Introduction to Aerospace Propulsion

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Module No. # 01

Lecture No. # 18

Rankine cycle, Brayton cycle, Stirling and Ericsson cycles

Hello and welcome to lecture 18 of this lecture series on introduction to Aerospace Propulsion starting with the last lecture number 17. We had started discussions on application of thermo dynamic principles to different engineering cycles. We had discussed about three different cycles in the last lecture, which were the otto cycle, the diesel cycle and the dual cycle.

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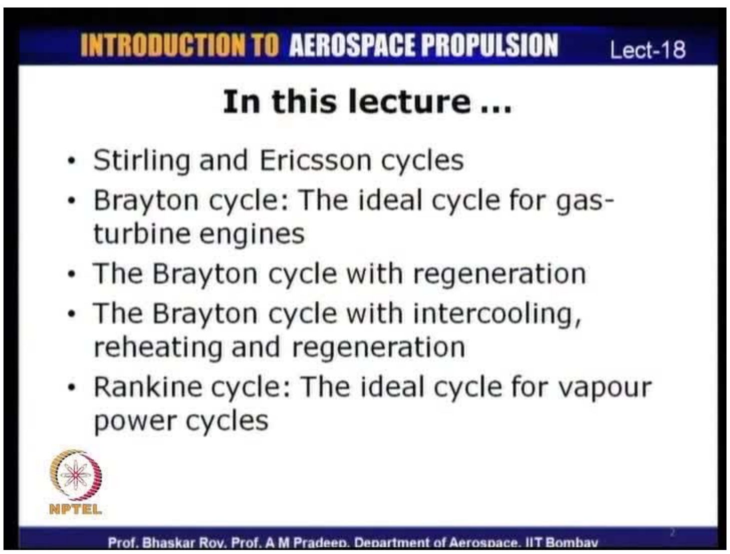

We shall continue our discussion on different power cycles in today's lecture. What we shall be discussing are - two cycles. We will start our discussion with two cycles, which are having efficiencies close to that or equal to that of the Carnot cycle or Carnot efficiency. These are the Stirling and the Ericson cycles. We shall then discuss about the

Brayton cycle, which forms the ideal cycle for gas turbine engines. We shall discuss some variance of the Brayton cycle that is Brayton cycle with regeneration, Brayton cycle with intercooling, reheating and regeneration. We will have some discussion on one of the vapor power cycles known as the Rankine cycle. Rankine cycle is the basic thermo dynamic cycle for steam engines or steam power cycles.

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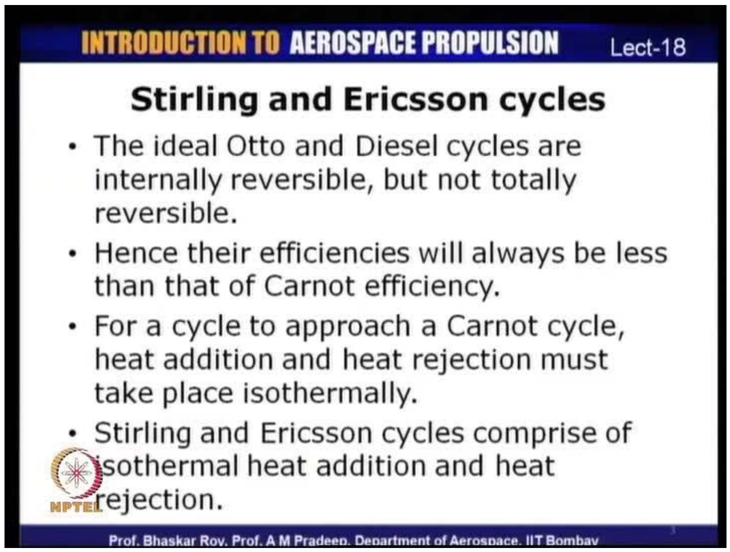

Now, let us start discussion on two conceptual cycles, which are supposed to have very high efficiencies. We already know that the ideal otto and diesel cycles are not totally reversible. They are internally reversible, but it is possible to have irreversible outside the cycle. It means that ideal otto diesel cycles are not totally reversible; this means that the efficiency of the ideal otto and diesel cycles can never be equal to the Carnot efficiencies, because they are not totally reversible. If a cycle has to have efficiencies, which are close to that of Carnot cycle efficiency, then they need to be reversible both internally as well as externally.

For a cycle to become externally reversible, it is important that the temperature difference between the source and the sink that is heat transfer takes place at a differential temperature dt. This does not happen in the otto and diesel cycles because we have seen that heat transfer takes place through a heat transfer rate of q in and heat transfer out at q out. Therefore, as long as there is a temperature differential, the cycle becomes internally reversible, but not externally reversible. So, for any cycle to become totally reversible, it is necessary that heat transfer takes place through a temperature difference, which does not exceed a certain differential amount of dt. How do you do this? How do you transfer temperature through a very small differential and still be able to have very high efficiencies? Stirling and Ericsson cycles are two cycles, which have isothermal heat edition.

Isothermal heat edition is something, which is there in a Carnot cycle, where you have a reversible isothermal heat additional as well as heat rejection. Stirling and Ericsson cycles comprises of isothermal heat edition and heat rejection through a certain process, which is known as regeneration.

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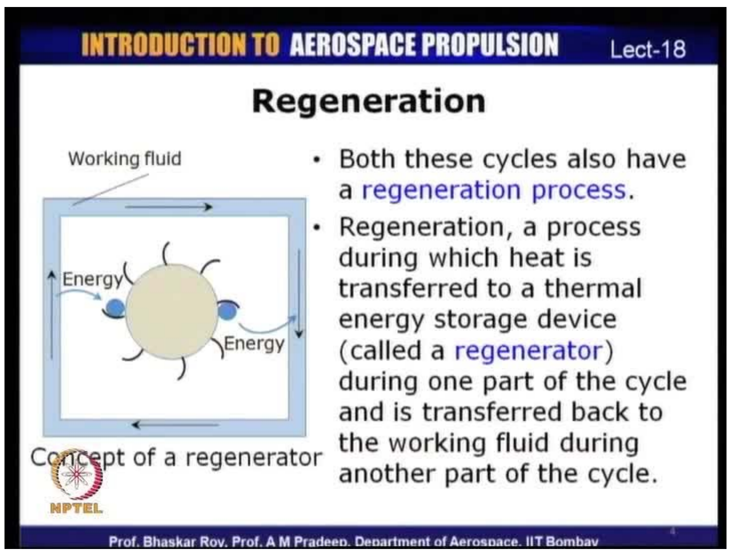

Let us understand what is meant by regeneration. Regeneration is a process, which is common to both Stirling and Ericsson cycles. Regeneration is basically a process, which involves heat transfer thorough a thermal energy storage device. It is a regenerator during one part of the cycle and the energy is transferred back to the cycle during another part of the cycle. It is just conceptually shown in this diagram here. We have a cycle, which consists of a certain working fluid, which has certain energy associated with that. There is a thermal energy storage device, which is a regenerator placed at the center here.

During one part of the cycle, we transfer energy to this device and this energy device transfers energy back to the working fluid during another part of the cycle. Energy is transferred to the fluid during another part of the cycle. So, energy is transfer to the fluid during one part of the cycle and transferred back to the working fluid during another part of the cycle. So, regeneration is something, which is common to both Stirling as well as Ericsson cycle. This is why it is possible that Stirling and Ericsson cycles can have isothermal heat edition and isothermal heat rejection. Basically, these cycles transfer heat using what is known as a regenerator. So, regeneration process or a regenerator is something, which is common to both Stirling as well as Ericsson cycles.

Regeneration is something, which we have just understood that it basically involves transfer of energy to a thermal storage during one part of the cycle and transfer that energy back to the working fluid during another part of the cycle. So, with this in mind that is regeneration enables a cycle to have isothermal heat edition and isothermal heat rejection, which is required. If you want to have efficiencies, which are close to that of Carnot cycle efficiencies. So, isothermal heat edition and isothermal heat rejection is an important aspect of a cycle, if it has to achieve Carnot efficiencies. Let us look at what are the different processes that constitute as Stirling cycle.

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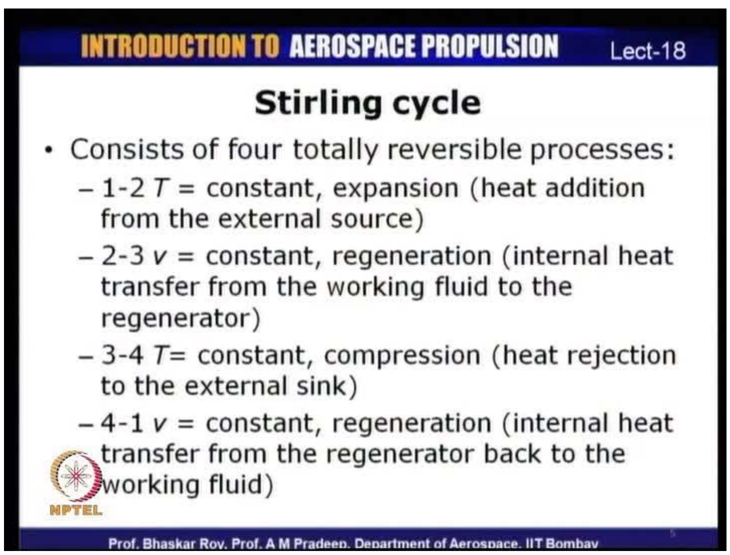

Let us look at what are the different processes that constitute as Stirling cycle. A Stirling cycle basically consists of four processes, which are totally reversible process. 1-2 is isothermal process and T is a constant. So, we have an isothermal expansion process during which, heat is added or heat addition takes place from an external source.

The second process is - constant volume regeneration process, where there is internal heat transfer from the working fluid to the regenerator. The third process that is process 3-4 is again constant temperature. It is an isothermal compression process, during which, heat is rejected to an external sink. The last process is a constant volume regeneration process, during which, there is an internal heat transfer from the regenerator back to the working fluid. So, these are the four different processes, which constitute a Stirling cycle that is there are two isothermal processes and two regeneration processes.

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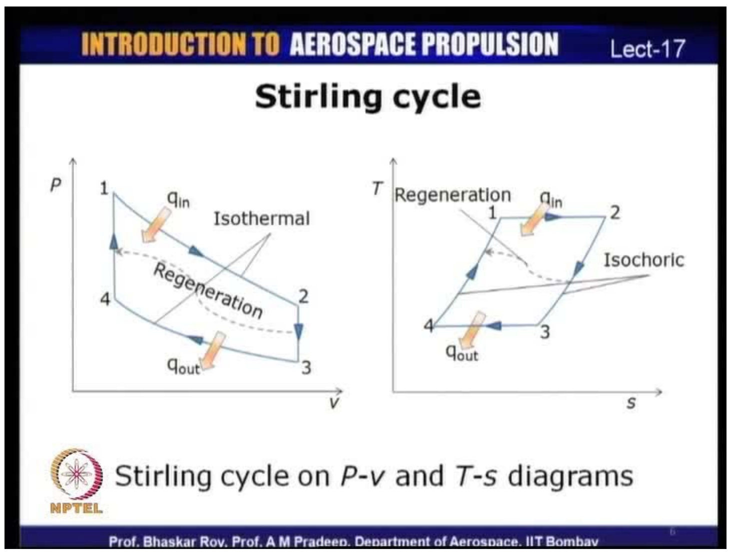

On a P-V and T-S scale or the Stirling cycle is represented in the following way. It starts with an isothermal process; T is equal to constant process. 1-2 is isothermal process and process 2-3 is constant volume regeneration process. It is during process 1-2 that is isothermal process; you have heat transfer from an external source to the cycle. Process 2-3 is a constant volume process. It is a regeneration process, during which, energy is transferred from the cycle or from the working fluid to the regenerator, which is a thermal energy storage device. Process 3-4 is an isothermal heat rejection process, during which, heat is rejected from the cycle. Process 4-1 is again a regeneration process, during which, heat is transferred back to the fluid from the thermal energy storage device.

On a T-S diagram, Stirling cycle look like this. First process is isothermal process. You have a horizontal line on the T-S diagram because it is isothermal heat edition. Process 2-3 is constant volume process, during which, regeneration takes place that is energy is transferred to the regenerator during this process. Process 3-4 is isothermal heat rejection process. Process 4-1 is again a constant volume process. It is a regeneration process, during which, heat is transferred or energy is transferred from the regenerator to the working fluid. So, this is Stirling cycle as seen in P-V and the T-S diagram.

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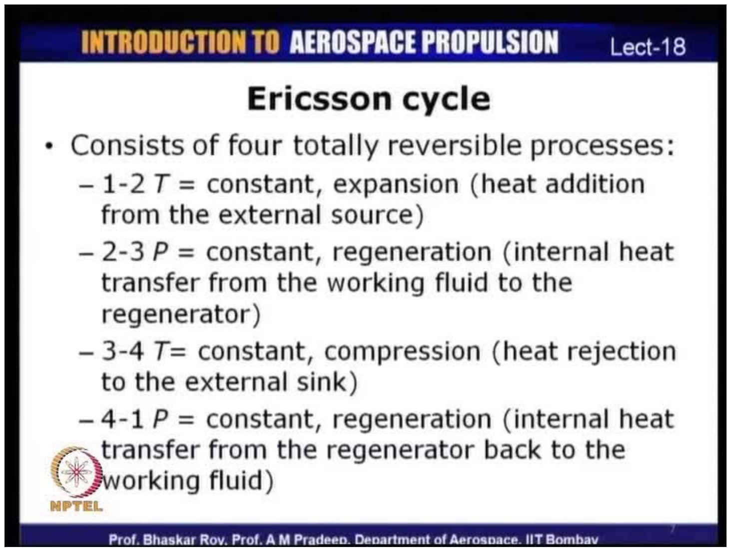

There is another cycle, which is very similar to a Stirling cycle. It also has two processes, which consist of regeneration processes and this is known as an Ericsson cycle. An Ericsson cycle consists of four totally reversible processes. Here again, you have an isothermal heat edition process, where there is heat edition from an external source. There is a constant pressure, heat regeneration. Unlike a Stirling cycle, which had constant volume regeneration, Ericsson cycle has a constant pressure regeneration process. There is again an isothermal heat rejection through a compression process and finally a constant pressure regeneration process, where there is internal heat transfer from the regenerator to the working fluid.

The difference between the Ericsson and the Stirling cycle is only in the regeneration process. In the Stirling cycle, the regeneration was constant volume. In the Ericsson cycle, it is constant pressure regeneration. The heat edition is isothermal in both the cycles, Stirling as well as the Ericsson cycles.

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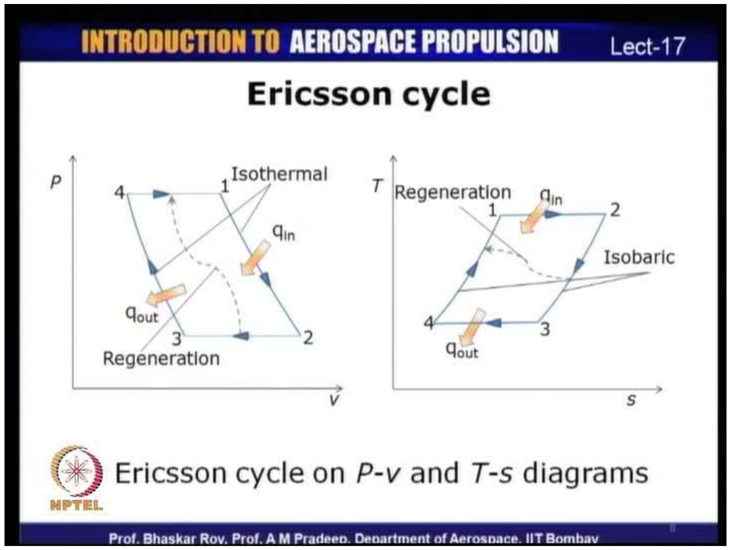

Let us look at the P-V and T-S diagram of the cycles. The P-V diagram or the P-V coordinates has the first process that is an isothermal process 1-2. The second process is basically a constant pressure process, which is a regeneration processes. 2-3 is regeneration process. 3-4 is an isothermal heat rejection. Process 4-1 is constant pressure and regeneration is heat transfer from the regenerator to the working fluid at constant pressure. So, processes 1-2 and 3-4 are isothermal processes. Process 2-3 and 4-1 are constant pressure processes, which are basically regeneration processes.

On T-S coordinates, the same cycle looks like this. We have isothermal heat edition isothermal heat rejection and constant pressure regeneration during process 2-3 and process 4-1. So, this is Ericson cycle on P-V and T-S diagrams. Both these engines are totally reversible cycles because they are any way internally reversible like otto and diesel cycles. They are also externally reversible because of the heat edition and heat rejection processes that are isothermal. Heat edition and heat rejection are taking place at a constant temperature, which means that they are also externally reversible.

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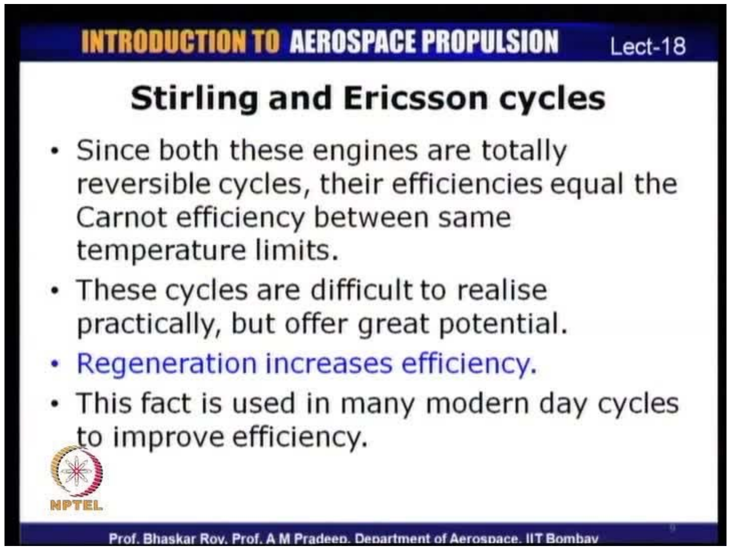

Since Stirling and Ericson cycles are totally reversible cycles, their efficiencies will be equal to that of the Carnot efficiencies. Both Stirling and Ericson cycles have efficiencies equal to that of Carnot efficiency cycle because they are totally reversible. Now, there have been attempts to built Stirling and Ericson cycles, but they are extremely difficult to build.

They are very cumbersome in nature and therefore, these cycles have been demonstrated in some way. Of course, there is some irreversibility, which will still take place. These cycles have very high efficiencies than the normal otto and diesel cycle efficiencies. They are very extremely cumbersome to build and obviously, they still cannot achieve Carnot efficiencies. The main point or the main aspect of Stirling and Ericson cycles is that regeneration increases efficiency.

If you have a cycle, which has some component of regeneration, it increases the efficiency of the cycle. This is one aspect that has been implemented in many modern day cycles for improving the efficiency. It means that regeneration within the cycle will always improve efficiency. This is one of the aspects or one of the understandings that we get from Stirling and Ericson cycles analysis. This is one aspect, which is used in many of the modern day cycles. We will not discuss further on how Stirling and Ericson cycles can be implemented and so on.

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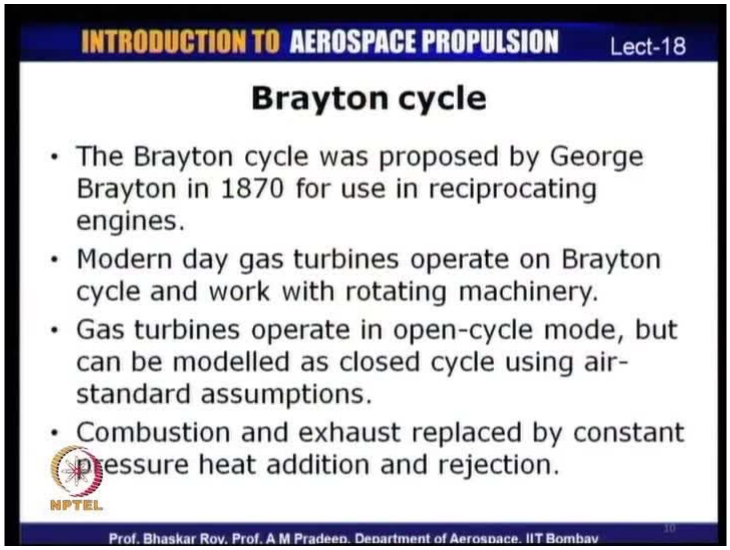

Let us take up another very important cycle. As aerospace engineers, this is one cycle, which we should be understanding in much detail. We shall be carrying out detailed analysis of this cycle. A lot more of this is known as the Brayton cycle. So, Brayton cycle forms the basic thermo dynamic cycle for gas turbine engines, though it was developed initially for reciprocating engines. It was developed or proposed by George Brayton in 1870 for reciprocating engines, but modern day gas turbine engines operate on Brayton cycle and work primarily with rotating missionary.

Gas turbine engines operate in an open cycle mode. We can model it as closed cycle using the air-standard assumptions, which we had discussed in the last lecture. Using these assumptions, we can assume that the gas turbine cycle operate in an open, though it operates in an open cycle mode. We can approximate that it is operating in close cycle mode. So, in a gas turbine engine, we will replace the combustion and exhaust by constant pressure, heat addition and heat rejection.

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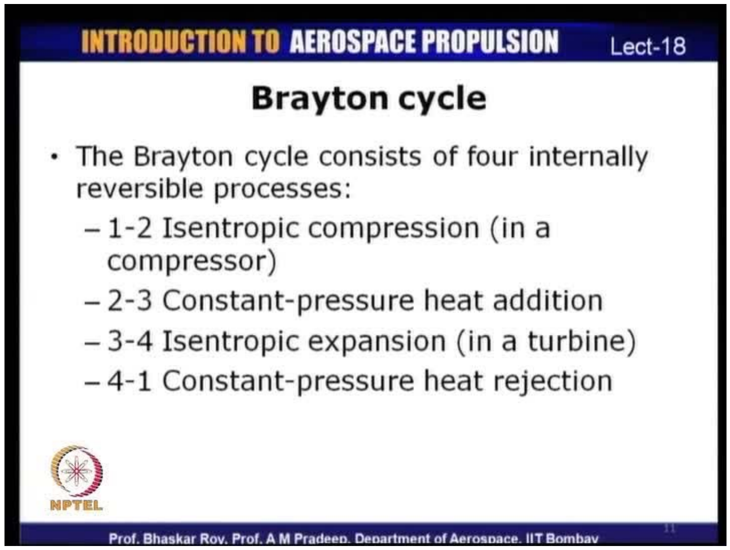

Brayton cycle basically consists of four internally reversible processes. Process 1-2 is isentropic compression. It is basically like compression in a compressor in the case of gas turbine. Process 2-3 is constant pressure heat edition. Process 3-4 is isentropic expansion. In the case of a gas turbine engine, it is in a turbine. Process 4-1 is constant pressure heat rejection. So, these are the four different processes and all of them are internally reversible, which constitute a Brayton cycle.

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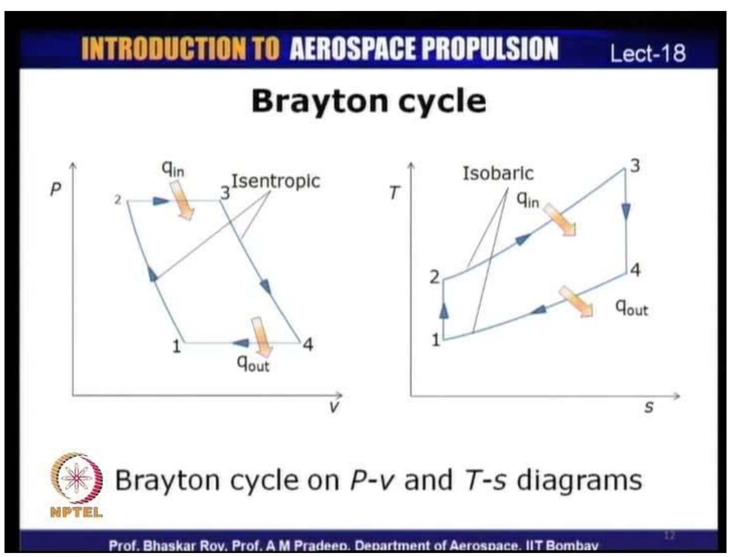

On P-V and T-S coordinates, the Brayton cycle looks like this. We have the first process, which is a compression process. Process 1-2 is isotropic compression and process 2-3 is constant pressure heat addition. So, heat addition at constant pressure, q in takes place during process 2-3. Process 3-4 is again isentropic process. It is an isentropic expansion process. Process 4-1 is constant pressure heat rejection process, q out takes place during process 4-1.

On T-S diagram or T-S coordinates, the Brayton cycle looks like this. The first process is isentropic; we have a vertical line here. Process 1-2 is isentropic, process 2-3 is constant pressure process, during which, heat addition take place. Process 3-4 is an isentropic expansion; it is again a vertical line. Process 4-1 is a constant pressure heat rejection. So, these are the four different cycles, which constitute a Brayton cycle. There are two isentropic processes: the compression and expansion processes are isentropic. We also have two constant pressure processes, during which, heat addition and heat rejection takes place.

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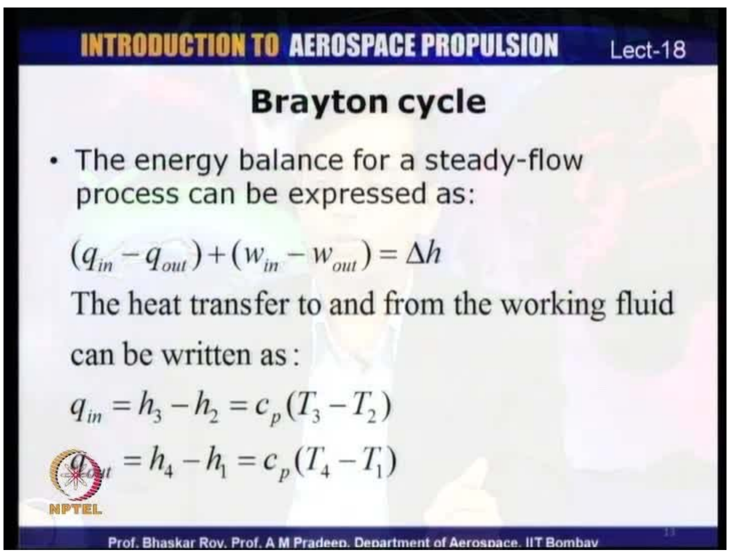

As we did in the case of otto and diesel cycles, we will now derive an expression for finding the efficiency of a Brayton cycle in terms of certain pressure ratios, which we will define little later. So, to derive an expression for efficiency, we will primarily be doing an energy balance.

We can assume the different constituents of the Brayton cycle to be steady flow systems. For steady flow process, the energy balance is basically q in minus q out plus w in minus w out equal to delta h. If you were to calculate the heat transfer to and from the working fluid, q in is equal to h 3 minus h 2 because it is a flow process or constant pressure heat addition. Therefore, it is equal to c p times t 3 minus t 2 q out. It is again a constant pressure heat rejection and therefore, it is h 4 minus h 1 that is c p times t 4 minus t 1.

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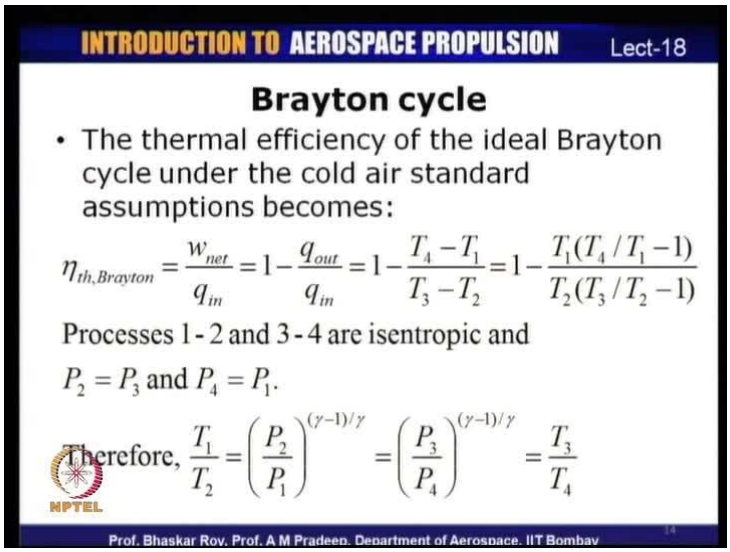

We can determine the thermal efficiency of the ideal Brayton cycle. Thermal efficiency is w net work output by heat input that is 1 minus q out by q in, which is 1 minus t 4 minus t 1 by t 3 minus t 2, which is equal to 1 minus t 1 multiplied by t 4 by t 1 minus 1 divided by t 2 multiplied by t 3 by t 2 minus 1.

We know that processes 1-2 and 3-4 are isentropic. Process 2-3 and 4-1 are constant pressure processes. Therefore, P2 is equal to P3 and P4 is equal to P1. From these processes, 1-2 and 3-4 are isentropic because we have T 1 by T 2 is equal to P 2 by P 1 raised to gamma minus 1 by gamma. It is equal to P 3 by P 4 raised to gamma minus 1 by gamma because P 2 is equal to P 3, P 4 is equal to P 1, which is in turn equal to T 3 by T 4.

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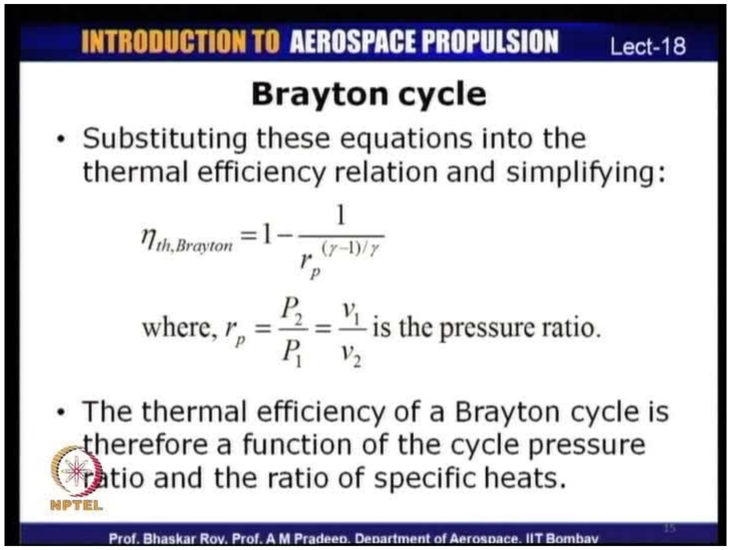

If you substitute these values in the equations, we get an expression for the thermal efficiency. So, thermal efficiency of a Brayton cycle is equal to 1 minus 1 by r subscript p raise to gamma minus 1 by gamma, where r p is basically the pressure ratio P 2 by P 1 and that is basically the pressure ratio of this cycle. Brayton cycle efficiency is primarily a function of the cyclic pressure ratio. It also depends on the ratio of specific heats as well. Brayton cycle efficiency is the expression very similar to that of an otto cycle. In an otto cycle, we have seen the efficiency was equal to 1 minus 1 by r raised to gamma minus 1 by gamma, where r was the compression ratio. In the case of Brayton cycle, the efficiency is 1 minus 1 by r p raised to gamma minus 1 by gamma, where r p is the cycle pressure ratio, the max pressure by the min pressure.

The efficiency of the Brayton cycle is primarily a function of the pressure ratio. It also depends on the ratio of specific heat in some way and which was also the case for an otto cycle as well. This was the simple Brayton cycle. Now, it primarily consists of these four different processes: two isentropic processes, an isentropic compression and an isentropic expansion and two constant pressure processes. One is isentropic, constant pressure heat edition, constant pressure heat rejection. So, all these four processes together constitute the Brayton cycle. A simple Brayton cycle forms the basic thermo dynamic cycle on which, all gas turbine engines operate.

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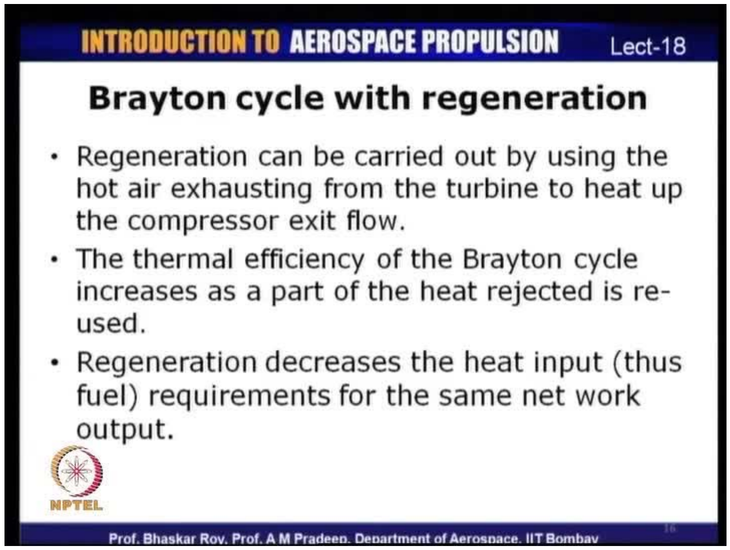

Now, we shall look at some of the modifications that can be done on the Brayton cycle to primarily increase the efficiency, improve the efficiency of the Brayton cycle. One such modification, which we will discuss is known as the regeneration. Regeneration is basically trying to use some of the energy, which is being wasted from the exhaust of the cycle. We would like to use some part of the heat rejected from the cycle and use it in some other part of the cycle. As we have seen regenaration for Stirling and Ericson cycle involves transfer of energy from one part of the cycle to another.

In the case of a gas turbine engine, regeneration can be carried out using hot air exhausting from the turbine to heat up the compressor exit flow. Before the air enters the combustion chamber, we could heat up the air using energy from the turbine exhaust. So, thermal efficiency of the Brayton cycle is lightly to increase because some part of the heat rejected is basically being reused. You are increasing the net work output by reusing the part of the heat, which is otherwise getting rejected or being wasted. It means that regeneration in some sense decreases the heat input. Therefore, fuel requirements for the same net work output because for generating the same net work output, you are using lesser fuel as you are using a part of heat, which is being exhausted and using that energy in some part of the cycle.

In the case of Brayton cycle, regeneration is primarily carried out by using part of the compressor part of the turbine exhaust, which is energy and it is primarily getting wasted in some sense. Heat register is used reused in another part of the cycle that is to heat up the compressor exit flow. So, regeneration is basically the understanding, which we had from the Stirling and Ericson's cycle. It was regeneration that increases or improves efficiency. In the case of a Brayton cycle, heat rejected from the cycle is being reused. Therefore, regeneration decreases the heat input and the fuel requirements are the same for net work output.

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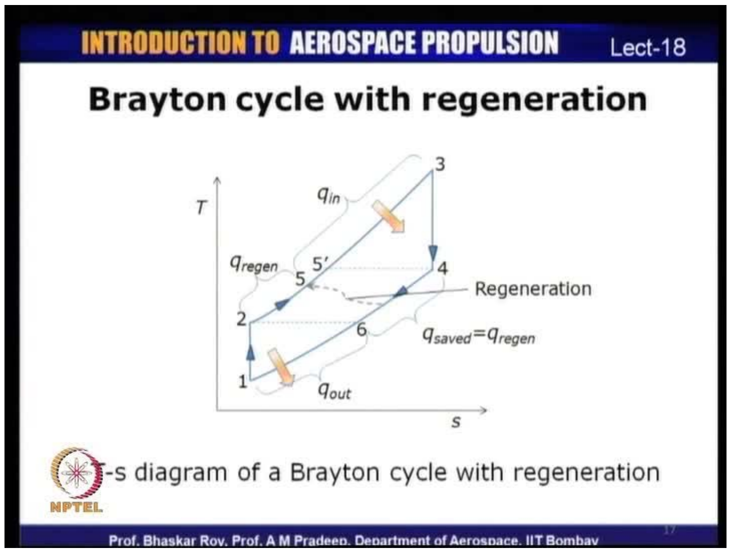

Let us now look at Brayton cycle with regeneration. Now, this was basic Brayton cycle. We had discussed on T-S coordinates process starting from state 1. Process 1-2 is an isentropic compression process. Process 2-3 is constant pressure heat edition. Process 3-4 is isentropic expansion and process 4 is constant pressure heat rejection. So, what happens in regeneration is that we can see the temperature at state 4. T 4 is much higher than temperature at state 2. So, regeneration is a process, where you would like to transfer some part of this heat, which is being rejected back to the cycle.

From state 4, the ideal scenario would be that we have an increase in temperature, which is equal to that of T 4 itself. It is obviously not possible in actual practice and so you would transfer some heat, which is indicated here as q region. It is the heat, which has been regenerated or transferred to the cycle. So, q region, which is equal to the q saved which has been transferred back to the cycle at the end of the compression process.

The heat rejected is q out equal to what is shown here, between this 1 and 6. Heat rejected in the simple Brayton cycle would have been equal to q 4 minus q 1. This has now been reduce to q 6 minus q 1. Since that much heat has been transferred to the cycle, the heat input required will now be instead of q 3 minus q 2. It is now equal to q 3 minus q 5. We can see that there is a tremendous saving, in terms of the heat required that is q in as well as the decrease for heat has been rejected because of heat regeneration on the simple Brayton cycle.

So, regeneration primarily involves transfer of energy. In this case, it has been shown as this part of heat, which has been transferred back to the cycle. So, q 4 minus q 6 has been transferred back. Therefore, heat input has also reduced significantly because of this. It means that ideally, you should be able get higher efficiencies because q in has now reduced.

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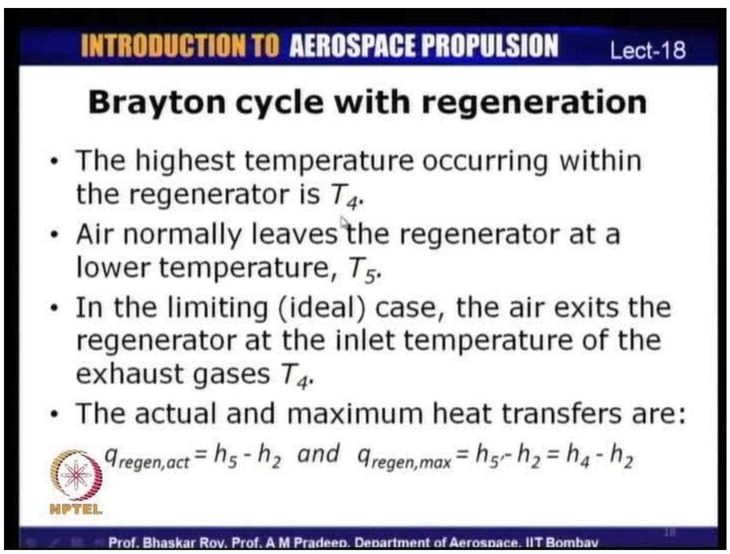

In an ideal case, you could have a scenario, where the air actually leaves the regenerator or exit the regenerator at the temperature of the exhaust gas, which was T 4. If that was the case, the maximum regeneration that you could get is h 5 dash minus h 2, which is h 4 minus h 2. Actual regeneration takes place to a temperature less than that. This is why the actual regeneration is h 4 minus h 2. On the T-S diagram, you should be able to get regeneration heat equal to h 5 prime minus h 2, which is equal to h 4 minus h 2. The actual regeneration is h 5 minus h 2.

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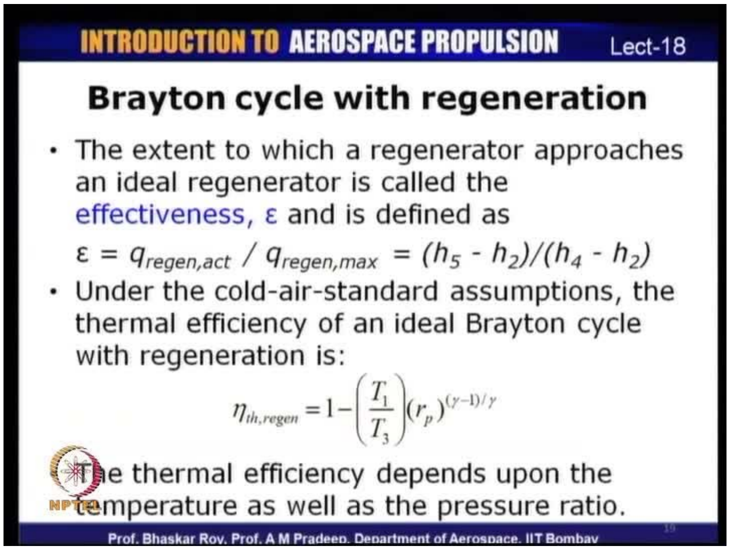

We can define what is known as effectiveness of a regeneration process or regenerator. Effectiveness is basically the ratio of the actual regeneration to the maximum regeneration. It is h 5 minus h 2 divided by h 4 minus h 2. So, we have already derived an expression for the thermal efficiency of an ideal Brayton cycle, the simple Brayton cycle with regeneration. If you were to derive an expression, we would get thermal efficiency equal to 1 minus T 1 by T 3 times r p raise to gamma minus 1 by gamma.

We have thermal efficiency, which is not just a function of the pressure ratio, it is also a function of the temperature ratio. For the simple Brayton cycle, we have seen that the thermal efficiency is only a function of the pressure ratio and as well as the ratio of specific heat with regeneration. Now, the efficiency is also a function of the temperature ratio. It means that as we increase or decrease the temperature ratio, it can affect the efficiency of the Brayton cycle, which has a regeneration process or regeneration mechanism.

Efficiency of a Brayton cycle basically can be improved using regeneration because you are reducing the heat input to the cycle. You are transferring some amount of heat, which is normally rejected back to the cycle. Therefore, the amount of heat that is required for generating the same work output will be reduced. It means that there has to be an increase in efficiency of the cycle. Brayton cycle with regeneration is primarily one of the mechanisms of improving the net work output of the efficiency of a Brayton cycle.

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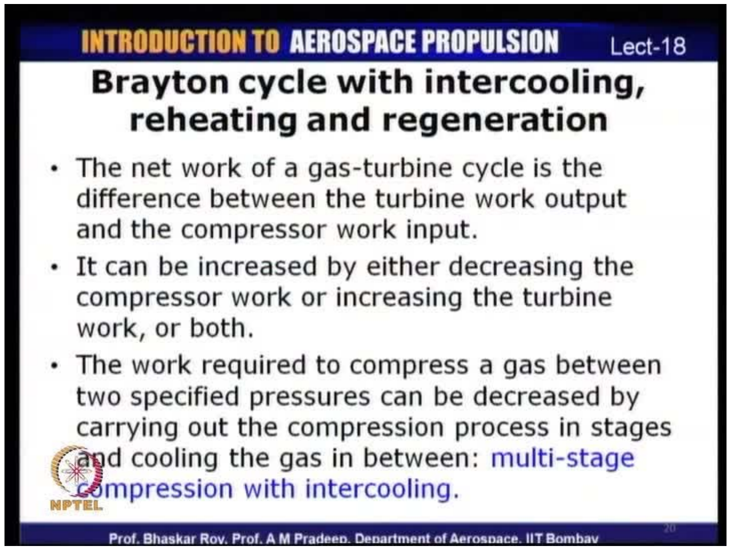

Now, there are other methods of increasing the efficiency or work output of a cycle. One such method is known as intercooling. The other method we shall be discussing is reheating. Now, intercooling is something, which consents the compression processes of a cycle. Reheating is something, which consents the expansion or the expansion part of the cycle. So, the net work output of a gas turbine cycle is basically the difference between the turbine work output and the compressor work input. It means that the net work output can be increased either by decreasing the compressor work or by increasing the turbine work or doing both. That is either you reduce the compressor work input or increase the turbine work output or you could do a combination of these two, which will eventually lead to an increase in the net work output. So, these are two options that we have for increasing the net work output of a cycle. It means that if we increase w net, we can increase the efficiency.

In the first case, if you wish to reduce the net work input for the compression process, we can do that by intercooling. We split the compression process into different stages and then between these different stages, we apply a certain cooling to bring down the net work required for carrying out the certain amount of compression process. So, the work required for a compressor to compress a gas between two specified pressures can basically be decreased by carrying out the compression process in stages and cooling the gas in between them. This is basically known as multi-stage compression with cooling that is between different compression processes or compression stages; we apply cooling of the gas in between them. This is known as multistage compression with intercooling.

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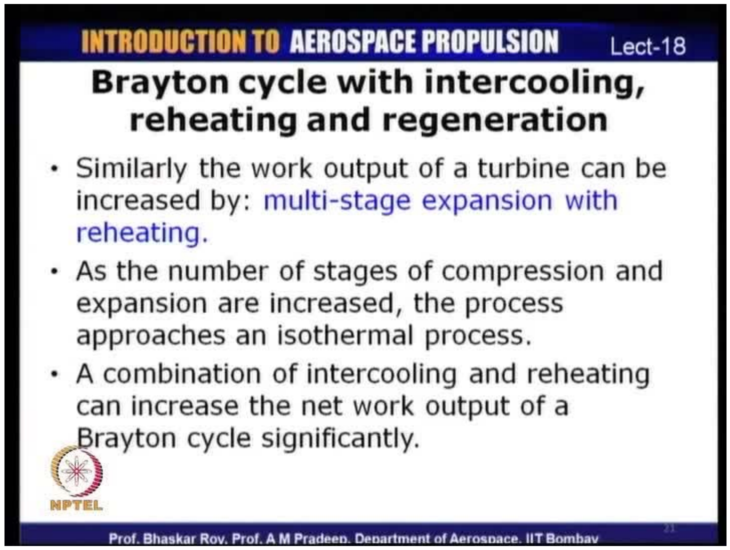

Similarly, the work output of a cycle of a turbine can be increased by multi-stage expansion with reheating. We split expansion process in two different stages and apply reheating between them, so that the network output of the turbine can be increased. In a limiting case, as we increase number of stages of compression and expansion, the process basically approaches an isothermal process.

A combination of intercooling and reheating will basically increase the net work output of a Brayton cycle. It is because; you are increasing the net work output by using intercooling and reheating. What we shall see a little later on that? Using either intercooling alone or reheating alone is not sufficient, it is also necessary that we use some amount of regeneration. So that the over all cycle efficiency can be improved. So, intercooling plus reheating with regeneration is one of the methods or mechanisms by which, one can increase the efficiency of a Brayton cycle significantly.

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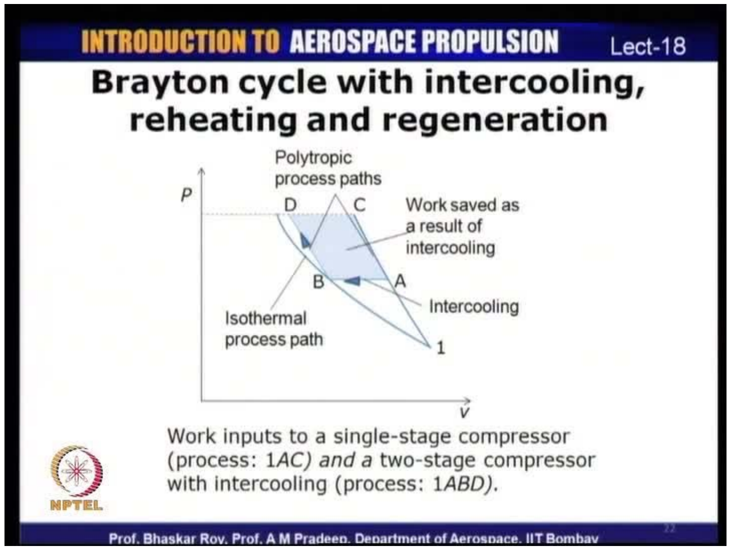

Let us look at how intercooling can be carried out thermo dynamically. As we look at a P-V diagram of a compression process, Process 1AC is the compression process without intercooling or in single stage compression. Now, if we were to split this compression processes into two-stage compression with intercooling, then this process becomes 1ABD. At the end of process 1-A, we apply cooling of the gas. Ideally, we assume that cooling takes place at constant pressure. It means after the gas, which is stated as A at the end of the first compressor.

As we apply cooling of the gas, it reaches state B at constant pressure. From B to D, we again apply the compression process, which takes it from B to D. Therefore, the amount of work has been saved as a result of intercooling. It is given by this shaded area, which is given here. This is the amount of work that is saved as a result of intercooling. So, process 1AC can be replaced, which is a single stage compression process. It can be replaced by process 1ABD, which is splitting the compression process into two stage compression process with intercooling. Similarly, we can also look at the reheating. We will also be able to see the benefits as we get higher work output by reheating in the end of the expansion process through a turbine.

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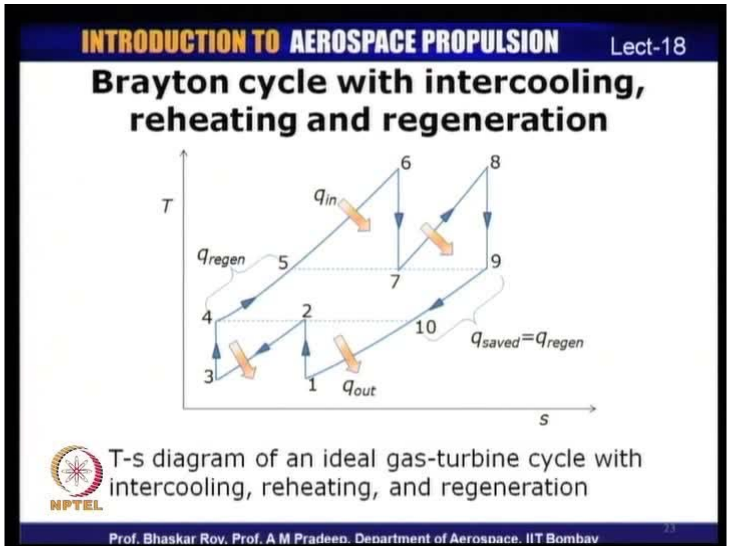

Let us look at one example of an ideal gas turbine cycle, basically with intercooling reheating and regeneration. What we have shown here is a two state compression process and a two state expansion process. The cycle begins with at state 1 and there is an isentropic compression, which results in state 2. At the end of state 2, we carry out intercooling. It means that the process will now move along this path process 2-3. It moves from state 3 to state 4 at the end of process. After it reaches state 4, it moves along the process path, which is a constant pressure process, from state 4 to state 6. What is shown here are the heat inputs and the heat rejection taking place. There is a certain amount of rejection taking place here because the gas has been cooled from state 2 to state 3. So, there is a heat rejection, which is also taking place during process 2-3.

Now, after the gas reaches state 6, which is the beginning of expansion process. 6 to 7 is expansion and 7 to 8 is reheating, which means there is heat input. So, q in takes place during constant pressure process 4-6 and as well as during 7-8. 8 to 9 is another expansion process; the second expansion process. 9 to 1 is the heat rejection process. Now, this is only with intercooling and reheating. So, intercooling of the compression process and reheating during the expansion process.

Now, if you apply regeneration during this process, then ideally we should be able to get a temperature equal to that of temperatures at 7 and 9. Therefore, the amount of heat that is saved is equal to the difference between 9 and 10. The heat has been regenerated and this much amount of heat has been saved or regenerated during this process. Heat input is during process 5-6 and 7-8. The heat rejection is during process 2-3 and process 10-1. This is one example of a Brayton cycle, which has intercooling, reheating as well as regeneration. Intercooling is during process 2-3, reheating is during process 7-8 and regeneration during process 9-10 or 4-5. So, Brayton cycle with all the three intercooling, reheating and regeneration is likely to have higher efficiencies than that of the simple Brayton cycle, which has no intercooling, reheating or regeneration.

Now, if we look at the benefits of intercooling or reheating, it has a standalone component towards the overall efficiency. It is always not the case and you have an improved efficiency. Intercooling alone or reheating alone normally does not mean that you would have efficiency. If it was not used in conjunction with regeneration, intercooling and reheating with regeneration can result in increased efficiency. Intercooling alone or reheating alone will necessarily lead to increased efficiency of the Brayton cycle.

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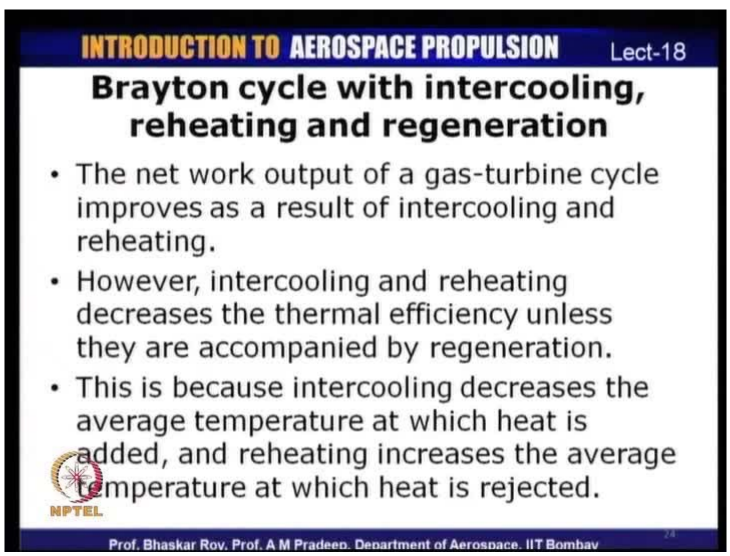

The net work output of a gas turbine cycle will increase, which is already known as a result of intercooling and reheating. For thermal efficiency to improve, it is required that regeneration takes place. During reheating, there is additional heat input that is required. It is possible that you may not necessarily get increased thermal efficiency. If regeneration is used, it is possible to basically have increased efficiency of the system.

Now, primarily what is happening is that during intercooling process, the average temperature at which heat is added decrease. Reheating basically tends to increase temperature at which heat is rejected. Basically, it necessarily does not mean that you get an increased thermal efficiency, unless you have regeneration applied in the process.

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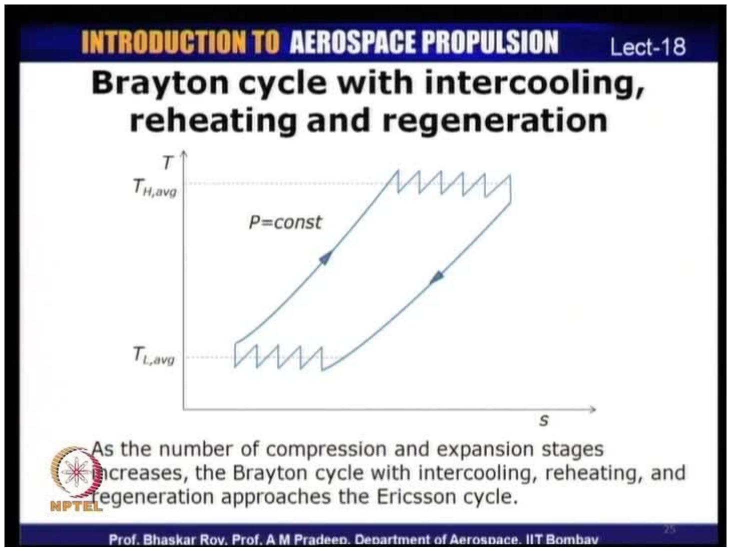

Now, as I mentioned, if you keep increasing the number of stages of intercooling and reheating, you can ensure that you have isothermal. It is possible that you have compression processes. If you extend the number of processes at which intercooling and reheating are taking place, then it is possible for us in an ideal scenario. If you have infinite number of compression stages and expansion stages, it means Brayton cycle with intercooling, reheating and regeneration.

Brayton cycle will approach an Ericson cycle. You have isothermal heat rejection as well as isothermal heat addition. If you apply regeneration, then this is like an Ericson cycle. Ericson cycle consists of two isothermal processes and two constant pressure processes. Brayton cycle with infinite number of intercooling, reheating and regeneration can approach an Ericson cycle. It means that this will have efficiencies, which are equal to that of the Carnot efficiency. So, Brayton cycle with several infinite number of intercooling, reheating and regeneration stages can cause efficiencies which are equal to that of Carnot cycle efficiencies. We have now discussed about the Brayton cycle, which forms a basic cycle for gas turbine engines.

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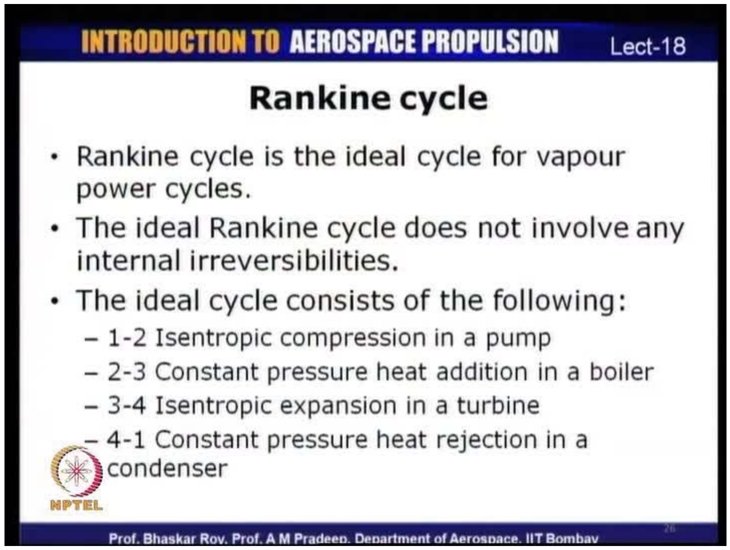

We will now have a very quick look at one of the vapor cycles. Most commonly used vapor power cycle is known as a Rankine cycle. Rankine cycle is the ideal cycle for vapor power plants like the steam power plants. We will have a very quick look at the Rankine cycle. Basically, like the other ideal cycles that we have discussed, Rankine cycle does not involve any internal irreversibility. An ideal Rankine cycle consist of four process- an isentropic compression, which takes place in the case of steam power plant in a pump.

Second process is process 2-3; it is a constant pressure heat addition, which could be in a boiler, in a steam power plant. Process 3-4 is an isentropic expansion, which is in the case of steam power plant in a turbine. Process 4-1 is constant pressure heat rejection, which could be in a condenser. So, these are the four different processes, which constitute a Rankine cycle. An isentropic compression, constant pressure heat addition, isentropic expansion and constant pressure heat rejection.

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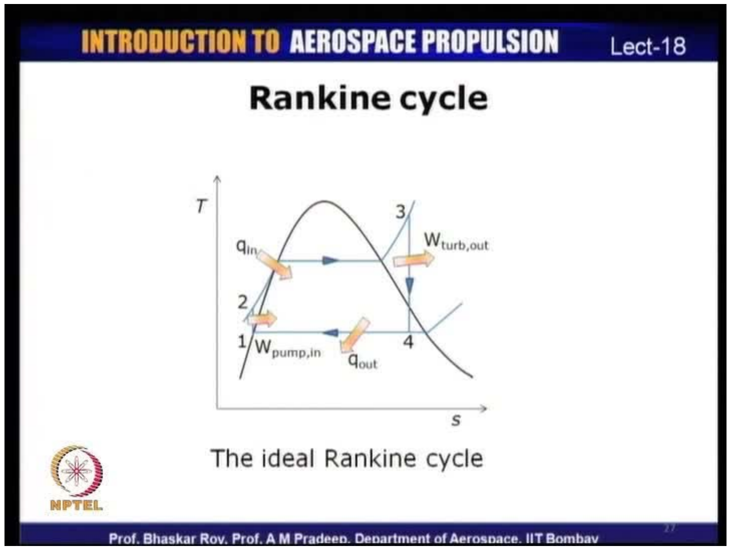

Let us look at a Rankine cycle. On one of the coordinates, we have been plotting these cycles with a T-S diagram. So, an ideal Rankine cycle on a T-S diagram looks like this. What is shown by the black curve here is the saturation line for water. It basically indicates that outside the saturation line, water exist as steam. There is no content of water in steam of this region. It is basically known as super-heated steam. Within this curve, you may have water in both these phases that is water as well as in steam.

Now, the process begins at state 1, state 1 is an isentropic compression. In the case of steam power plant, it is through a pump. Process 2-3 is constant pressure heat addition process. So, constant pressure lines on a saturation curve are shown here. This line here corresponds to a constant pressure line. Process 2-3 is a constant pressure heat addition process, as you add heat, water moves from it and saturates to become a super heat steam at state 3. Process 3-4 is the isentropic expansion process. During process 3-4, there is a net work output from the turbine at the end of process. The third process is expansion process. We have a constant pressure heat rejection. So, process 4-1 is a constant pressure heat rejection process. So, these are the four different processes, which constitute the steam power cycle.

Process 1-2 is the work input in the case of compression. In the case of steam power plant, it is through a pump. So, it is an isentropic compression. Process 2-3 is the constant pressure process, during which, heat is added to the cycle. Process 3-4 is the isentropic expansion process. There is a net work output from the turbine and process 4-1 is constant pressure heat rejection from the cycle. So, the net work output here is the difference between the turbine work output and the pump input. There is a power required for the pump. The difference between the turbine work output and the pump input is the net work output heat input. Difference between q in and q out is the net heat transfer during this cycle.

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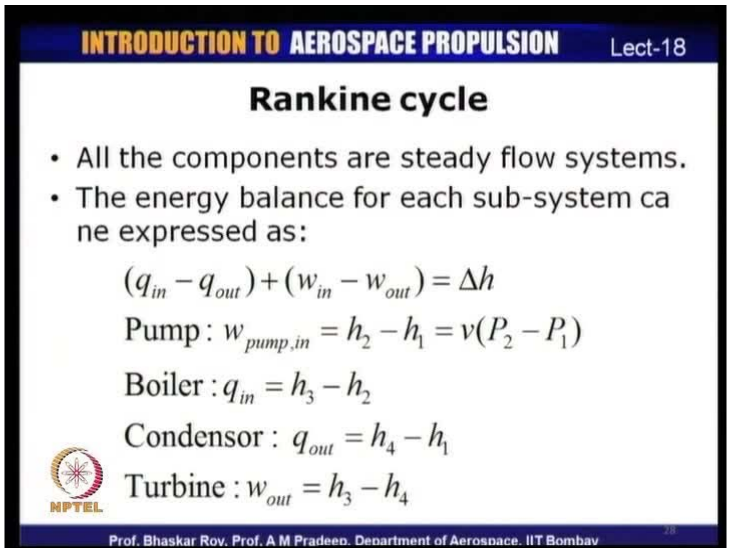

Now, carry out the energy balance for this particular cycle. We again assume that all the components are steady flow and internally reversible systems. The energy balance for each of the systems can be basically expressed, as q in minus q out plus w in minus w out is delta h. Let us look at the each of the components, the pump, we have work required for the pump. Work input is h 2 minus h 1, which is basically v times P 2 minus P 1. For a boiler, there is heat input q in equal to h 3 minus h 2. For condenser, heat rejection is q out, which is h 4 minus h 1. For the turbine, it is work output as h 3 minus h 4.

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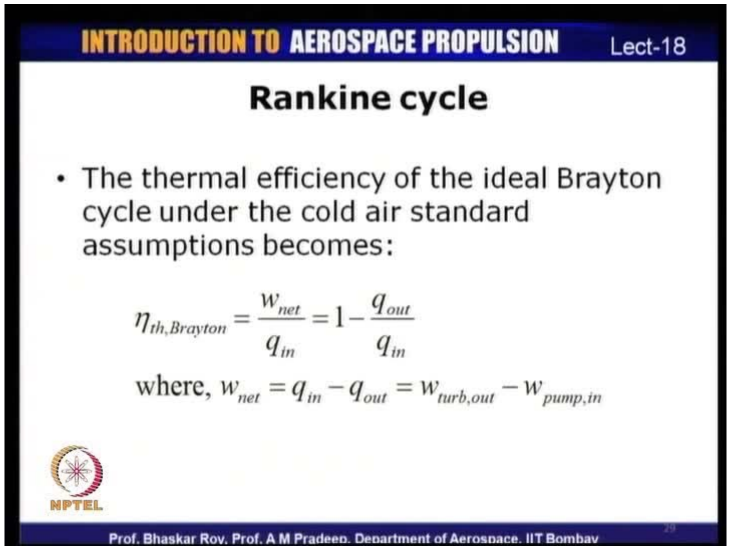

Basically, the thermal efficiency of the ideal Rankine cycle can be determined using the cold air standard assumptions. The Rankine cycle efficiency is w net by q in, it is 1 minus q out by q in. W net is equal to q in minus q out, which is in fact equal to w turbine output minus w pump input. So, these are the different components or constituents of the efficiency. We can calculate the network output and the heat input to determine the thermal efficiency of a Brayton cycle of a Rankine cycle.

For a Rankine cycle efficiency, we need to look at the different constituents of the Rankine cycle because you have the work input for the pump, work output from the turbine, heat input at the boiler end and heat output from the condenser. From this, we can calculate the net work output and the heat input. This can help us in determining the thermal efficiency of a Rankine cycle.

So, Rankine cycle efficiency again depends upon many of these parameters. Unlike an otto cycle or diesel cycle, they are not really able to calculate or express the efficiency in terms of one parameter like a cycle pressure ratio and so on. So, it involves multiple faces. In the case of vapor power cycles, you have different faces of the working fluid that is water, which can exist as water in the pump, super-heated steam in the turbine, saturated steam in the condenser and so on. It is not possible for us to express the efficiencies in a single term.

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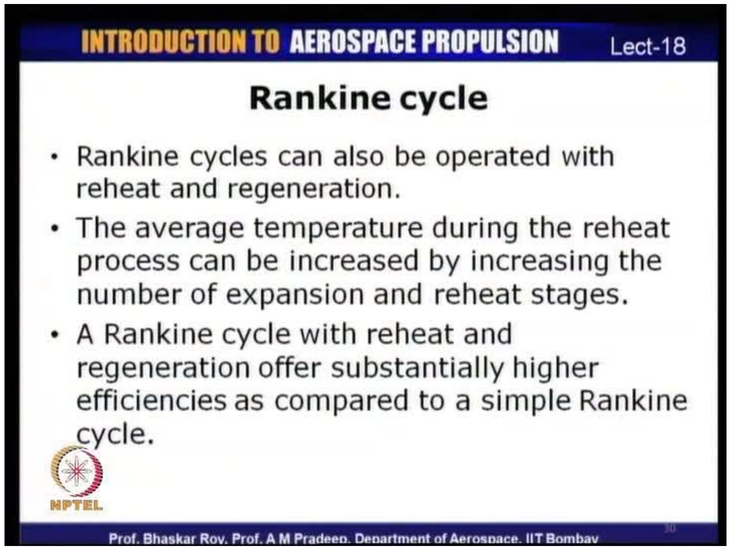

Now, Rankine cycle can also be operated with reheat and regeneration and also with intercooling by multiple staging. So, Rankine cycle operated with reheat and regeneration can increase the net work output and efficiency substantially. Average temperature during reheat can be increased by multiple stages of reheat. You can also increase the number of expansion stages during the reheat process. So that you can increase the average temperature, during which heat is added and therefore, a Rankine cycle with reheat.

Regeneration will have efficiencies, which are substantially higher as compared to the simple Rankine cycle. I will not be taking up discussion on reheat and regeneration during this lecture. I guess I leave it to you as an exercise. Look at Rankine cycle with reheat and regeneration. We have already discussed that for the Brayton cycle. So, it should be possible for you to extend the same for a Rankine cycle.

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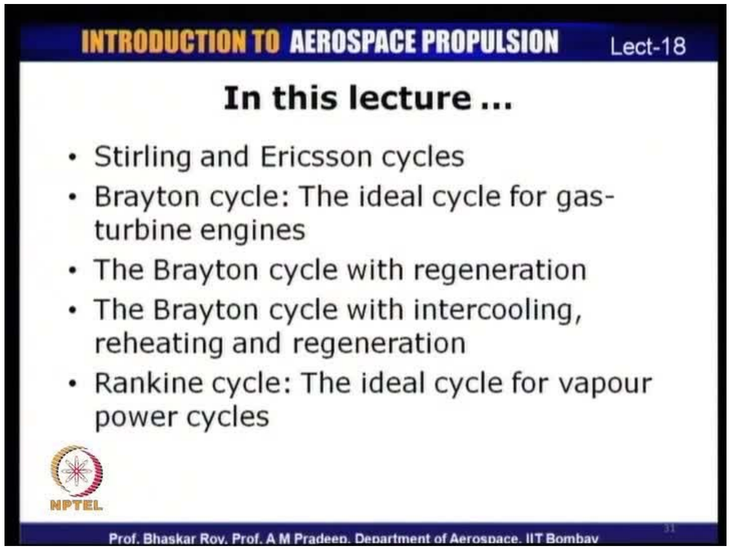

Let us look at what we had discussed in today's lecture. We started our discussion in today's lecture with Stirling and Ericson cycle, which are basic ideal cycle. They have efficiencies as high as that of Carnot cycle because they are totally reversible cycles. Brayton cycle is the ideal cycle for gas turbine engines. We had discussed about Brayton cycle and different variants of the Brayton cycle, methods of improving efficiency Brayton cycle with regeneration, Brayton cycle with intercooling, reheating and regeneration. We also discussed about the Rankine cycle that is the ideal cycle for vapor power cycles.

So, in today's lecture, we had discussed a lot about the various power cycles that are used in engineering applications. Some of the power cycles, which we discussed today were the otto cycle, diesel cycle and the dual cycle as well as the Brayton cycle with many modifications. We also discussed in short about the vapor power cycle. What we are going to discuss in the next lecture is a slightly different topic. It is nothing to do with power cycle. It is basically something to do with basic thermo dynamic relations. So, we will be discussing a lot about some of the important thermo dynamics relations that are used very commonly in thermo dynamic analysis.

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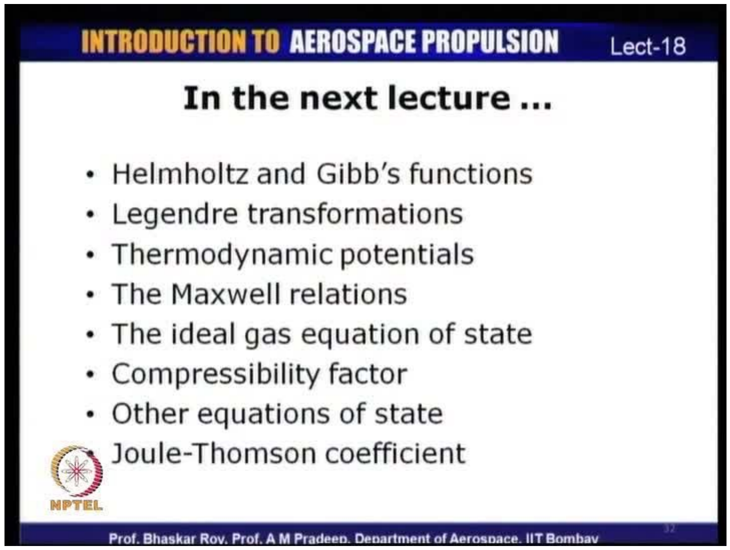

Let us take look at what we are going discuss in the next lecture. In the next lecture, we will have some discussion on what are known as Helmholtz and Gibb's functions. We shall then talk about the Legendre transformations, which are basically used on the Gibb's equation. We will discuss in the next lecture and then we will also discuss about thermo dynamic potentials. We will then discuss a very important set of relations known as Maxwell relations. Maxwell relations are very basic thermo dynamic relations, which are very commonly used in analysis.

We will spend some time on discussing about the Maxwell relations. We will talk about the ideal gas equation of state. I guess you are already familiar with the equation of state. What we should remember is that the equation of state which known as p v equal to r t. It is basically for an ideal gas. We have tried to apply it for real gases and there are certain effects that need to be considered.

We will then talk about the compressibility factor, which is applied for real gases. We will also discuss about some of the other equations of state like the Van der Waal's equation etc. We will discuss about those equations in little bit of detail. Towards end of the next lecture, we will be talking about Joule Thomson effect. It is basically to do with fluid passing through a throttling device. So, these are some of the topics I shall be taking during our lecture19.