Introduction to Aerospace Propulsion

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Module No. # 01

Lecture No. # 20

Tutorial

Hello and welcome to lecture number 20 of this lecture series on introduction to aerospace propulsion.

Over the last several lectures, we have been discussing about lot of aspects of thermodynamics, principles of thermodynamics and also the significance of these thermodynamic analysis. We also had several tutorial sessions where we have solved problems from different aspects of thermodynamics.

What we shall do today is to take up a tutorial session on some of the power cycles which we have analyzed during last 2-3 lectures and what we are going to do in today's lecture is to solve problems from some of these cycles which we have analyzed. If you recall, during the last few lectures we were discussing about ideal thermodynamic cycles of those engines like the spark ignition engines and the diesel engines; basically the Otto cycle and the diesel cycle which are basically the thermodynamic cycles - ideal cycles of these engines.

We also discussed about the dual cycle which is a combination or which has some of the processes which are common to both these cycles. We subsequently discussed about two cycles which can have efficiencies which can be as high as that of the Carnot cycle; those are the Stirling and Ericsson cycles.

Then we discussed about a very important cycle which is of importance to aerospace engineers that is the Brayton cycle. Brayton cycle forms the basic thermodynamic cycle for all gas turbine engines.

We have also seen some of the modifications that can be done on Brayton cycles to improve their efficiencies. Then, later on, we also discussed in very brief about the basic thermodynamic cycle of steam engines - that is the Rankine cycle.

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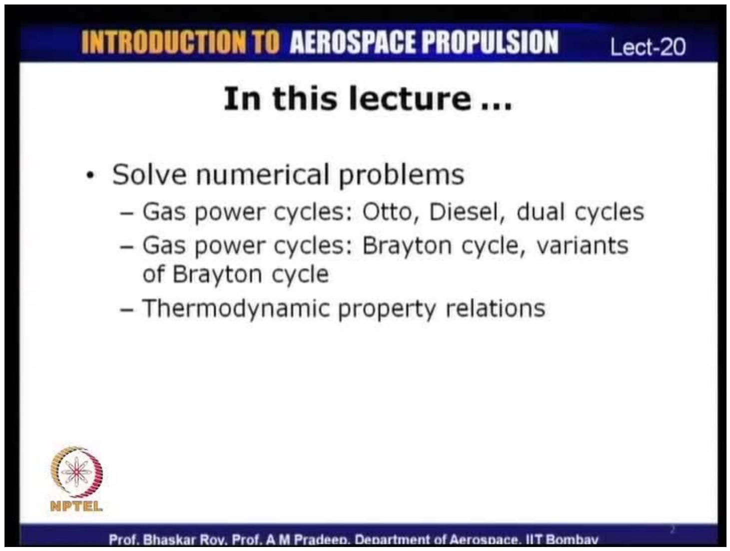

So, what we shall do today is to solve problems - numerical problems - from some of these topics. We shall begin with numerical problems on Otto and diesel cycles and then we shall solve problems from Brayton cycle and some of the variants of the Brayton cycle. We may probably not solve the thermodynamic property relation, but primarily we shall be solving problems from the gas power cycles that is the Otto diesel cycles and the Brayton cycle and the variants of the Brayton cycle.

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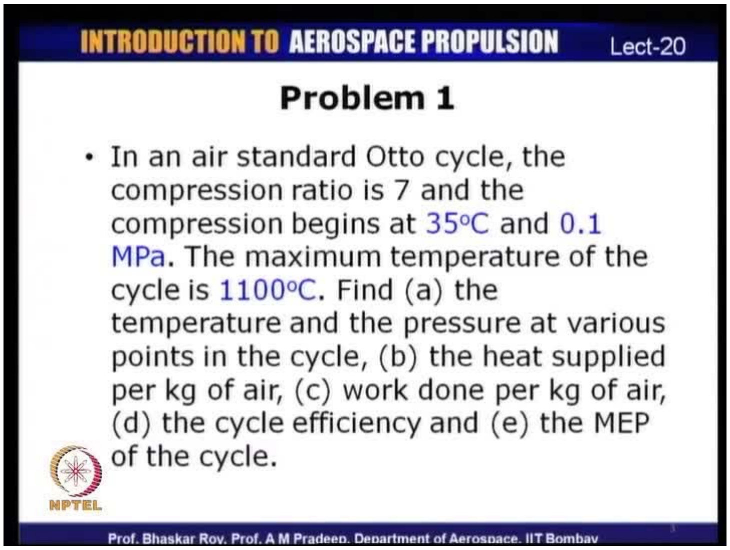

Let us take a look at the first problem that we have for today. Problem statement 1 is that of an Otto cycle. The problem statement is that in an air standard Otto cycle, the compression ratio is 7 and the compression begins at 35 degree celsius and a pressure of 0.1 megapascal. The maximum temperature of the cycle is 1100 degree Celsius. Find: part a - the temperature and pressure at various points in the cycle; part b is heat supplied per kilogram of air; part c is work done per kilogram of air; part d is cycle efficiency and part e is the mean effective pressure that is MEP of the cycle.

This particular problem is that of an Otto cycle. We have already discussed about Otto cycle. We have also derived expressions for calculating the cycle efficiency based on the compression ratio.

In this problem, we have been specified some of the temperatures and pressures. We are also given the compression ratio. We are required to find the efficiencies, temperatures and pressures at different points in the cycle and the work done per kilogram, mean effective pressure, etcetera. It is important that when we start analysis, the first thing that we need to do is to draw the cycle diagram for such a problem. This is an Otto cycle problem. You could either draw the cycle on APV diagram or TS diagram as per your convenience.

Then mark those points for which data is available and the heat input and heat output from the cycle and so on because once the cycle diagram is there, it makes problem solving a lot simpler and the chances of making errors in calculation is minimized, if you were to draw a constructor cycle diagram for this process.

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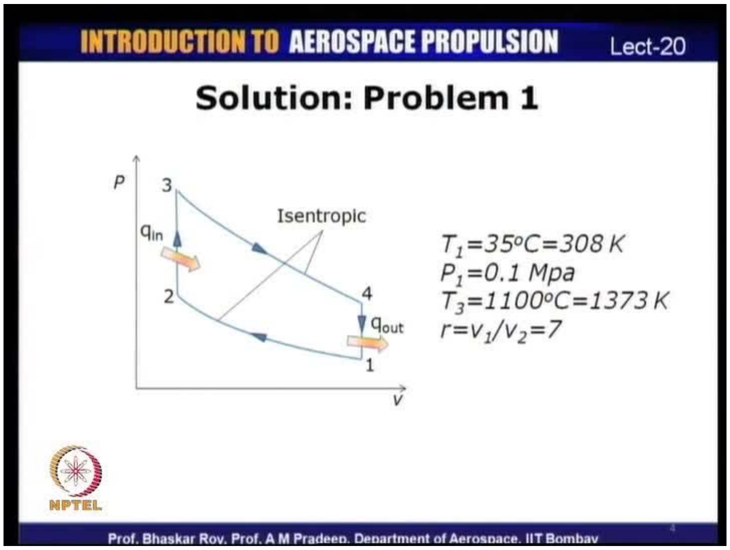

Let us take a look at this cycle diagram for this process. I have in this problem used APV diagram in some of the later problems I have been I would be using TS diagram as well, but it is entirely up to you to draw either PV or TS or both these diagrams.

In the PV diagram, an Otto cycle process looks something like this. The process begins with an isentropic compression that is process 1-2 isentropic compression and after the process reaches state 2 then there is heat addition at constant volume. So, heat addition q in takes place at constant volume. At state 3, there is a an isentropic expansion which takes the process to state 4 and at 4, there is a constant volume heat rejection that is q out takes place at state 4.

These are the four different processes that constitute an Otto cycle. As I have indicated here, two of these processes are isentropic. We have been specified these temperatures and pressures. We have T 1 that is temperature at the beginning of the compression process is 35 degree celsius which corresponds to 308 kelvin, pressure at 0.1 is 0.1 megapascal, temperature at 0.3 that is maximum temperature in the cycle that is T 3 is 1100 degree celsius which is 1373 kelvin, compression ratio is given as 7 that is ratio v 1 by v 2 or v 4 by v 3 that is given as 7.

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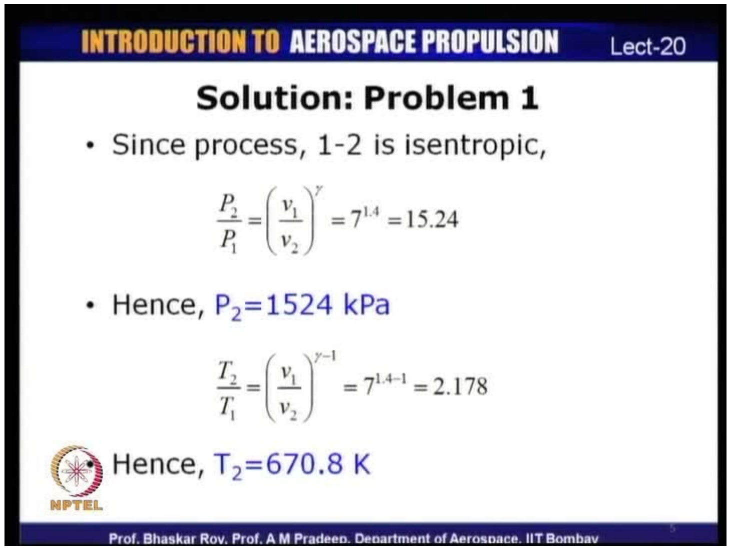

These are the data that have been specified in this problem and based on this data we are required to find several aspects of this particular cycle. Now, we know that process 1-2 is isentropic; compression is taking place isentropically. Therefore, for any isentropic process we already know that P v raise to gamma is a constant and therefore, we have P 2 by P 1 is equal to v 1 by v 2 raise to gamma. Compression ratio that is v 1 by v 2 has been specified it is given as 7 and therefore, we can calculate this ratio P 2 by P 1 from the compression ratio. Therefore, it is 7 raise to 1.4 which is 15.24.

Since P 1 is already given as 0.1 megapascal, P 2 is equal to 0.1 into 10 raise to 3 multiplied by 15.24 and therefore, you get P 2 is equal to 1524 kilopascals.

(Refer Slide Time: 07:48) Now, we have solved for this particular point where we have determined the pressure from the isentropic relation. Once you know the pressure at this point, you can also find the temperature at station 2 from the compression ratio. Again using the isentropic relation, we have T 2 by T 1 is equal to v 1 by v 2 raise to gamma minus 1 and here I missed to mention that gamma which has been used here is the ratio of the specific heats.

In most of these ideal cycle analysis, we will be assuming that the air is the primary medium or working medium and for air the ratio of specific heats that is gamma is equal to 1.4. So, we will be assuming gamma as 1.4 in this as well as the remainder problems.

So, T 2 by T 1 is equal to v 1 by v 2 raise to gamma minus 1. Therefore, this is equal to 7 raise to 1.4 minus 1 which is 2.178. Therefore, you can calculate T 2 because T 1 is already specified as 303 kelvin and so T 2 is equal to 670.8 kelvin. We have now found out the properties at state 2 from the isentropic relations because process 1-2 is isentropic and so you can apply isentropic expressions to determine the properties at state 2.

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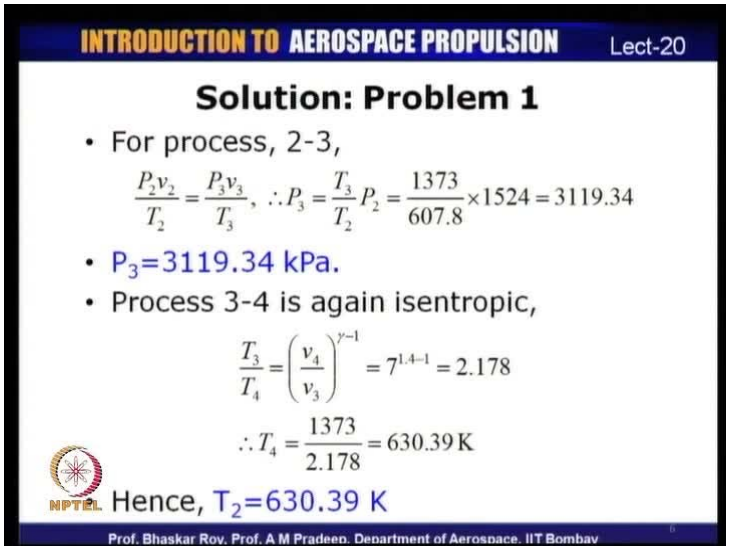

Similarly, we shall be determining the properties of the cycle at state 3 and state 4 and in the process we will also find the work done per kilogram efficiency and mean effective pressure. After solving for state 2, let us move on to process 2-3; process 2-3 as we know it is a constant volume process. If we apply the ideal gas equation which is P v by T is equal to r then applying this ideal gas equation for state 2 and state 3, we get P 2 v 2 by T 2 is equal to P 3 v 3 by T 3.

Since it is a constant volume process, v 2 is equal to v 3; therefore, P 2 by T 2 is equal to P 2 by T 3 and therefore, P 3 is equal to T 3 by T 2 into P 2. All these parameters are already specified we know temperature at state 3 which is 1373 temperature, at state 2 we have just calculated as 607.8 and the pressure at state 2 which was 1524 kilopascals. Therefore, we can calculate P 2 from this and we can determine P 3 as 3119.34 kilopascals.

Now, this process once Now, we know the pressure and temperature at state 3 because temperature is already been specified as 1373 kelvin at state 3. We have determined pressure at state 3. For process 3-4, that is a process which is again isentropic and the compression ratio remains the same for this process also which is v 4 by v 3 which is 7.

So, using isentropic expressions, we determine T 3 by T 4 is equal to v 4 by v 3 raise to gamma minus 1 and which is equal to 7 raise to 1.4 minus 1 which is 2.178. Therefore, T 4 is equal to 1373 by 2.178 that is 630.39 kelvin. Therefore, temperature at state 4 is equal to 630.39.

What we have done now is to calculate the pressures and temperatures at the salient points of the cycle like at state 1, state 2, 3 and 4. State 1 of course, was specified; we have now determined the temperature and pressure at state 2, 3 and 4. Some of them were already specified like for example, temperature at state 3 was specified.

Now, after we have determined the pressures and temperatures at all these points, we can now determine the work done and other parameters that are required to be found for this particular problem.

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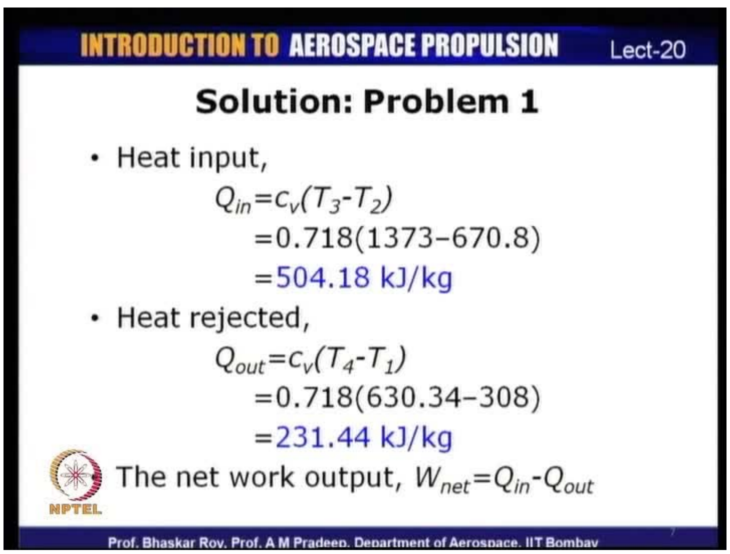

We know that heat input for an Otto cycle is during the constant volume process - that is during process 2-3. Therefore, heat input is equal to C v into T 3 minus T 2 and C v is specific heat at constant volume. For air, we have already assumed that air is the working medium because it is an air standard cycle. For air, specific heat at constant volume is taken usually taken as 0.718 kilojoules per kilogram kelvin. Similarly, we will see later on that specific heat at constant pressure is taken as 1.005 kilojoules per kilogram kelvin.

Therefore, the ratio specific heat C p by C v, if you calculate you would get this as equal to 1.4. Heat input takes place during the constant volume process 2-3 and therefore, heat input as we know, it is C v times T 3 minus T 2. C v is something we have assumed for air as 0.718 multiplied by T 3 minus T 2, T 3 has already been specified in the problem as 1373 kelvin and T 2 we have calculated from the isentropic expressions.

If you substitute for T 3, T 2 and C v, we get heat input as C v times T 3 minus T 2 that is 0.718 into 1373 minus 670.8, that is 504.18 kilojoules per kilogram. So, this was the heat input to the cycle.

Similarly, we can also find heat rejected from the cycle because heat rejection in an Otto cycle is also during the constant volume process for 1. Q out is again equal to C v times T 4 minus T 1 which is 0.718 into 630.34 minus 308. Therefore, you get Q out that is heat rejected as 231.14 kilojoules per kilogram.

So, we have now calculated heat input and heat output from the cycle. For a cyclic process, we know that net work done should be equal to net heat transfer in the cycle. W net is equal to the difference between heat input and heat output and therefore, W net will be equal to Q in minus Q out. We have already determined Q in and Q out and therefore, difference between the two will gives us the work done by the cycle.

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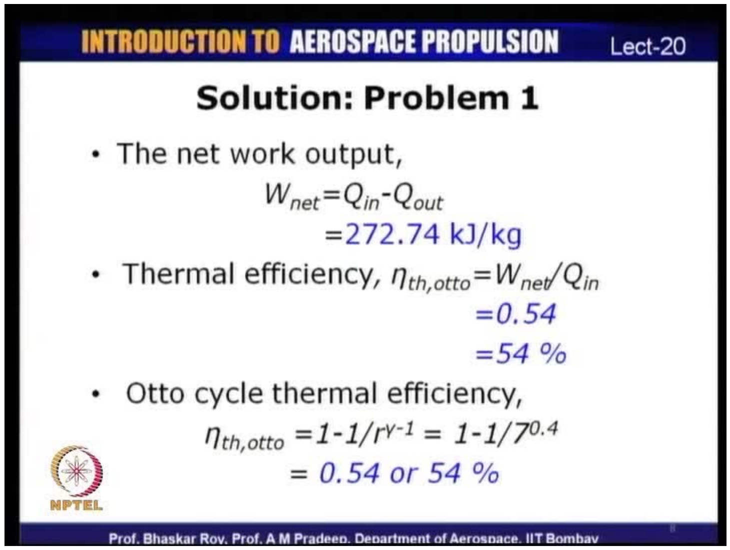

Net work output for the cycle is W net is equal to Q in minus Q out. Q in was calculated previously as 504.18 and Q out as 231.44. Therefore, W net is equal to 272.74 kilojoules per kilogram.

Now, we have calculated W net and we also know Q in. Thermal efficiency should be by definition is equal to net work output by heat input. Thermal efficiency would be equal to W net by Q in that is 272.74 divided by Q in which is 504.18. Therefore, thermal efficiency is 0.54 or 54 percent.

Now, it is also possible for us to calculate the Otto cycle thermal efficiency from the compression ratio and the ratio of specific heat. Compression ratio has already been specified as 7. We have already derived an expression for the Otto cycle efficiency in terms of the compression and ratio of specific heats. Otto cycle efficiency is 1 minus 1 by r raise to gamma minus 1, where r is the compression ratio.

Since compression ratio is already known as 7, if you substitute for that and gamma and calculate, we get the Otto cycle efficiency as 0.54 which is what we have already calculated in terms of W net and Q in.

So, there are two different ways of calculating efficiency in such problems. you could either If the volume compression ratio is known, you could use that for calculating the cycle efficiency or if you were to calculate the net work output and heat input, that is another way of calculating efficiency and both these efficiencies will obviously turn out to be the same.

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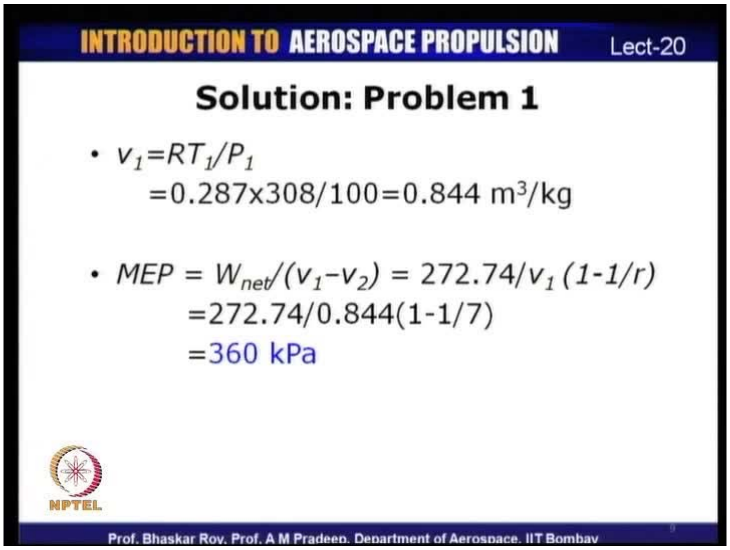

We have now calculated the cycle efficiency, work done and so on. What remains to be calculated is the mean effective pressure; mean effective pressure as we have defined earlier is W net by the ratio or difference in the volume - displacement volume. That is W net by v 1 minus v 2. If we know either v 1 or v 2, we can solve this equation because compression ratio v 1 by v 2 is already given and W net has already been calculated.

We can calculate v 1 from this state equation. v 1 is equal to R T 1 by P 1, where R is the gas constant for air which will be equal to the universal gas constant divided by the average molecular weight for air and universal gas constant as we know it is 8314 joules per kilogram kelvin and average molecular weight is usually taken as 29. If we were to do that, the gas constant for air comes out to be 0.287 kilojoules per kilogram kelvin.

If you substitute for gas constant, the temperature and pressure, we can calculate the specific volume at state 1. Once we calculate that, we can actually calculate the mean effective pressure because we know the compression ratio and therefore, we can express v 2 in terms of v 1.

Let us substitute for these values here. Mean effective pressure will be equal to W net by v 1 minus v 2 which is 272.74 divided by v 1 into 1 minus 1 by r and because v 1 by v 2 is equal to r. This is 272.74 divided by 0.844 which is the specific volume at state 1 into 1 minus 1 by 7. So, mean effective pressure comes out to be 360 kilopascals.

In this particular problem that we have solved for an Otto cycle, we were given pressures and temperatures at some of the points in the cycle and we were required to calculate the pressures and temperatures at other salient points of the cycle and then the heat input, heat output, net work done by the cycle and the efficiencies. The way we have solved it is that for isentropic processes, we have used the isentropic relations to determine the properties at the end of the state like for example, process 1-2 was isentropic and process 3-4 is also isentropic and the second process, that is process 2-3, is a constant volume process were in we can calculate heat input as C v into the temperature difference. Similarly, the heat rejection is also a constant volume process were we calculate heat rejected as C v times the temperature difference. Difference between the heat input and heat output gives the net work output and the ratio of net work output by heat input is the cycle efficiency and to determine mean effective pressure, we divide net work output by the displacement volume that is v 1 minus v 2. Now that we have solved this problem for an Otto cycle, let us take a look at the second problem which will be for a diesel cycle.

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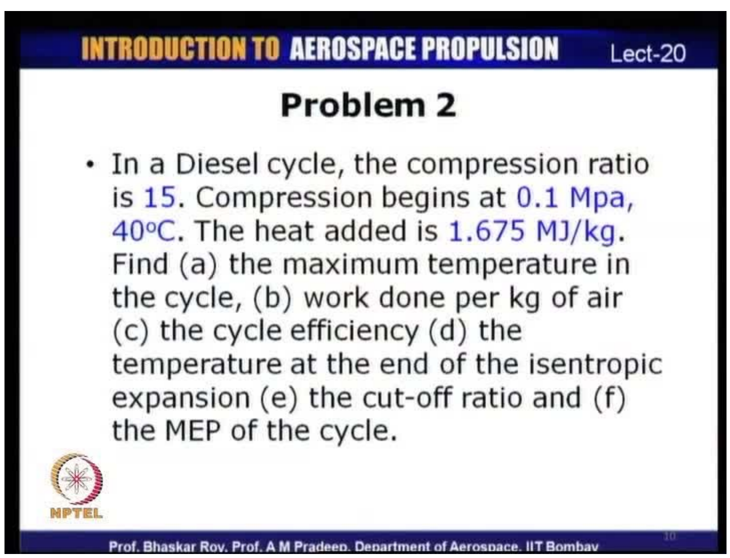

The problem statement for the second problem is that in a diesel cycle, the compression ratio is 15 and the compression begins at 0.1 megapascal and 40 degree celsius. The heat added is given as 1675 mega joules per kilogram.

Based on this data find: part a - maximum temperature in the cycle; part b - work done per kilogram of air; part c - the cycle efficiency; part d - the temperature at the end of the isentropic expansion; part e - the cut-off ratio; part f - the mean effective pressure of the cycle.

In this problem for diesel cycle, as we have seen in the previous case we have pressures and temperatures at some point and the compression ratio and the heat added given here. the compression begins at That is temperature and pressure at state 1 is specified and given as 0.1 megapascal and 40 degree celsius. Compression ratio is given as 15 and heat added is given as 1.675 mega joules per kilogram.

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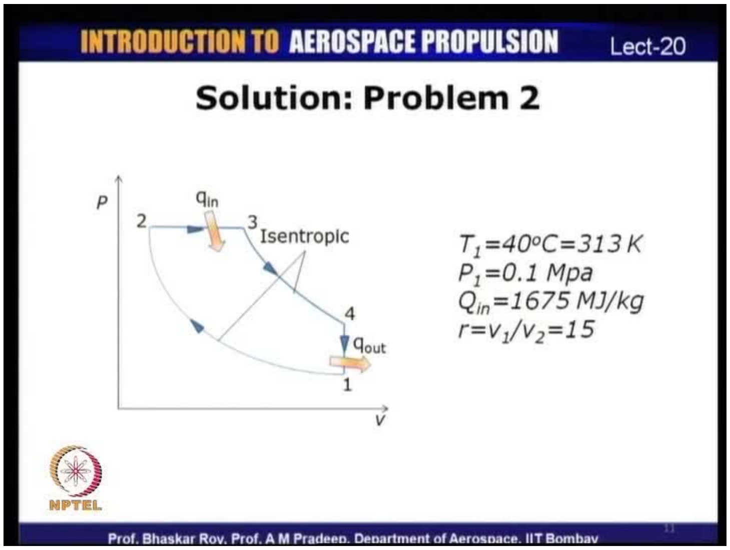

As we have done for the previous problem, the first thing that we should be doing is to sketch the P V diagram for this problem for a diesel cycle and also note the points at which data has been already provided. P V diagram of a diesel cycle has been plotted here and as we had discussed during our lecture on Otto and diesel cycles, the only difference between an Otto and diesel cycle is in the heat addition process. In an Otto cycle, heat addition is at constant volume and in a diesel cycle, heat addition takes place at constant pressure.

The process begins at state 1 and there is an isentropic compression which takes it to state 2. From state 2 to state 3, it is a constant pressure process during which heat is added into the cycle. q in take place at between state 2 and state 3. Process 3 to 4 is isentropic expansion and process 4 to 1 is the heat rejection process, which is at constant volume.

Data specified in this problem are T 1 that is temperature at state 1 is 40 degree celsius that is 313 kelvin, P 1 is 0.1 megapascal; Q in that is heat input is 1675 mega joules per kilogram and the compression ratio that is v 1 by v 2 is given as 15. So, compression ratio for this diesel cycle is given as 15.

This is the data that has been specified for this problem and we are required to calculate host of parameters and work done, heat input, efficiency and mean effective pressures and so on.

So, like we have solved previous problem we would need to determine the pressures and temperatures at the different points of the diesel cycle by using the isentropic expressions or for example, the second process is a constant pressure process and so we know heat input is C v times the temperature difference and so on. Let us start solving the problem from state 1 state 2 and we have already been given the heat input for this particular problem.

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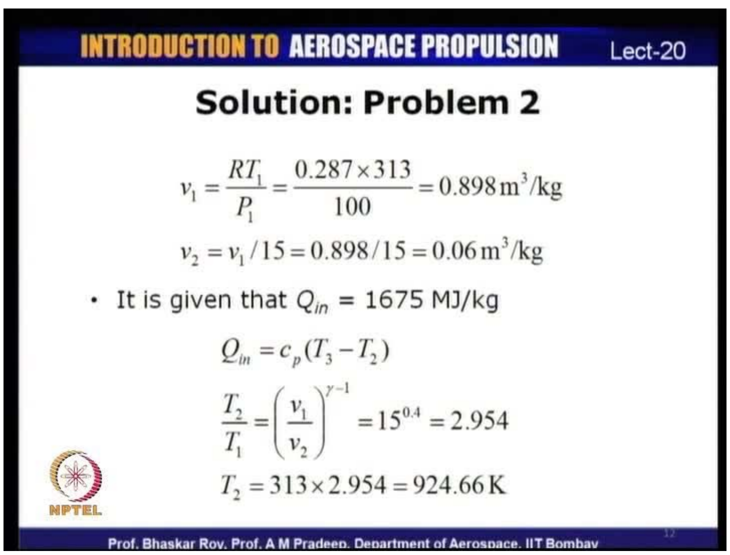

If you look at state 1, we know the pressure and temperature and therefore, we can calculate the specific volume at state 1 using the state equation. v 1 is equal to R T 1 by P

1 which is 0.287 which is the gas constant for air into 313 which is temperature divided by P 1 that is 100 kilopascals. This comes out to be 0.898 meter cube per kilogram.

Since the compression ratio is given as 15, volume at state 2 that is v 2 is equal to v 1 by 15 that is 0.898 by 15 which is equal 0.06 meter cube per kilogram. We have been given Q in that is heat input as 1675 mega joules per kilogram. Q in is equal to c p times T 3 minus T 2 because the heat addition takes place at constant pressure. Therefore, we use the specific heat for constant pressure for air for this particular process and Q in is equal to c p into T 3 minus T 2.

We need to find out the temperature at state 2 from an isentropic relation because process 1-2 is isentropic and so, we can apply isentropic relations for process 1-2.

So, T 2 by T 1 is equal to v 1 by v 2 raise to gamma minus 1. This is true for an isentropic process and in this diesel cycle, the process 1-2 is isentropic. Since T 2 by T 1 is equal to v 1 by v 2 raise to gamma minus 1 which is equal to 15 raise to 0.4 that is 1.4 minus 1. So, temperature ratio comes out be 2.954.

(Refer Slide Time: 26:34) T 2 is equal to T 1 into 2.954. T 2 is equal to therefore, 313 into this and that is 924.66 kelvin. So, temperature at state 2 is 924.66 kelvin.

Now, heat input has already been specified as 1675 mega joules. We know c p for air as 1.005 kilo joules per kilogram kelvin. We have now calculated temperature at state 2. Therefore, we should be able to calculate temperature at state 3 from this equation which is Q in is equal to c p into T 3 minus T 2.

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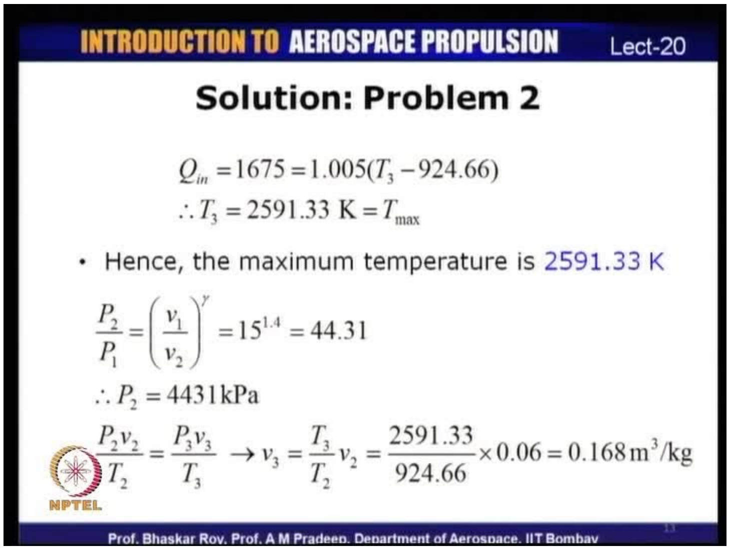

If you substitute for all these values, we get 1675 is equal to 1.005 into T 3 minus 924.66 which is temperature at state 2. Therefore, T 3 is equal to 2591.33 kelvin which is the maximum temperature in the cycle. (Refer Slide Time: 27:41) If you take a look at the diesel cycle, maximum temperature occurs at state 3 and therefore, we have calculated the maximum temperature based on the heat input relation.

Let us calculate the pressure at state 2. We have already calculated temperature at state 2. We can also calculate pressure at state 2 because we need to basically calculate pressures and temperatures at all the points to be able to solve this problem in terms of net work input and so on.

For process 1-2 as it is isentropic, we have P 2 by P 1 is equal to v 1 by v 2 raise to gamma which is 15 raise to 1.4 and therefore, P 2 is equal to 44.31 into 0.01 megapascal and therefore, we get P 2 equal to 4431 kilopascals. So, pressure at state 2 is 4431 kilopascals.

Now, for process 2-3, we apply the state equation that is P v by T is equal to constant and therefore, P 2 v 2 by T 2 is equal to P 3 v 3 by T 3 and for process 2-3, the pressure is a constant - it is a constant pressure heat addition process. Therefore, P 2 is equal to P 3 and hence v 3 that is specific volume at state 3 is equal to T 3 by T 2 into v 2. We know T 3 which has already been calculated, T 2 has already been calculated and v 2 is also known. Therefore, we can calculate v 3 as equal to 2591.33 divided by 924.66 into 0.06. So, specific volume at state 3 is equal to 0.168 meter cube per kilogram.

We have now solved the properties or we have determined properties at state 2 and also at state 3. One of the parts of the question was to find the cutoff ratio and cutoff ratio as we know is the ratio of specific volume at state 3 to state 2. v 3 by v 2 is the cutoff volume. We have just now calculated v 3; v 2 has already been calculated. So, we can calculate the cutoff ratio and similarly, we can also determine the heat rejected from the cycle and net work output and the efficiency.

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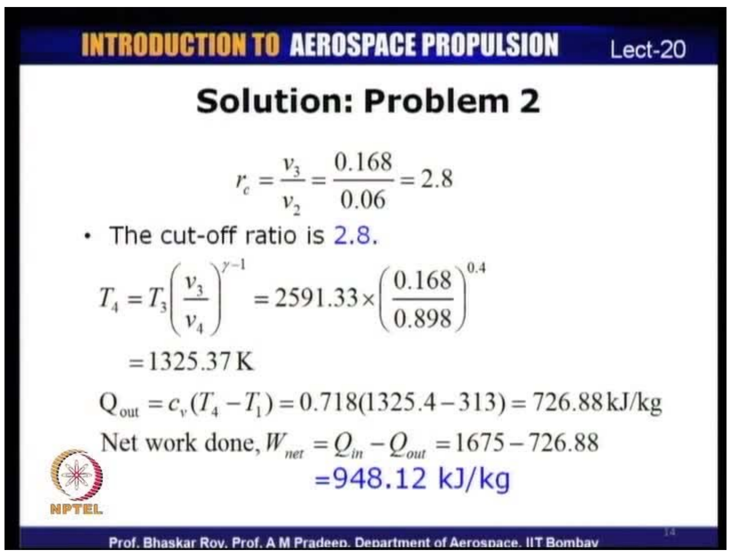

The cutoff ratio is r c which is equal to v 3 by v 2 which is 0.168 divided by 0.06, that is 2.8. The cutoff ratio is therefore, 2.8

To calculate temperature at state 4, process 3-4 is also isentropic. Therefore, T 4 is equal to T 3 into v 3 by v 4 raise to gamma minus 1 which is equal to 2591.33 which is temperature at state 3 multiplied by v 3 by v 4, that is 0.168 by 0.898 raise to 0.4, that is gamma minus 1. So, temperature at state 4 is 1325.37 kelvin.

Once you find temperature at state 4, we can now find the Q out from the cycle that is heat rejected from the cycle. In a diesel cycle, heat is rejected at constant volume and therefore, Q out is equal to c v into T 4 minus T 1 that is equal to 0.718 multiplied by 1325.4 minus 313. Heat rejected comes out to be 726.88 kilojoules per kilogram. Since we know heat input as well as heat output, net work done will be equal to the difference between the heat input and the heat output. W net will be equal to Q in minus Q out and so that is calculated as Q in minus Q out as 1675 which is Q in minus 726.88. W net is equal to 948.12 kilojoules pressure kilogram.

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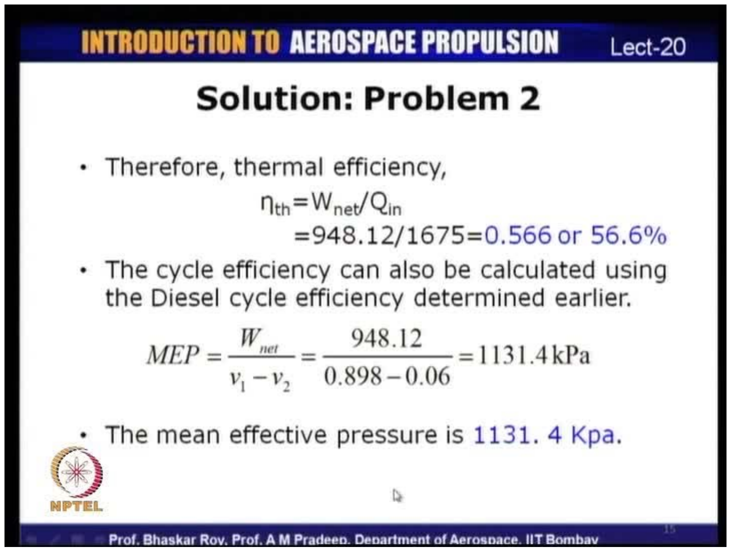

Having calculated the net work output, we can calculate the thermal efficiency. Thermal efficiency will be equal to W net by Q in that is 948.12 divided by 1675 which will be equal to 0.566 or 56.6 percent. This is the cycle efficiency as calculated from the net work output and heat input.

We can also calculate the cycle efficiency using the efficiency equation we had derived when discussing about the diesel cycle which was in terms of the compression ratio and the cutoff ratio. We already have calculated the cutoff ratio and the compression ratio and so, we can determine the cycle efficiency using that formulae as well and you should be getting the same efficiency even if you calculate it by the other formulae. Either you use the net work output and heat input or from the diesel cycle efficiency formulae, the efficiency would come out obviously to be the same.

The last thing that we need to calculate in this problem is the mean effective pressure. Mean effective pressure as we know it is W net by v 1 minus v 2. v 1 and v 2 have already been calculated, W net is known and therefore, the mean effective pressure is simply the ratio of the net work output to the displacement volume.

So, MEP that is mean effective pressure is W net by v 1 minus v 2 which is 948.12 divided by 0.898 minus 0.06. This is equal to 1131.4 kilopascals. So, the mean effective pressure is equal to 1131.4 kilopascals.

We have now solved all the aspects of this particular problem which was for a diesel cycle were in we were required to calculate the different temperatures and pressures at various salient points in the cycle using the corresponding process properties like for an isentropic process, we use the isentropic relations for calculating pressures and temperatures. Subsequent to calculating pressures and temperatures and specific volumes, we can calculate the heat input and heat rejected and therefore, net work done which is difference of heat input and heat output and from the net work output we also calculate the efficiency which is W net by Q in. Once we calculate efficiency, we also can calculate mean effective pressure which is W net by the displacement volume.

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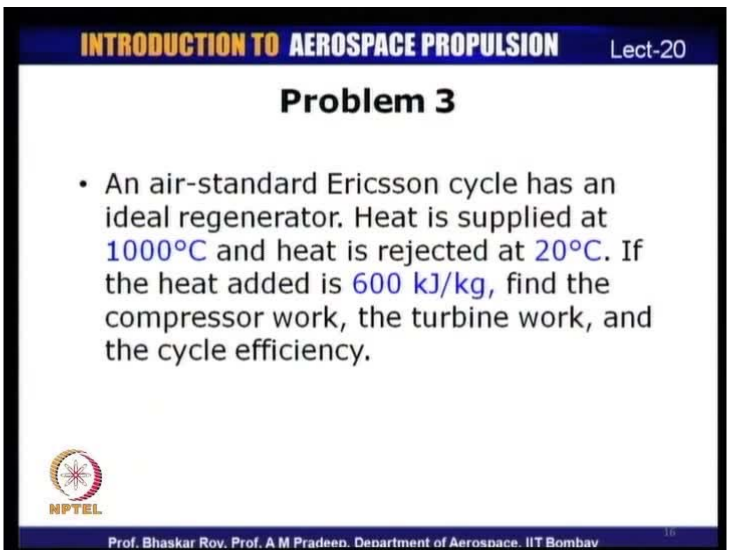

So, this was the second problem which was on a diesel cycle. The first problem we solved was an ideal Otto cycle and second problem was on a diesel cycle. Let us take a look at the third problem and third problem is on an Ericsson cycle.

So, problem definition for the one third problem is an air-standard Ericsson cycle has an ideal regenerator heat is supplied at 1000 degree celsius and heat is rejected at 20 degree celsius. If the heat added is 600 kilo joules per kilogram, find the compressor work, the turbine work and the cycle efficiency. So, in an Ericsson cycle for this particular problem we have the temperatures of at which heat is added and heat is rejected and also the amount of heat that is added in this particular cycle.

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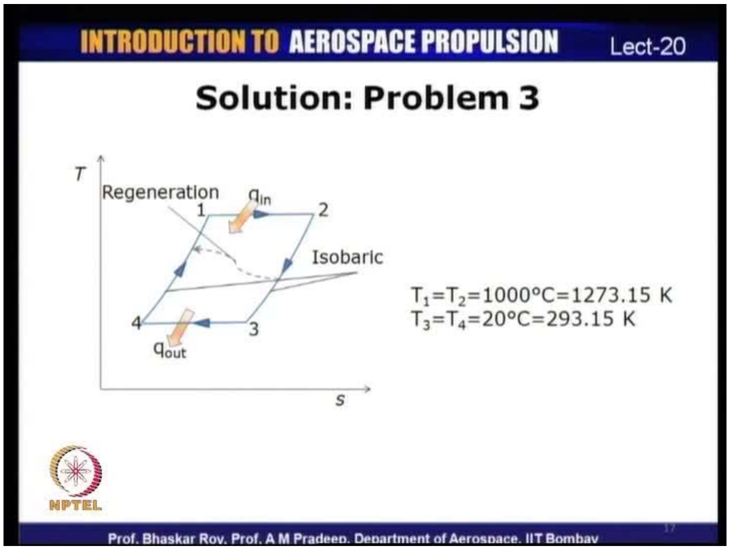

We have already discussed about the PV and TS diagrams for Ericsson as well as for Stirling cycles earlier on. What I have used here is a TS diagram for this Ericsson cycle and an Ericsson cycle is characterized by isothermal heat addition and isothermal heat rejection and constant volume regeneration processes.

The cycle begins at state 1; there is heat addition at constant temperature that is isothermal heat addition and if you were to implement Ericsson cycle using compressors and turbines and a boiler then the first process that is heat addition takes place through the compressor.

First process is isothermal compression which is basically through the compressor; heat input during the compression process. The second process is constant volume regeneration, that is process 2-3 is a regeneration process in which heat is transferred to energy storage system and then during the fourth process, the energy which has been stored is recovered from the thermal storage.

Process 2-3 is a constant volume regeneration process. The third process is an isothermal heat rejection process which is basically an expansion process -isothermal expansion which is also the process during which heat is rejected and the last process is again a constant volume regeneration process during which energy which was stored during the second process is transferred back to the system.

Now, as we have seen if a cycle has to have efficiencies approaching Carnot cycle efficiency, it should have no irreversibilities within the system as well as from outside the system - that is it should be both internally and externally reversible. If that were to happen, all cycles should have heat rejection as well as heat addition taking place at constant temperature - that is isothermal heat addition and isothermal heat rejection can cause efficiencies to be equal to the Carnot efficiencies which is why in a Stirling and Ericsson cycles we have temperatures or heat addition and heat rejection taking place at constant temperature. So, in this Ericsson cycle we have heat addition taking place during the isothermal compression and heat rejection taking place during the isothermal expansion.

Now, in this problem for the Ericsson cycle, we have temperature of heat addition which is T 1 is equal to T 2 because it is isothermal. Heat addition taking place at constant temperature which is 1000 degree celsius and that is 1273.15 kelvin and heat rejection takes place at constant temperature again. Therefore, T 3 is equal to T 4 which is 20 degree Celsius and that is 293.15 kelvin.

These are the temperatures specified, heat input is also given, temperature at which heat is added, temperature at which heat is rejected and the heat added that is during cycle process 1-2. These are the parameters given. We need to find the compressor work, the turbine work and the efficiency of the cycle.

In this Ericsson cycle, we know that the regenerator has been defined as being ideal and therefore, for this ideal regenerator whatever heat is stored in the thermal storage will be absorbed back during the fourth process that is the constant volume heat regeneration process - that is process 4-1.

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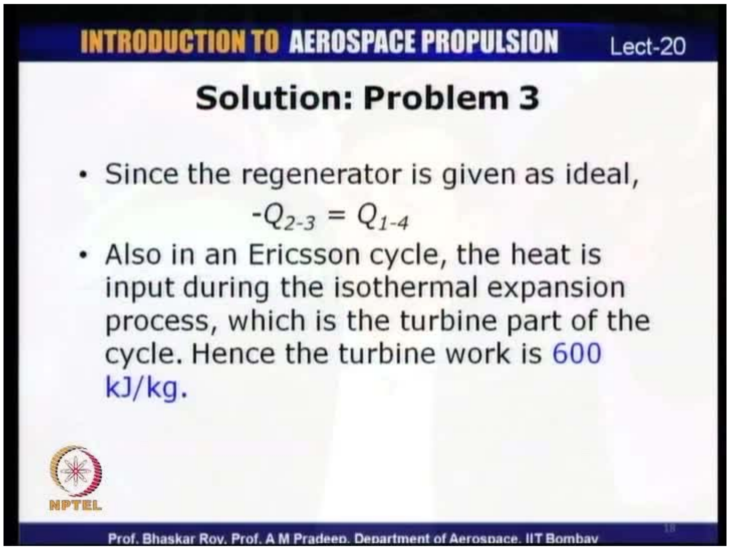

So, because it is an ideal regenerator heat rejected during process 2-3 will be equal to the heat absorbed during process 1-4 that is minus Q 2-3 will be equal to Q 1-4. (Refer Slide Time: 40:26) If you were to look at Ericsson cycle in terms of the PV as well as TS diagrams, we have the Ericsson cycle which starts with an isothermal expansion process and that is the process during which heat is added to the cycle and that is process 1-2. Therefore, process 1-2 is the one during which heat is added that is an isothermal process - an expansion process which is primarily the turbine part of the cycle. Since heat is added during the isothermal expansion process and that happens to be the turbine of this particular cycle in an Ericsson cycle, the heat added during this process that is process 1-2 is basically equal to the turbine work because that is the expansion process of an Ericsson cycle. Since it is already given that heat added during this expansion process, that is Ericsson cycle, is 600 kilo joules per kilogram, the turbine work will also be equal to 600 kilo joules per kilogram because that is the process during which heat is added to the cycle.

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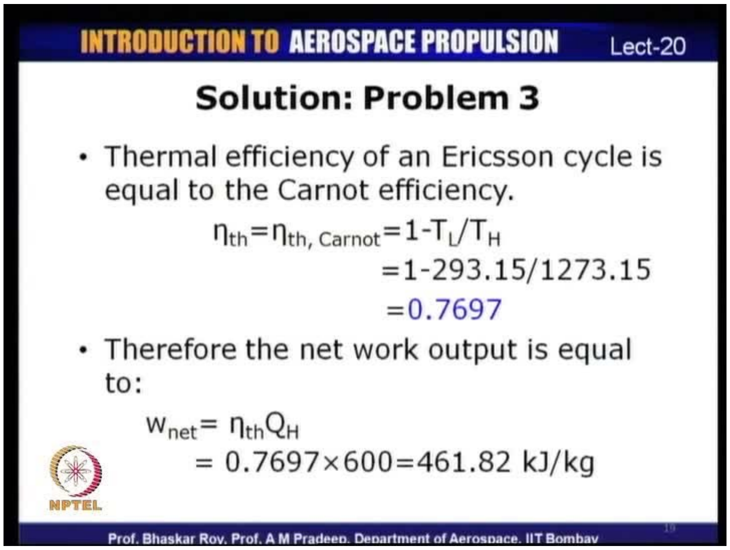

To calculate the thermal efficiency of an Ericsson cycle, we know that thermal efficiency of Ericsson cycle will be equal to the thermal efficiency of a Carnot cycle. Therefore, thermal efficiency is equal to that of Carnot cycle efficiency which is related to the minimum and maximum temperatures of the cycle. That is thermal efficiency is 1 minus T L by T H. Since heat rejection temperature and heat addition temperatures are known, we can calculate the thermal efficiency for an Ericsson cycle which will be equal to the efficiency of a Carnot cycle as well, operating between the same temperature limits.

Once we calculate the thermal efficiency, we can calculate net work output. Net work output will be equal to thermal efficiency times the heat input that is 0.7697 is the thermal efficiency for this Ericsson cycle and that multiplied by Q H, that is the heat input will be the net work output. That can be calculated as 461.82 kilo joules per kilogram. So, net work output is equal to the product of the thermal efficiency and the heat input and that is 0.7697 into 600 that is 461.82 kilo joules per kilogram.

We have calculated the net work output; we know also the turbine work that is basically the isothermal expansion process during which heat is added. Compressor work will be equal to the difference between the turbine work and the net work output. Therefore, compressor work is equal to the turbine work minus the net work output.

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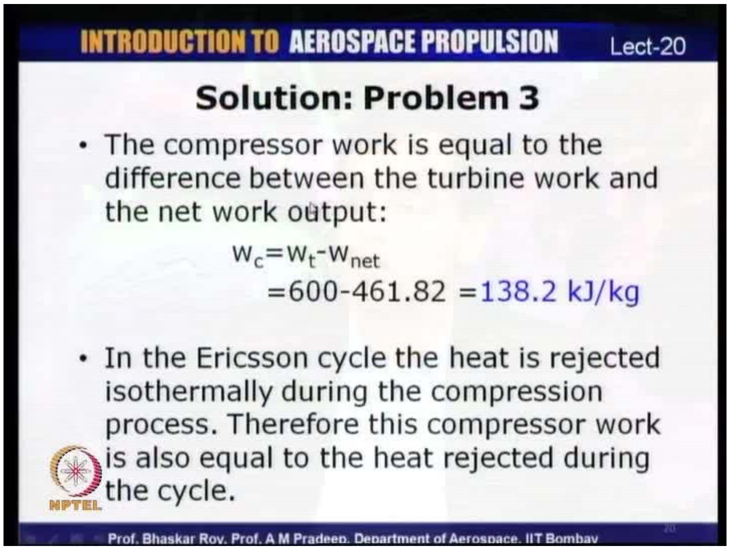

Therefore, w c will be equal to w t minus w net that is 600 minus 461.82 - that is 138.2 kilojoules per kilogram. In an Ericsson cycle, as we have seen heat is rejected isothermally during the compression process and this compressor work that we have calculated, that is 138.2, will also be equal to the heat rejected during the cycle that is during the Ericsson cycle. Heat is added during the expansion process, heat added was equal to turbine work, heat rejection is during the compression process and therefore, this is also equal to the heat rejected during this particular cycle.

We have calculated the turbine work, the compressor work and the efficiency for an Ericsson cycle. Efficiency was basically equal to the Carnot efficiency which is operating between the same temperature limits. The next problem that we shall solve is for a Brayton cycle, an ideal Brayton cycle. The first problem we will solve is for simple Brayton cycle and the same problem we shall be solving for a Brayton cycle with regeneration.

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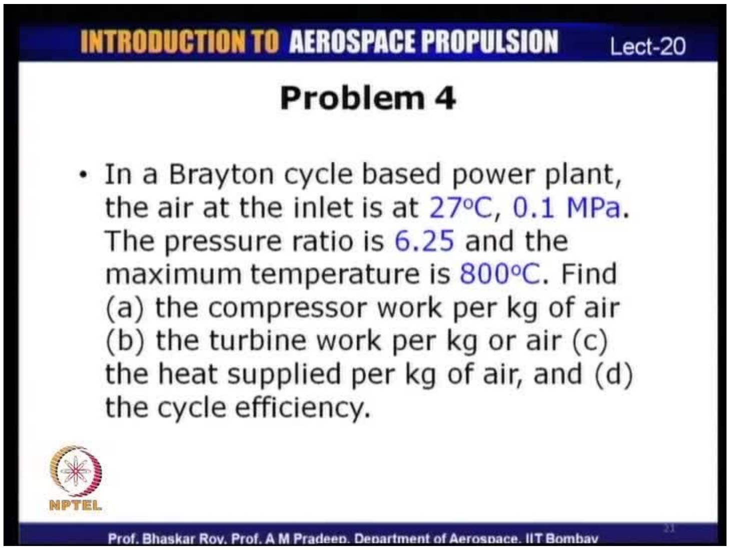

The problem statement for a Brayton cycle case is in a Brayton cycle power plant the air at the inlet is at 27 degree celsius and 0.1 megapascal, the pressure ratio is 6.25 and the maximum temperature is 800 degree Celsius. Find the compressor work per kilogram of air, the turbine work per kilogram of air, the heat supplied and the cycle efficiency.

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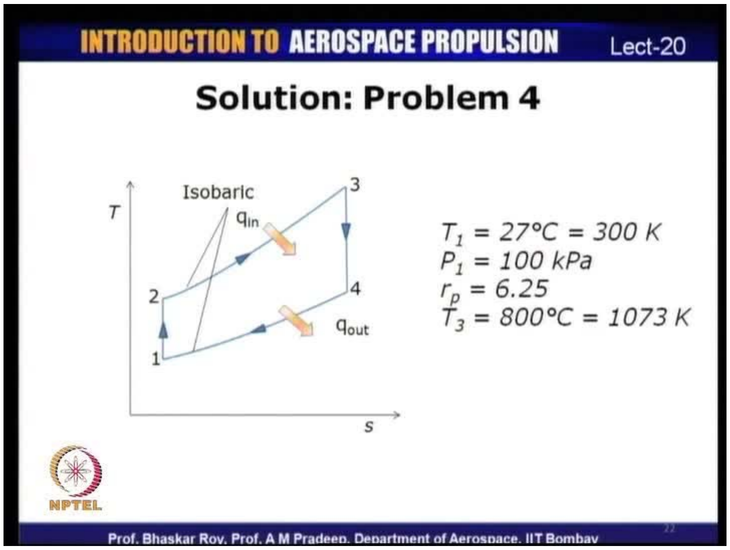

We shall first take a look at the cycle diagram for the Brayton cycle in terms of TS coordinates. This is how a Brayton cycle looks like. Brayton cycle begins at state 1 with isentropic compression process which is between states 1 and 2. So, process 1-2 is isentropic compression. Then there is constant pressure heat addition that is q in at constant pressure during process 2-3, process 3-4 is isentropic expansion and process 4-1 is constant pressure heat rejection. Temperature at state 1 is given as 27 degree celsius which is 300 kelvin, pressure is given as 100 kilopascals, the pressure ratio is given as 6.25 and temperature at state 3 is given as 800 degree celsius which is 1073 kelvin.

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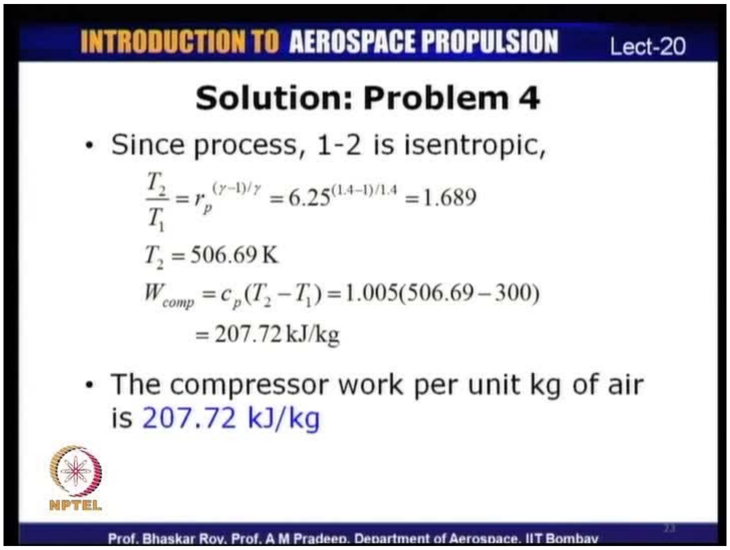

As we have solved for diesel and Otto cycles, since process 1-2 is isentropic, the temperature ratio T 2 by T 1 will be equal to pressure ratio that is P 2 by P 1 raise to gamma minus 1 by gamma, where gamma is the ratio of specific heat for air. Here we will assume the working medium is air and therefore, pressure ratio is given as 6.25. Hence T 2 by T 1 is equal to 6.25 raise to 1.4 minus 1 by 1.4 that is 1.689. Hence T 2 is 506.9 kelvin.

Therefore, the compressor work can now be calculated because we know temperature at state 2 and state 1. and therefore, compressor work for this because Compressor is basically a steady flow unit and we have already calculated this during the discussion on the first law were in we calculated compressor work as the difference in enthalpy which is basically c p into the temperature difference. c p into T 2 minus T 1 which is 1.005 into 506.69 minus 300. Therefore, the compressor work is 207.72 kilojoules per kilogram. So, compressor work per unit kilogram of air is calculated as 207.72 kilojoules per kilogram.

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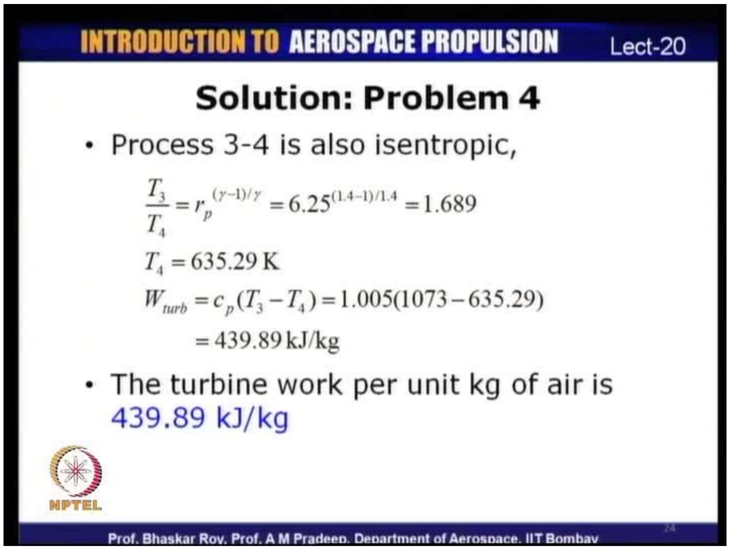

Process 3-4 is also isentropic which means that we can calculate temperature at end of process 3-4 that is at T 4. From the isentropic relation, T 3 by T 4 is equal to P 3 by P 4 raise to gamma minus 1 by gamma. Therefore, temperature at state 4, T 4 is calculated as 635.29 kelvin.

Turbine work is again equal to c p into the temperature difference. That is c p into T 3 minus T 4 which is equal to 1.005 into 1073 minus 635.29.

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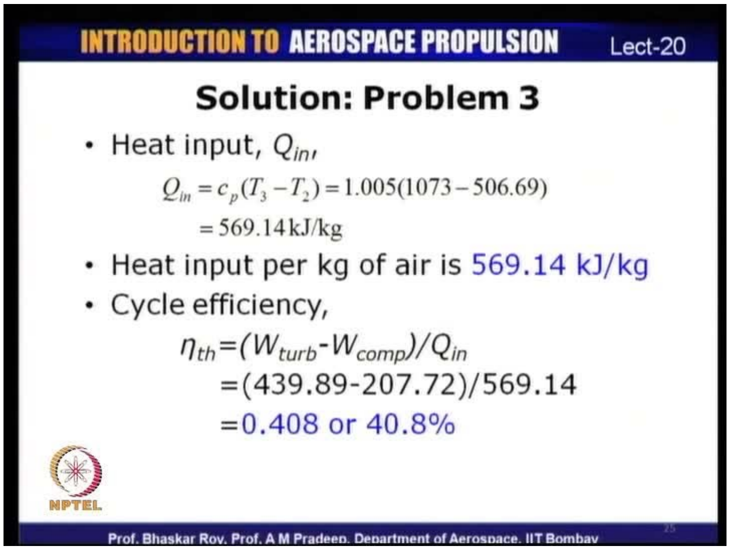

So, the turbine work is 439.89 kilojoules per kilogram and since we have calculated the turbine work and the compressor work, net work output would be difference between the turbine work and the compressor work and heat input is during process 2-3 which is a constant pressure process. Q in is equal to c p into T 3 minus T 2 which is 1.005 into 1073 minus 506.69 that is 569.14 kilojoules per kilogram. Therefore, heat input per kilogram of air is 569.14. Once we have calculated this, the cycle efficiency is net work output by heat input that is turbine work minus compressor work by Q in which is equal to 0.408 that is 40.8 percent.

So, this is the cycle efficiency for this particular Brayton cycle. You can also calculate cycle efficiency for Brayton cycle using the formulae we had derived during the Brayton cycle analysis which we have done few lectures earlier on.

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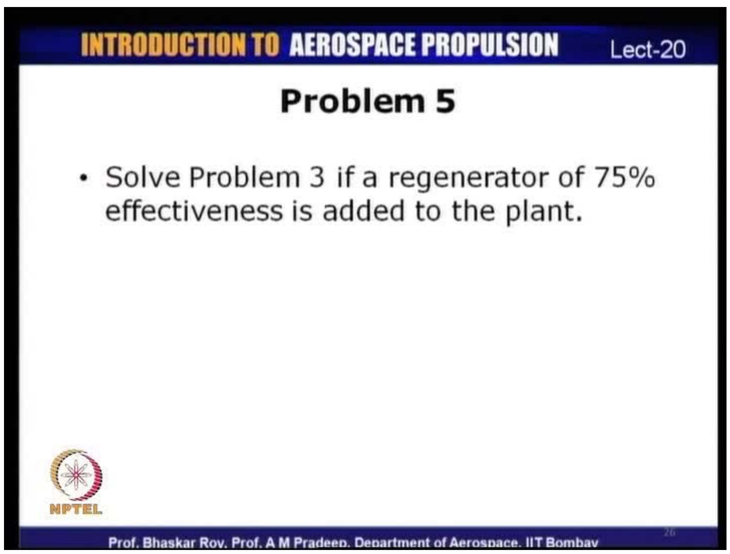

Now, we can solve this particular problem also using the efficiency. So, problem 5 is solve problem 4 if a regenerator of 75 percent effectiveness is added to the plant.

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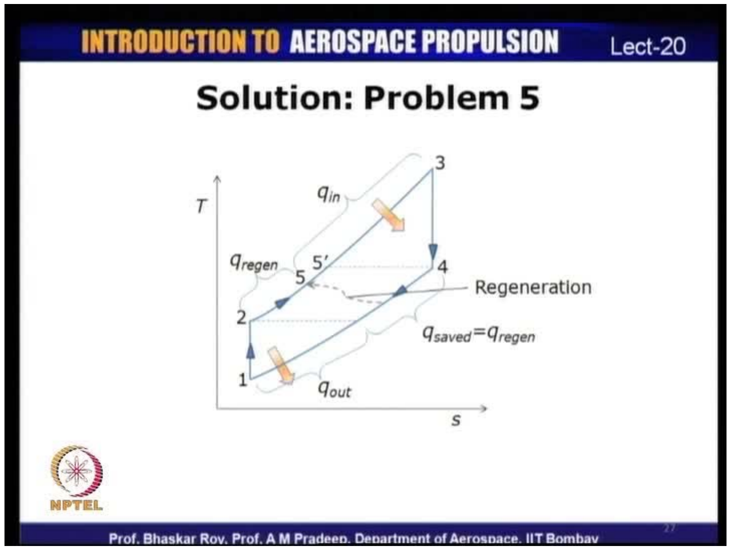

Brayton cycle with regeneration is shown here that is during regeneration process, the amount of energy that needs to be added is this part, which is the regenerated part and the heat input is reduced to this fraction that is T 3 minus T 5 and so q regenerated is basically the q saved.

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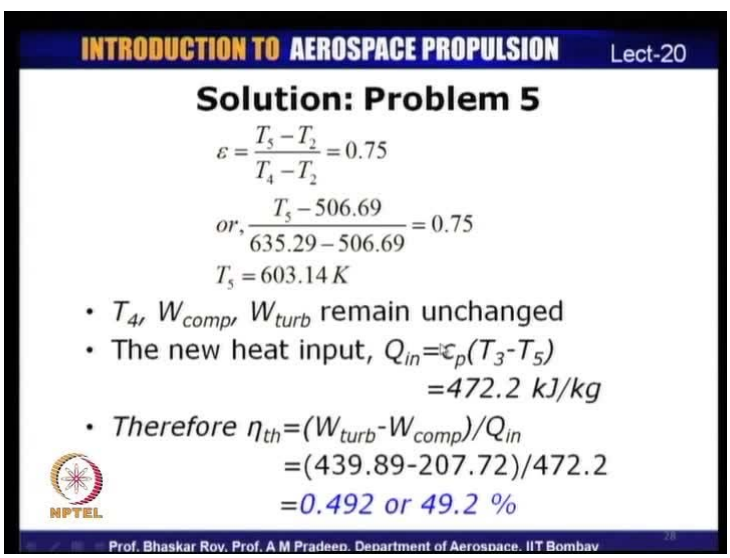

Effectiveness is given as T 5 minus T 2 divided by T 4 minus T 2 which is given as 0.75. All other temperatures are known except T 5. So, we can calculate T 5 from this which comes out to be 603.14 kelvin. T 4 and turbine work, compressor work, etcetera remain unchanged. Only thing that changes is heat input. Heat input is equal to c p into T 3 minus T 5 which is 472.2 kilo joules per kilogram. Based on that, we now calculate the new efficiency. Efficiency, if you calculate substituting new values of Q in, we will get 439.89 which is turbine work minus compressor work - 207 divided by 472, efficiency is 49.2 percent. So, we can see that with adding a regenerator which has an effectiveness of 0.75, efficiency can be raised from 40 percent to 49 percent using a regenerator.

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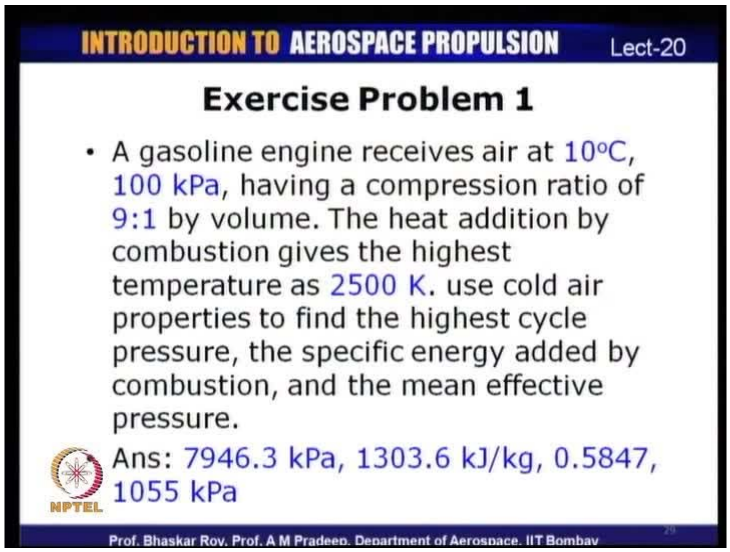

This was problem number 5 and what I have now is a few exercise problems which you can solve based on our discussion during the earlier lectures as well as the tutorial that we have discussed today. Exercise problem 1 is on an Otto cycle. A gasoline engine receives air at 10 degree Celsius, 100 kilopascals having a compression ratio of 9 is to 1. The heat addition by combustion gives the highest temperature as 2500 kelvin and if we use cold air assumptions, we need to find the highest cycle pressure, specific energy added by combustion and the mean effective pressure.

So, the highest pressure The answer to this is highest pressure is 7946.3 kilopascals, the energy added is 1303.6 kilojoules per kilogram and the efficiency is 0.5847 and the mean effective pressure is 1055 kilopascals. This was a problem on an Otto cycle because it is given as a gasoline engine and so, it is based on an Otto cycle.

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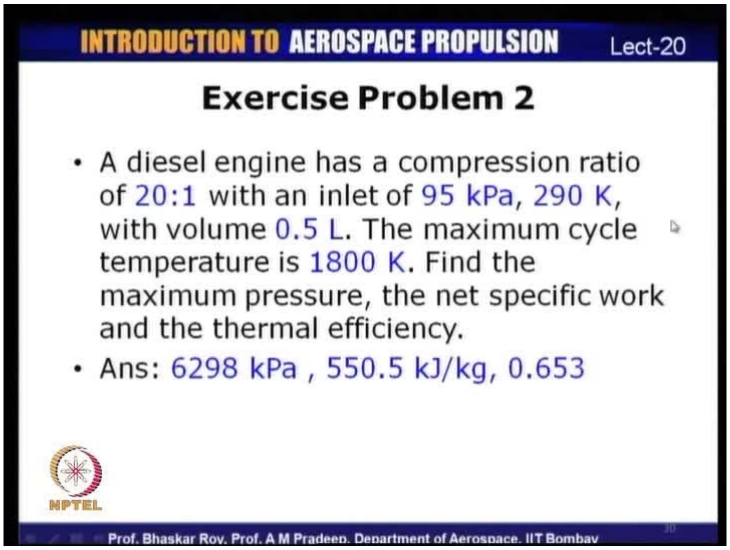

The second problem is on a diesel cycle. A diesel engine has a compression ratio of 20 is to 1 with an inlet temperature and pressure of 290 kelvin and 95 kilopascals with a volume of 0.5 liters. The maximum cycle temperature is 1800 kelvin. Find the maximum pressure, the net specific work and the thermal efficiency.

So, for the diesel cycle problem, the maximum pressure comes out to be 6298 kilopascals, specific work is 550.5 kilojoules per kilogram and thermal efficiency is 0.653.

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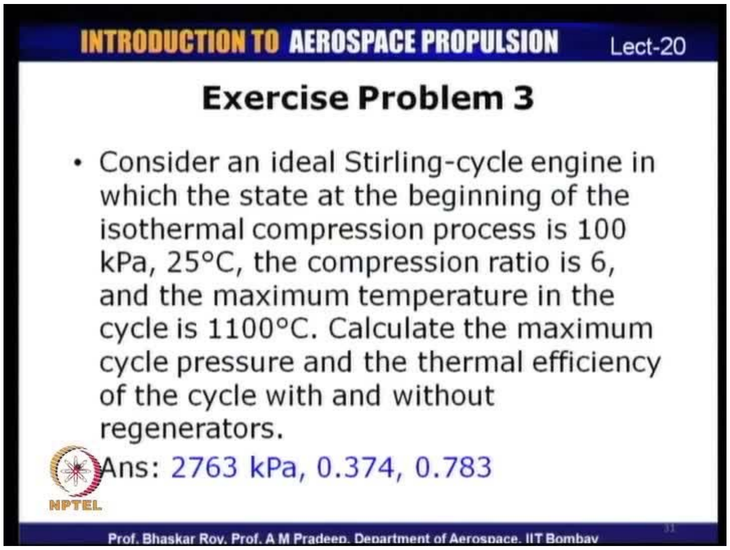

Problem number 3 is on a Stirling cycle. Consider an ideal Stirling cycle engine in which the state at the beginning of isothermal compression is 100 kilopascals and 25 degree celsius. The compression ratio is 6; the maximum temperature in the cycle is 1100 degree celsius. Calculate the maximum cycle pressure and the thermal efficiency of the cycle with and without regenerators. So, the maximum pressure comes out to be 2763, without regeneration, the efficiency is 0.374 and with regeneration, the efficiency is 0.783.

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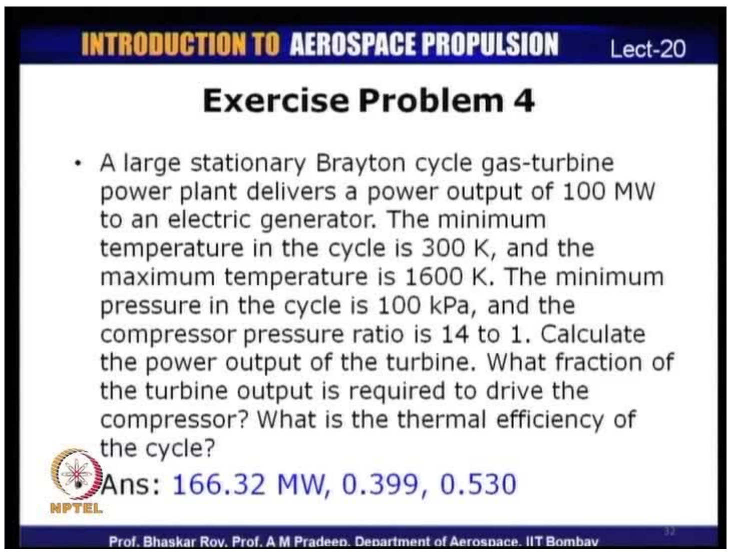

The last problem is on a Brayton cycle. A large stationary Brayton cycle gas turbine power plant delivers a power output of 100 megawatts to an electric generator. The minimum temperature of the cycle is 300 kelvin and the maximum temperature is 1600 kelvin. The maximum cycle pressure is 100 kilopascals and the compressor pressure ratio is 14 is to 1. Calculate the power output of the turbine and what fraction of the turbine output is required to drive the compressor. What is the thermal efficiency of the cycle?

So, we need to calculate the power output which comes out to be 166.32 megawatts, fraction of the turbine work output required to drive the compressor, it is the ratio of turbine work and the compressor work and is 0.399 and thermal efficiency comes about to be 0.530 that is 53 percent.

What we shall be discussing in the next lecture? In today's lecture, we were basically solving problems from ideal Otto and diesel cycles, the Ericsson cycle and the Brayton cycle with and without regeneration and in the next cycle we shall be discussing about some of the aspects of pure substances and gas and vapour mixtures.

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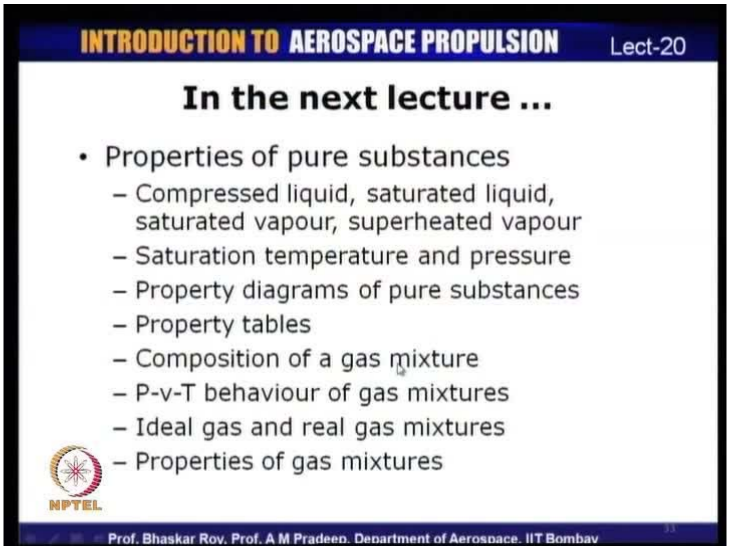

In the next lecture, what we shall be discussing are the following: We shall be talking about properties of pure substances, we will be discussing about what is meant by compressed liquid, saturated liquid, saturated vapour and super-heated vapour and then saturation temperature and pressure. We shall be discussing about property diagrams of pure substances and property tables, then composition of gas mixture, P-v-T behaviour that is pressure, volume, temperature behavior of gas mixtures, ideal gas and real gas mixtures and properties of gas mixtures. So, these are some of the topics that we shall be taking up for discussion during our next lecture that will be lecture number 21.