessed, while comparing to Brayton cycle based power plants.

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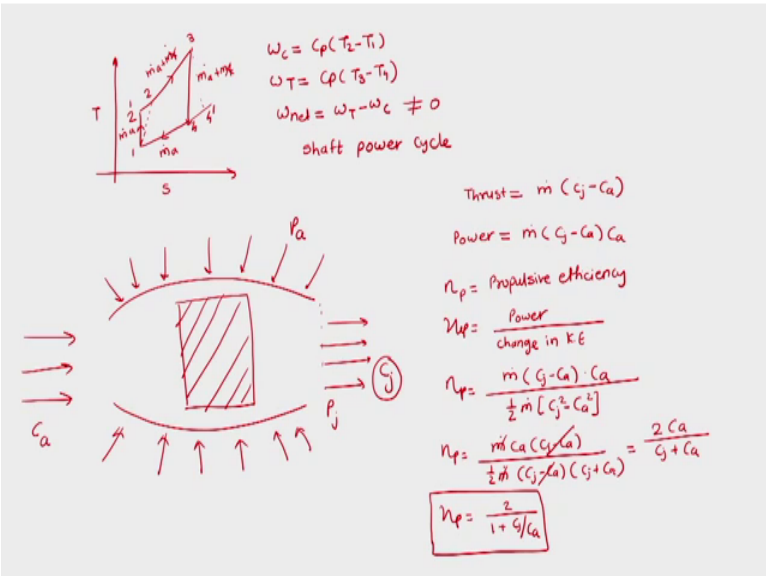

So, first what we are going to see here is what is thrust as what we saw earlier that what is w net, which was required in that case. But, now we are interested in thrust, so what is thrust in this case, we define thrust as from the Newton's law, we can find out thrust is equal to m dot into c j minus c a. This is the thrust the rate of change of momentum is thrust applied or thrust gain thrust generated by the power plant, so this is thrust.

So, what is thrust power, what is the power, we know that we use power concept for all the kind of engines we say that our two-wheeler has certain HP engine or four- wheeler a certain HP engine, tell you we use horsepower. So, same way, we are using horsepower for the gas turbine based transportation power plant. So, power is this is thrust into velocity. So, what is the velocity, velocity is c a. This analysis is same, where basically we are at this movement considering that engine is stationary, and air is coming with velocity c a, and the gas is living with velocity c j.

So, but in real flight what would happen, flight will move with velocity c a, which is c a aircraft velocity, and jet will move at velocity c j. So, the same thing if we change a coordinate system, then we can make the flight to be stationary, we can have the air to be entering with c a velocity, and then you just jet with c j corresponding c j velocity. So, this is the power.

Now, we have to define this power is to be compared with the actual input energy which was given to generate this power, so that corresponding comparison is called as propulsive efficiency propulsive efficiency. And propulsive efficiency is thrust power divided by input energy. So, what is energy, what is input energy in this case, input energy change in kinetic energy between outlet and inlet, so that is change in kinetic energy.

And change in kinetic energy, we know that now thrust power is m dot c j minus c a into c a divided by half m dot into c j square minus c a square. So, this we can rewrite, and we can say that m dot c a c j minus c a divided by half m dot, and this we can split into c j minus c a into c j plus c. So, here c j minus c a will cancel, m dot will cancel, and then we get 2 c a divided by c j plus c a. So, we have propulsive efficiency as 2 upon 1 plus c j upon c. So, this is the formula for propulsive efficiency of a gas turbine power ok. So, this propulsive efficiency will be judged with thee between the two engines to understand which is a better engine having more propulsive power more propulsive efficiency.

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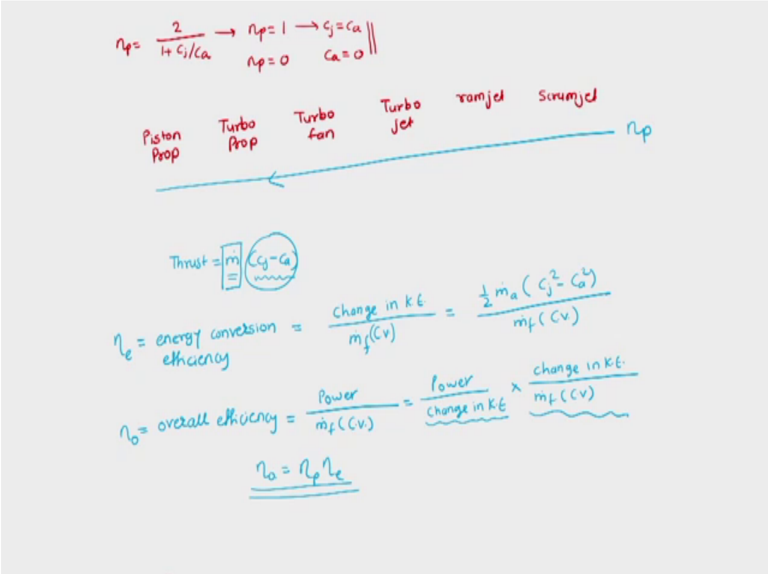

So, then what would happen in this case that we can see that propulsive efficiency is 1 is basically 2 upon 1 plus c j upon c. So, when propulsive efficiency is maximum, this formula clearly says that propulsive efficiency is equal to 1 if c j is equal to c a. If c j is equal to c a ok, and then propulsive efficiency is 0, if we have c a is equal to 0.

So, we have two extreme cases. One and in both the extreme cases, there is no flight. When c j is equal to c a propulsive efficiency is maximum, but then there is no flight taking place. And then in this case, c a is equal to 0, then that is also we will not have any flight. So, these are the extreme cases which are corresponding to extreme values of propulsive efficiency.

So, what is actually propulsive efficiency going to decide first? So, there we have to remember a point that there are many aircrafts in the reality. We have aircrafts like we have piston prop, we have turboprop, we have turbofan, and we have turbojet, we have ramjet, and we have scramjet. So, these are the different aircrafts, what we can generally see in the sky or in the present situation, we have different aircrafts with us. So, these different aircrafts basically have different propulsive efficiencies, and their propulsive efficiency can be compared.

So, in this case, propulsive efficiency is in this direction. So, propulsive efficiency increases in this direction. So, of lowest propulsive efficiency is for scramjet, highest propulsive efficiency is for ramjet, and then turbojet, turbofan, turboprop, and piston prop will have increasing propulsive efficiencies. So, here what we have to understand is that the thrust or here in this case is gained by the two things, we have seen that what is the thrust.

Thrust formula for (Refer Time: 18:57) thrust was m dot into c g minus c, this was the formula for thrust. So, thrust is gained by an aircraft for a given mass, it will gain the thrust by changing velocity between the inlet and outlet. So, for that there are some aircrafts which will have very large number of c j minus c a very large value of c j minus c a. If value of c j minus c a is large, then obviously propulsive efficiency decreasing.

So, if jet which is coming out of the aircraft is having very large velocity as compared to aircraft velocity, and those aircraft would have lower propulsive efficiency. And then that is the case with scramjet, ramjet, turbojet. So, these aircrafts and parallely with turbofan. So, these aircrafts would have jet velocity much higher than the velocity of the aircraft or the air which is coming into the engine.

And then they handle lower mass flow rate of the air as compared to the other engines. But, their belief is upon their design in the upon increasing the kinetic energy more or increasing the velocity more. But, then there can be one more v to increase the thrust by not changing much the c j minus c a, but deal with large amount of mass of air.

And in this category, we have turboprop and piston top, these are propeller based aircrafts. We are going to see these aircrafts in the next class, but this class is mainly upon the cycle. So, we are just touching this point that how the different engines would have different propulsive efficiencies. So, these engines like turboprop enter piston prop, they are driven by propeller, where propeller (Refer Time: 21:01) large amount of mass of air, it deals with large amount of mass of air.

So, what would happen is it will have not much difference in c j minus c a, but it will get larger thrust. So, a large amount of mass of air is dealt by propeller based engine, so they have higher propulsive efficiency. But, there is one more attitude to look into that they need large amount of mass, so they need large amount of mass. So, then they cannot be travelling at larger altitude, so they will be travel at lower altitudes.

But, the other engines which belief upon the larger velocity of jet, they can handle a lesser more amount of mass, so they can go with the higher altitudes. So, this is how propulsive efficiency is going to define, how the design of the engine is going to be. So, in the same case now if we go ahead, and then we define that there is something like energy conversion efficiency. So, energy conversion efficiency is the efficiency energy conversion efficiency, energy conversion efficiency is basically, we got propulsion due to change in kinetic energy. So, change in k, but who helped us to change this kinetic energy, so there we had fuel.

So, we had some fuel burnt, and then we had some calorific value of the fuel. So, we used chemical energy to change the kinetic energy. So, kinetic energy change which has happened, which took place across the turbine or across the power plant gas turbine power plant is due to chemical energy. So, change in k divided by chemical energy is the basically our energy conversion efficiency. So, we have half m dot a into c j square minus c a square divided by m dot f into calorific value ok. So, this is what the formula for energy conversion efficiency.

Then we have next formula which is called as overall efficiency overall efficiency of the power plant. So, overall efficiency means, we have basically different energies. And then first what we considered was propulsive efficiency. In propulsive efficiency, we considered two energies. One energy we considered was thrust power with kinetic energy. In energy conversion efficiency, we considered kinetic energy with chemical energy; overall efficiency is basically power with chemical energy which is m dot f into calorific value.

So, we can decompose it with power divided by change in k into change in k divided by mass of fuel into calorific value. And we know that now overall efficiency would become this is propulsive efficiency, and then this is energy conversion efficiency. So, this is the formula for overall efficiency of a power plant. So, these are the aspects, what they are going to define the comparison between or quantification how to quantify, and how to compare between two power plants.

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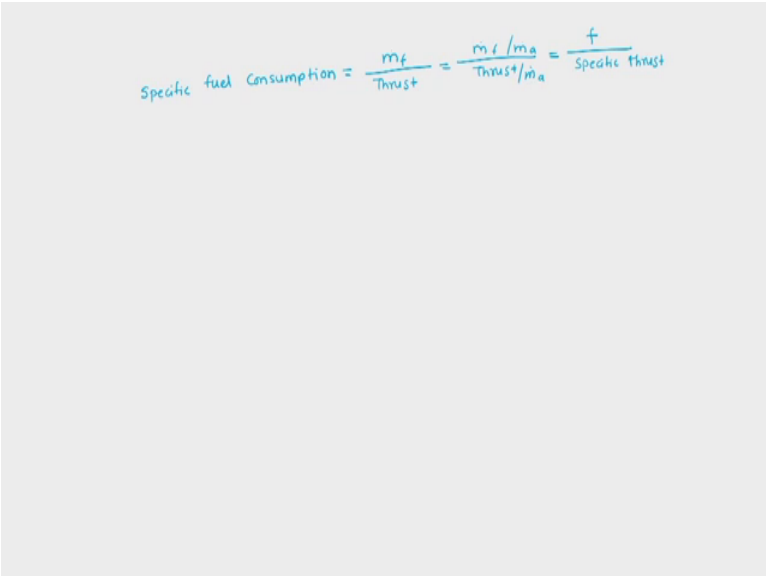

There is one more thing which we can use for comparison is the specific fuel consumption specific fuel consumption. And specific fuel consumption is defined as the mass flow rate of fuel divided by thrust power so mass flow rate of fuel divided by thrust. So, here we can divide by mass flow rate of air in both the case, so this becomes f which is fuel air ratio, and then this becomes specific thrust. So, this is how we have specific fuel consumption defined.

So, specific fuel consumption is basically, we have some requirement of fuel to generate; you need value of the thrust. So, this is what the definition of specific fuel consumption. So, when we want higher thrust basically, we basically parallely mean that we want to lower specific for your consumption. So, we want lower specific fuel consumption, we want higher price propulsive power, we want higher energy conversion efficiency, we want higher overall efficiency of a power plant. So, this is how we have defined?

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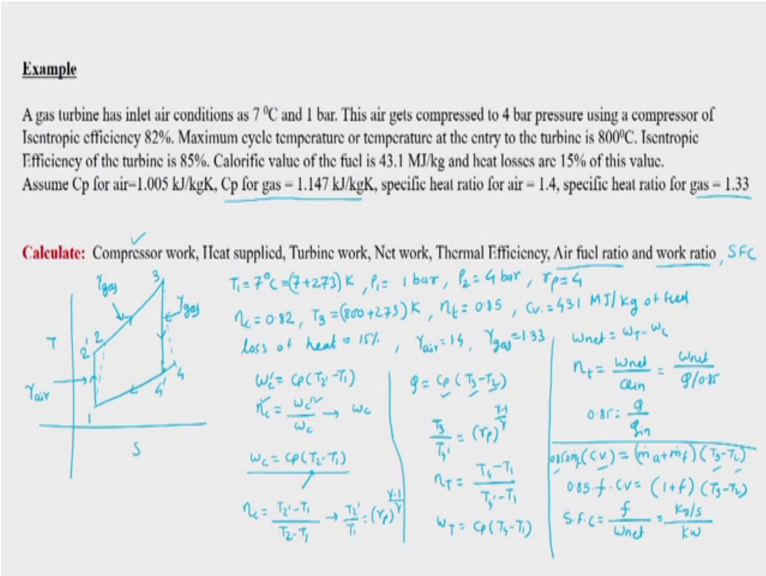

So, now next using this concept of specific fuel consumption, and then the concept of work ratio. We will solve an example which is not exactly related with this power plant based application, but for the application what we had earlier considered for electricity generation. So, this example deals with the fact that there is a gas turbine which has inlet temperature and 7 degree Celsius and pressure as 1 bar. This air gets compressed to 4 bar pressure using a compressor of isentropic efficiency 82 percent. Maximum cycle temperature or temperature at the entry to the turbine is at 800 degree Celsius, isentropic efficiency of turbine is 85 percent calorific value of the fuel is 43.1 mega joule per kg, heat losses are 15 percent.

And then we are given with certain standard data specific heat ratio for gas, this is a new concept which is given to us specific heat ratio for the gas ok. And then we are supposed to find out, what is the thermal efficiency, compressor over heat supplied, apart from that we have to find out air fuel ratio, and we will also find out work ratio, and we will find out what is specific fuel consumption for the power plant.

So, in this case we are so again going to draw the TS diagram for the cycle. This is T, this is S 1 to 2 dash, then 2, then 3, then 4 dash, and then 4. So, this is how our cycle is going. Now, what is given to us, we are given with T 1 7 degree Celsius which is 7 plus 273 Kelvin. We are given with P 1 is equal to 4 bar P 1 is equal to 1 bar, we are given with P 2 is equal to 4 bar, so we are given with r p is equal to 4.

We are told that compressor efficiency which is isentropic efficiency of compressor is 0.82, we have been given that T 3 is equal to 800 plus 273 Kelvin. And then we are given that turbine isentropic efficiencies 0.85, we have calorific value of fuel is 43 mega joule 43.1 mega joule per kg. Here one point we have to remember this mega joule per kg is per kg of fuel. So, we mean here that 1 kg of fuel if it is burnt in air, we get 43.1 mega joule of energy. So, this is not per kg of air ok. So, this point to be remembered.

Then there is loss, loss of heat in the combustion chamber is 15 percent, these are the things which are given to us ok. We are parallely given that gamma for air is air is 1.4, and gamma for gas is 1.3. Here we have to keep1 point in mind. Here in this section, we use gamma for air; in this section, we use gamma for gas; and in this section, we use gamma for gas.

Since air is getting compressed in the compressor. So, we should use compressor with air as working medium, so we have gamma air. But, in the combustion chamber, we are burning the air with the fuel. So, we have gas which is a combustion product. And that gas gamma is 1.33. And then in turbine, we do not have air; it is the gas which is get expanded. So, we have gamma gas to be used in these sections.

So, there is one more thing which we could have used as m dot f plus m dot a here, m dot a plus m dot f here, and only am not a here. But, that m dot f would be negligible in comparison with m dot a, so we used only m dot a everywhere. Having said that we can quickly find out compressor work, where w c is equal to we know that w c dash which is ideal which is c p into T 2 dash minus T 1.

So, we can know T 2 dash, we can know T 2 dash from r p, where T 2 dash upon T 1 is equal to r p raised to gamma minus 1 upon gamma, where r p is given to us, T 1 is known to us, so T 2 dash can be found out. Then we can use compressor efficiency formula which is w c dash upon w. So, this is ideal compressor work divided by actual compressor work using, this formula we can find out w c. Since, we would know w c dash, and we know eta c, which is compressor efficiency. So, first thing is done.

Then we want to find out, what is heat supplied. Heat supplied is simple here q is equal to c p into we are given with c p gas also. We are given with c p gas T 3 minus T 2. So, we know T 2 we know T 2 from the, we could find out rather T 2, here w c can be as also find out as c p into T 2 minus T 1, but in this case we need to find out T 2.

So, for T 2 we used to formula as T 2 dash minus T 1 divided by T 2 minus T 1. So, here T 2 dash would be found out from T 2 dash upon T 1 and r p raised to gamma minus 1 upon gamma. So, r p is known, T 1 is known, gamma for air will be used, then we can find out T 2 dash T 2 dash will be put over here. T 1 is known, compressor efficiency is known, T 2 can be found out. And then that is way we can find out compressor work or otherwise we could have found out in this way from T 2 dash and compressor efficiency.

But, now if we go by this way, we would know, what is T 2? So, T 2 is known, T 3 is given, c p of gas is given here we have to use c p of gas, we can find out q in that is actual heat which is going into the into the gas turbine power plant. Then we can find out turbine work, so for that obviously we will have to use r p. So, r p usage will give us T 4 dash upon T 3 basically we know that T 3 upon T 4 dash is equal to r p raised to gamma minus 1 upon gamma.

We can find out T 4 dash. Then once T 4 dash is found out, we can use turbine efficiency formula which is T 4 minus T 1 divided by T 4 dash minus T 1. So, this T 4 is known, T 1 is known, turbine efficiency is known, we can find out T 4. Once T 4 is known, we can find out turbine work as c p into T 4 minus T 1. And this T 4 is obtained from thermal efficiency, but this c p is c p for gas again this has to be remembered.

So, using this we can find out w net, which is turbine work minus compressible ok. And then we need to find out, what is the thermal efficiency. And this is a little tricky. So, here thermal efficiency of the plant is w net upon Q in. But, for Q in, we have a problem that the Q in what we calculated here this Q is the Q which is actually received. But, Q in is supplied energy, and this is supplied more since there are losses of 15 percent, so this is w net upon Q divided by 0.85 ok.

So, this is like this would increase basically Q by dividing the losses, basically this can be also treated as combustion chamber efficiency. So, Q in is actual received, Q is actually received Q, but Q is practically the chemical energy which was available only eighty four as 85 was received. So, basically 0.85 is equal to Q upon Q in ok. And then that would help us in finding out, what is the thermal efficiency of the cycle.

Now, major objective is to find out air fuel ratio. So, what is air fuel, air fuel ratio is to apply the energy conservation equation in the two three case. So, if we apply energy conservation then mass of fuel is burnt, and then has released calorific value amount of energy, and it here it was used to heat mass of air into mass of fuel ok, mass of air from T 3 minus T 2, but only 0.85 percent was used. So, it is 85 percent was used, so this is like this.

So, here we know calorific value, we know point this efficiency which is combustion chamber efficiency, we know T 3, we know T 2. Then we can divide everywhere by mass of air, and then 0.85 into f which is mass of fuel upon mass of air which is fuel air ratio into calorific value is equal to 1 plus f into T 3 minus T 2. And that is how we can find out fuel air ratio or 1 upon f is air fuel ratio can be found out everything is known to us.

Now, we have our formula of SFC Specific Fuel Consumption, and then we found that it is f divided by w net. So, this f divided by w net, but this w net has to be specific workout thrust power we have seen that if it is a thrust power, then w net will come into picture ok. So, this is specific fuel consumption of the power plant which is basically used for the electricity generation. But, similarly if we would have, the gas turbine based power plant for electricity generation, then this is the thrust power this is f ok.

So, but generally it is having unit of mass of fuel, it is having unit of mass of fuel divided by the thrust power, so it has unit of kg per second divided by kilowatt ok, but it is represented as kg per hour also. So, we have to multiply by 3600 to get kg per hour per kilowatt, so that is how per kg of air ok. So, this is how we have the basically the specific fuel consumption to be found ok.

So, here we end the basically our discussion on some aspects of the cycle. In the next class, we will see about the details of the different power plants which are used for the electricity which are used for the propulsion applications. The discussion which we half continued or which we touched for the propulsive efficiency, those engines aircraft engines will be seen in the detail in the next class.

Thank you.