# Jet Aircraft Propulsion

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## Module No. # 01
## Lecture No. # 06
## Ideal and Real Brayton Cycles

Hello and welcome to lecture 6 of this lecture series on Jet Aircraft Propulsion. The last few lectures you must have been introduced to different types of aircraft engines and also some of the basic performance parameters that are used in analysis of these jet engines. And in today's lecture what we shall do is to discuss about, the basic thermodynamic cycles based on which all these jet engines, the air breathing engines operate.

And what we shall discuss in today's lecture would be the basic Brayton cycle, which I am sure you would have learnt in your thermodynamics course or if you have done the first course on introduction to aerospace propulsion.

And so, we will first look at take a relook at the Brayton cycle the, ideal Brayton cycle, the variants of the ideal Brayton cycle, that is Brayton cycle with reheating, regeneration and intercooling and also will understand about; what is what are the actual Brayton cycle. So, what is the difference between an ideal Brayton cycle and an actual Brayton cycle?

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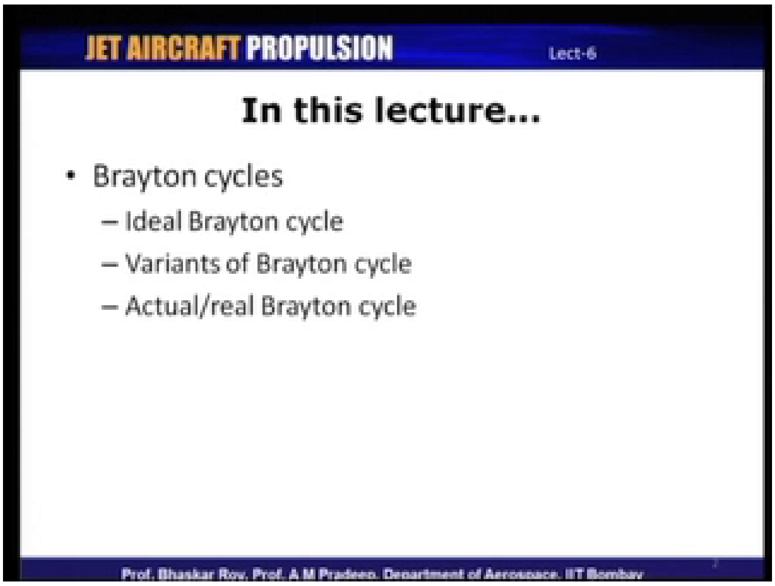

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## In this lecture...

- Brayton cycles
  - Ideal Brayton cycle
  - Variants of Brayton cycle
  - Actual/real Brayton cycle

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So, these are some of the topics, that we shall be discussing in today's lecture, we will began with the ideal Brayton cycle, subsequently will discuss about the variants of the Brayton cycle and then we will discuss about actual or real Brayton cycle.

So, Brayton cycle was something which was proposed by George Brayton in 1870's and the initially it was proposed to be used for reciprocating engines but, as we know it now that Brayton cycle forms the basis for all jet engines, which are rotary in nature that these are not essentially reciprocating engines, they are rotary engines.

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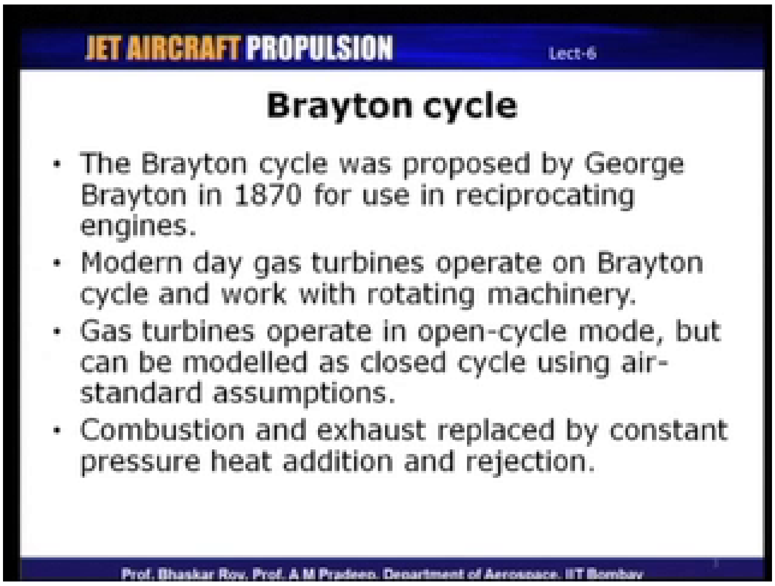

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## Brayton cycle

- The Brayton cycle was proposed by George Brayton in 1870 for use in reciprocating engines.
- Modern day gas turbines operate on Brayton cycle and work with rotating machinery.
- Gas turbines operate in open-cycle mode, but can be modelled as closed cycle using air-standard assumptions.
- Combustion and exhaust replaced by constant pressure heat addition and rejection.

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And so, modern day gas turbine operate on Brayton cycle but, was it basically works with rotating machinery and one of the main differences between the gas turbines and the basic thermodynamic cycle is that, the gas turbines operate in an open cycle mode. Whereas, the Brayton cycle that we shall discuss today is basically a closed cycle system and but, you can still model the gas turbine engines, even though they are open cycle they can be modeled as closed cycle using the air standard assumptions, that as we assume that the combustion products can also be modeled as air.

And so, using that assumption we can still continue to use the Brayton cycle analysis for gas turbine engines even even though, the gas turbine engines operate in open cycle mode. And in Brayton cycle analysis, what we will see is that the combustion process which is what is there in an actual engine as well as the exhaust process is replaced by heat addition and heat rejection processes. We shall not be exactly modeling combustion or exhaust but, we will model them as heat addition process because thermodynamically that is much easier to analyze.

So, heat addition is basically representing the combustion process in a gas turbine and the exhaust is modeled using a heat rejection process. And then one of the later lectures we will we will actually be using the Brayton cycle analysis with combustion and exhaust etcetera put into place, but in today’s lecture we will actually be discussing them with these assumptions.

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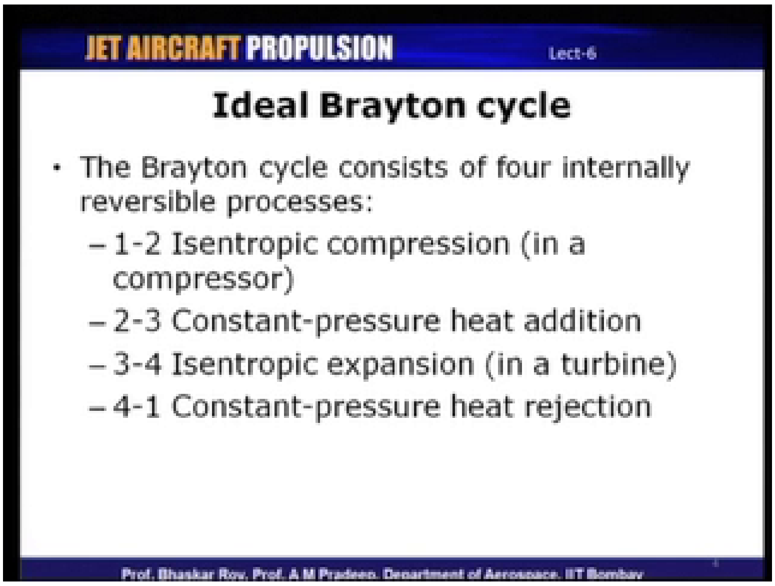

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**Ideal Brayton cycle**

- The Brayton cycle consists of four internally reversible processes:
  - 1-2 Isentropic compression (in a compressor)
  - 2-3 Constant-pressure heat addition
  - 3-4 Isentropic expansion (in a turbine)
  - 4-1 Constant-pressure heat rejection

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And so, Brayton cycle as we know it consist of four processes, the ideal Brayton cycle consist of four internally reversible processes and there are two isentropic processes and two constant pressure processes. So, the first process in the Brayton in the in the ideal Brayton cycle is the isentropic compression process, which could be in a compressor, so process 1 to 2 is isentropic compression in a compressor.

The second process in the ideal Brayton cycle is the constant pressure heat addition, which is from process which takes the process from state 2 to state 3. The third process, which is between states 3 and 4 is isentropic expansion and in a gas turbine this is basically happening in a turbine. And the last process is the constant pressure, heat rejection process between states 4 and 1.

So, these are the four different processes, which constitute a Brayton cycle an ideal Brayton cycle and in an ideal Brayton cycle all these processes are internally reversible in the sense that, there are no irreversibility’s occurring within the system, there could be a irreversibility’s outside the system but, we are not really concerned about that.

So, an ideal Brayton cycle consist of these four processes, the first process is an isentropic compression, where during the compression process the pressure and temperature of air increases and the second process is where you add heat to the system, you add its heat addition process, which in a gas turbine engine is basically the combustion process where fuel is burned and energy is released.

And after the second process, which is a constant pressure process, because it is an internally reversible process, the third process is an expansion process, where the high temperature and pressure air is expanded and in a gas turbine engine it is partially done through turbine and then through a nozzle which we will discuss later on. And after the expansion process, heat is released and in Brayton cycle it is basically a constant pressure heat rejection process. So, these are the four different processes, which constitute an ideal Brayton cycle, so let us, take a look at how these processes look like on pressure verse volume graph as well as temperature verses and entropy graph.

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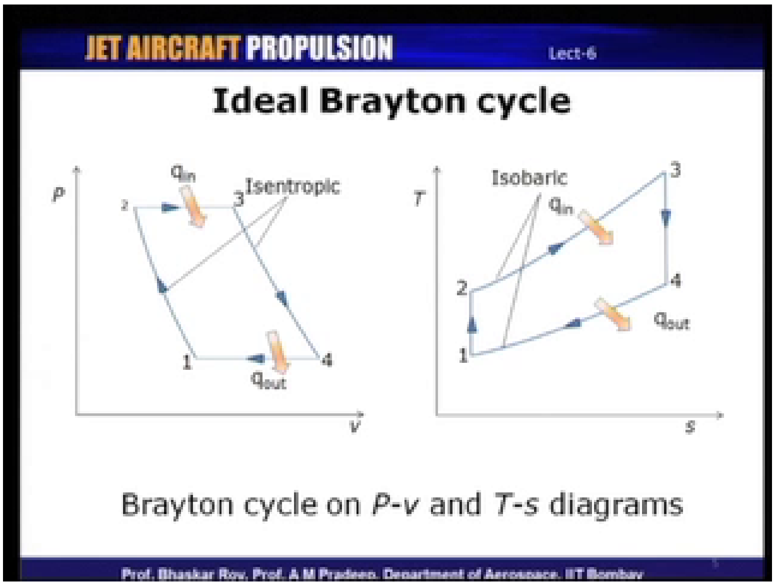
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Ideal Brayton cycle

Brayton cycle on *P*-*v* and *T*-*s* diagrams

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So, the Brayton cycle on P v and T s diagram are shown here, so let us take a look at the P-v diagram first here, we have a process which starts at state 1, the first process is isentropic compression process, because it is a compression process, there is a decrease in this specific volume; we can see that at the end of these process this specific volume is lower than what is was at state 1 and there is an increase in in its pressure at state 2.

So, there is tremendous increase in it is pressure from between states 1 and 2, at the end of this process, where in the state 2 heat is added and heat is added at constant pressure, so pressure is a constant between states 2 and 3. So, heat is added that is q in as show shown here, at state 3 there is another expansion process is which increases during which the specific volume increases and because it is an expansion process, there is a drop in the pressure and this again is an isentropic process.

The fourth process is the heat rejection process, which is again constant pressure process and therefore, there is no change in pressure between states four and state 1 and heat is rejected during this process which is represent by q out. So, all these four processes are shown here, on a temperature verses entropy plot, the first part first process between states 1 and 2 the isentropic compression process is vertical line, because it is isentropic process. So, entropy at states 1 and state 2 are the same but, because it is a compression process, there is increase in temperature.

Now, during the second process, which is a constant pressure heat addition process, there is an increase in temperature, there is also an obvious increase in the entropy of the system; heat is added during this process pressure remains a constant during process 2 3. The third process is isentropic expansion and thus this happens between states 3 and 4 again it is a vertical line because it is isentropic the fourth process between states 4 and 1 is constant pressure heat rejection process, during which heat is rejected from the system and therefore, is an isobaric process.

So, these are the four processes as represented on pressure volume and temperature entropy plots and it is very important that you understand these different processes, because they going to use these diagrams very frequently during the cycle analysis, which is what we will do over the next two, three lectures.

So, make sure that you understood the representation of the Brayton cycle on these different processes, what we will do next is to carry out an energy balance for this particular cycle the ideal Brayton cycle and then we can derive an expression for efficiency of a Brayton cycle. And what we will see later on is that, the efficiency of a Brayton cycle is a function of just the pressure ratio, the cycle pressure ratio rays to some function of the specific heats ratio of specific heats.

So, we will now carry out an energy balance across the Brayton cycle, that we have just discussed from the steady flow analysis, because the whole process Brayton cycle involves the use of steady flow devices and therefore, from steady flow process analysis which you must have studied during thermodynamics course, we can actually derive an expression for the Brayton cycle efficiency.

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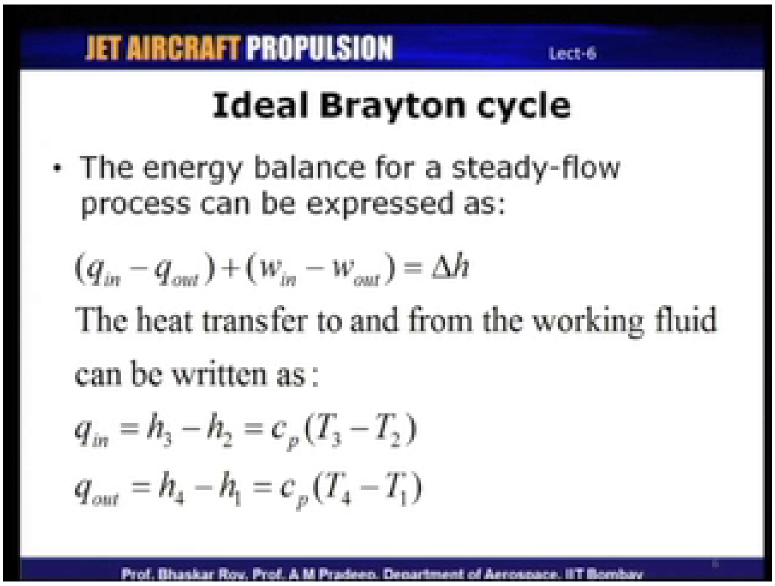

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### Ideal Brayton cycle

- The energy balance for a steady-flow process can be expressed as:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta h$$

The heat transfer to and from the working fluid can be written as:

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

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So, energy balance for a steady flow process, we can express in terms of what is shown here, the heat input the work output and delta h. So, q in minus q out is the difference the net heat added to the system q in is the heat added, q out is the heat rejected from the system. So, the net heat transferred to the system is q in minus q out and what is the net out work output from the system w in is the work input, which is basically the work required for the compression processes; w out is the work output of the system which is basically the work done by the turbine during the expansion process.

So, the net heat added is given by the first term that is q in minus q out, net work output given by the second term which is w in minus w out. And some of these two therefore, should be equal to delta h, which is the net change in enthalpy of the system. So, what are these terms q in and q out, so q in is the net heat transfer to the system which is basically, the net change in enthalpy between states 3 and 2, because that those are two states during which heat is added to the system; so difference between the enthalpy's at states 3 and state 2 is basically the net heat input.

So, q in is equal to h 3 minus h 2, because h 3 is the enthalpy at state 3 minus h 2 which is enthalpy at state 2, which is basically equal to C p times T 3 minus T 2 because, we know that enthalpy is a function of these specific heat at constant pressure times, the pressure temperature. And therefore, if you assume that, specific heat at state 2 and 3 are the same for an ideal cycle that that should be fine and therefore, C p multiplied by T 3 minus T 2 will give us the net heat added during the second process that is heat addition process.

And similarly, the heat rejected during process four will be equal to the net change in enthalpy's between states 4 and 1, which will be equal to h 4 minus h 1 and therefore, that is equal to C p times T 4 minus T 1, that is the product of the specific heat multiplied by the change in temperature occurring during that particular process.

So, q in and q out can actually be expressed in terms of functions of the specific heat at constant pressure multiplied by the change in temperature during, which this process occurs. So, q in and q out can be expressed as these functions, similarly what we will do is, we can also do the same thing for the work done by the system and we know that efficiency of any cycle can be expressed as the ratio of the net work output of the system divided by heat input of to the system.

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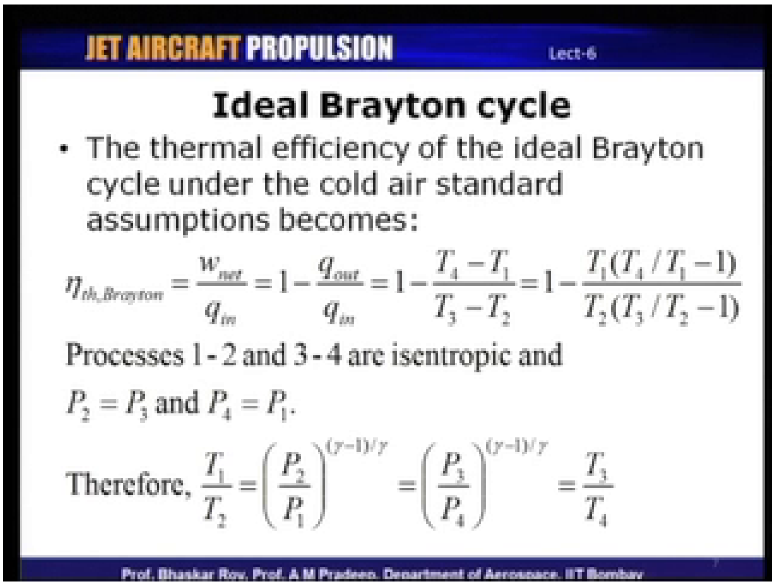

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Ideal Brayton cycle

- The thermal efficiency of the ideal Brayton cycle under the cold air standard assumptions becomes:

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

Processes 1 - 2 and 3 - 4 are isentropic and

$P_2 = P_3$ and $P_4 = P_1$.

Therefore, $\frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma} = \left(\frac{P_3}{P_4}\right)^{(\gamma-1)/\gamma} = \frac{T_3}{T_4}$

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So, thermal efficiency of an ideal Brayton cycle, if we want to assume the air standard assumptions will be eta Brayton that is eta thermal thermal efficiency of the Brayton cycle should be equal to w net by q in, which is equal to one minus q out by q in and why is that for a cyclic process. If you recall from thermodynamics, we know that W net should also be equal to q net and q net is q in minus q out; therefore, w net divided by q in reduces to 1minus q out by q in, we have already derived expressions for q out and q in, q out is equal to C p times T 4 minus T 1 q in is equals to C p times T 3 minus T 2.

Therefore we can reduces this to 1 minus T 1 multiplied by T 4 by T 1 minus 1 divided by T 2 into T 3 by T 2 minus 1, now process 1 2 and 3 4 are isentropic that something we have already discussed that the first that is the compression process and the expansion processes are isentropic. And because, the isentropic as well as the fact that the second process and the forth process are constant pressure processes, where P 2 is equals to P 3 and P 4 is equals to P 1, we have T 1 by T 2 is equals to P 2 by P 1 raise to gamma minus 1 by gamma this is from the isentropic relations.

Now, since P 2 is equals to P 3 and P 4 is equal to P 1, this should be equal to P 3 by P 4 raise to gamma minus 1 by gamma, which in turn is equal to T 3 by T 4; that means, we can replace there temperature ratios T 1 by T 2 with T 3 by T 4.

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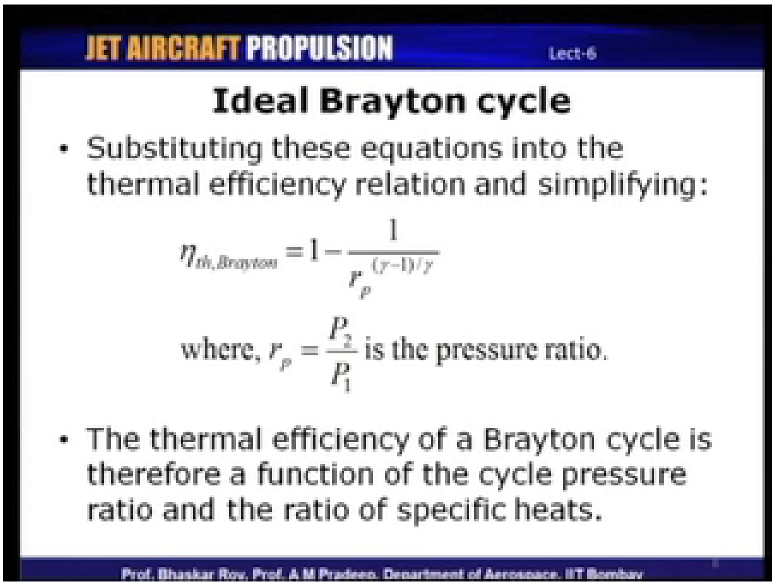

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### Ideal Brayton cycle

- Substituting these equations into the thermal efficiency relation and simplifying:

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

where, $r_p = \frac{P_2}{P_1}$ is the pressure ratio.

- The thermal efficiency of a Brayton cycle is therefore a function of the cycle pressure ratio and the ratio of specific heats.

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And if we do that what happens, that if you want to substitute for T 1 by T 2 with T 3 by T 4, we can actually reduce the thermal efficiency of the Brayton cycle as 1 minus 1 divided by r subscript P rise to gamma minus 1 by gamma where r subscript P is the pressure ratio which is P 2 by P 1. So, what we see here is that the thermal efficiency of a Brayton cycle is something, which is relatively simple x; in the sense that you can very simply by knowing the pressure ratio and assuming the ratio of specific heats.

One can very easily express, thermal efficiency of a Brayton cycle in terms of two simple parameters, that is one is the pressure ratio, that is the cycle pressure ratio P 2 by P 1 and the other parameter, that is involved here is the ratio of the specific heats that is gamma.

So, thermal efficiency of a Brayton cycle of an ideal Brayton cycle is 1 minus 1 divided by r P which is the pressure ratio rise to gamma minus 1 by gamma and so, using this simple expression, one can actually estimate, what would be the efficiency of an ideal Brayton cycle. In fact, what we will discuss little later is that, even for real Brayton cycles, one can get an estimate of how much the efficiency, maximum efficiency can be because, as you already know that actual engines will; obviously, have efficiencies, which are lower than that of the ideal corresponding ideal cycles.

And so, if you know the ideal Brayton cycle analysis, you can determine the efficiency of such a Brayton cycle and that will give as the maximum efficiency, that the actual cycle is going to have and that, where the significance of an ideal cycle comes into picture, in the sense that, it is gives or it set this standard for the performance of actual engines.

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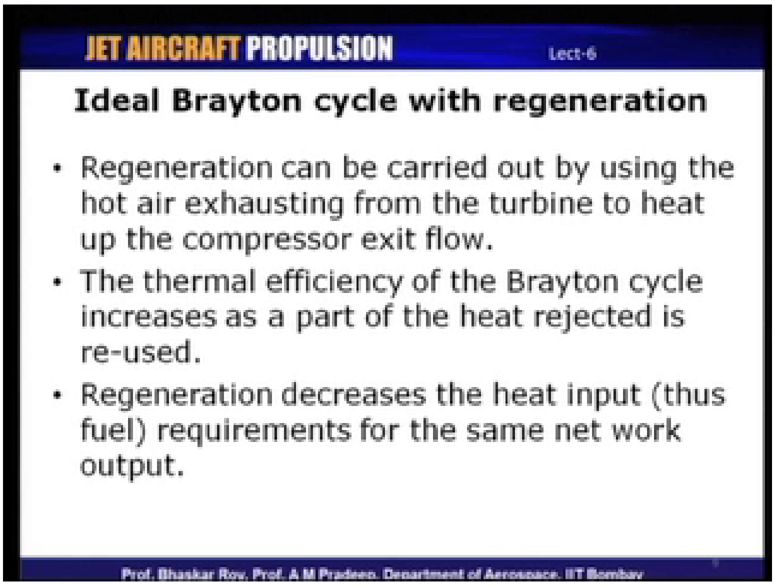

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**Ideal Brayton cycle with regeneration**

- Regeneration can be carried out by using the hot air exhausting from the turbine to heat up the compressor exit flow.
- The thermal efficiency of the Brayton cycle increases as a part of the heat rejected is re-used.
- Regeneration decreases the heat input (thus fuel) requirements for the same net work output.

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And so, what we will do, now is to take a look at the difference combinations or modifications, that can be done to an ideal cycle and therefore, an enhance the performance of an ideal cycle, one of the first modification, that we will be discussing is an ideal Brayton cycle with regeneration.

So, regeneration has you might be knowing is the process there, during which one can transfer energy during one part of the cycle and to some storage device and then during another part of the cycle recover the energy back. Now in a Brayton cycle regeneration can be carried out using the hot air exhausting from the turbine to heat up the compressor exit flow, that is we all one could heat up the fuel that is going into the combustion chamber and so on.

So, that we are recovering part of the heat, which would have the wise be lost, so using regeneration one can improve the efficiency of a Brayton cycle, because we are reducing the q out at the same time we are also reducing the q in; in the since that we can reduce the amount of heat that is to be added, because we are using the part of heat, which would have otherwise be rejected.

So, regeneration is a very cleaver technique of increasing the efficiency of systems, thermodynamically of course, it is very easy to implement, but as we will discuss may be little later, that practical implementation of regeneration for an aircraft engine as it is issues and problems; because anything that we try to do here on an aircraft engine mightily to increasing weight of the system, which is something that an aircraft designer would never want to happen, because weight of the aircraft is always to be kept as low as possible.

And unless of course, that this increase in weight leads to substantial increase in efficiency in performance, that it can out way the extra weight that the aircraft has to carry. So, basically regeneration would decrease the heat input requirements for the same amount of network output and therefore, we know that as we reduce the heat input with the same amount of work output the efficiency can increase.

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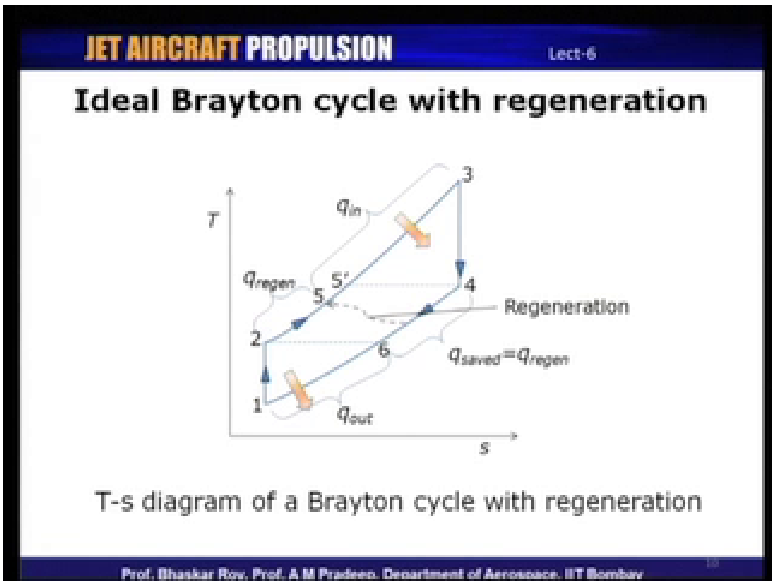

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## Ideal Brayton cycle with regeneration

T-s diagram of a Brayton cycle with regeneration

Let us take a look at regeneration cycle on a T s diagram, again for an ideal Brayton cycle, so this process between 1, 2, 3 and 4 represents an ideal Brayton cycle on a T s diagram, were process is 1 2 and 3 for an isentropic, 2, 3 and 4 1 are constant pressure processes.

Now, we know that heat addition takes place during this process, that is process 2 three, which means that the amount of heat that would have to be added, that is q in should be between states 2 and 3. Similarly heat rejected for simple ideal Brayton cycle would be between states 4 and 1, now regeneration is a process by which we can transfer a small part or part of this heat which is rejected, back to this process 2 3, that is this heat between states 4 and 1 is something which is rejected.

So, which means that if you can reduce the amount heat rejected here and transfer it back here into q in q in also will also reduce therefore, the net heat input will will be reduced. So, regeneration as is shown here, can take base between these two, let us say for an ideal cycle the amount of heat, that has been transferred or recovered or saved is between 4 and 6, that is this much amount of heat has been transferred to this process 2 3.

We know that you cannot have six below this level, because that would mean that the temperature is lower than, that of the compression which is something we we which is not possible thermodynamically, so this the maximum that we can save, that can be regenerated transferred back to the cycle.

And so, let; that means, that would be the ideal ly q regenerated would be between 2 and five prime, that is we can heated all the way up to a temperature, which is equal to the expansion temperature and therefore, q in also has reduced now. So, this is the new q in that is because, of the amount of heat that has been transferred back to this heat addition process.

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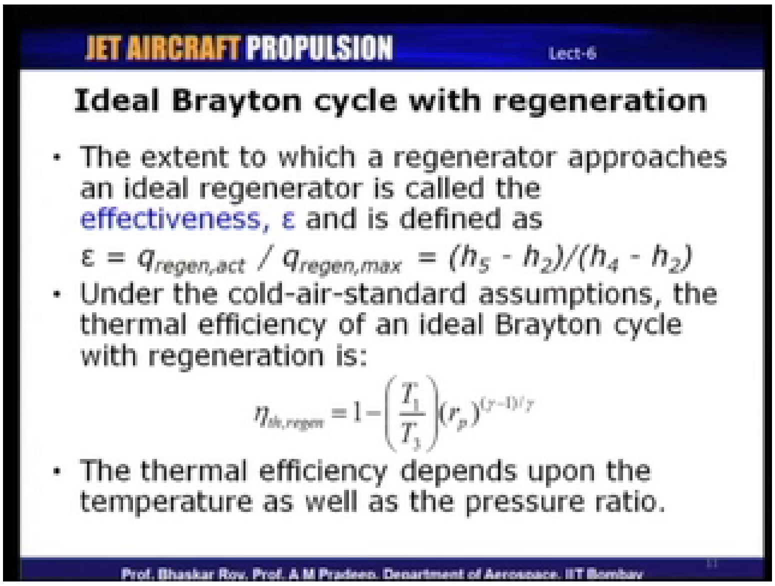

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**Ideal Brayton cycle with regeneration**

- The extent to which a regenerator approaches an ideal regenerator is called the effectiveness, ε and is defined as
  $\varepsilon = q_{regen,act} / q_{regen,max} = (h_5 - h_2)/(h_4 - h_2)$
- Under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle with regeneration is:

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(\gamma-1)/\gamma}$$

- The thermal efficiency depends upon the temperature as well as the pressure ratio.

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So, as a result of heat regeneration, basically we have been able to recover some amount of heat, now the extent to which regenerated can approach an Ideal regenerator if we have an ideal regenerator; that means, amount of heat that can be transferred is between states four and 2, that is h 4 minus h 2 would be the maximum regeneration that is possible that is this much amount of heat can be recovered; well as you know it in in actual practice that will not be possible actual heat regenerated, would be equal to this that is it would be up to a temperature lower than the maximum temperature.

So, q regeneration actual would be h 5 minus h 2, the maximum regeneration possible is h 4 minus h 2 ratio of this is given by what is known as the effectiveness of the regenerator, this is something probably will discuss little later, when we take up the real cycle analysis later on.

So, effectiveness will tell us, the how much amount of regeneration as actually been carried out as compared to what is maximum possible, now if you use the cold air standard assumptions the thermal efficiency of an ideal Brayton cycle with regeneration we can derive an expression; which will be what is shown here thermal efficiency of a regenerating Brayton cycle is 1 minus T 1 by T 3 into r subscribe P rise to gamma minus 1 by gamma.

So, what we can immediately see here, is that the thermal efficiency depends upon yet another parameter in a simple Brayton cycle, we have discuss that the thermal efficiency is a function of the pressure ratio as well as of course, the ratio of specific heats but, in a cycle with regeneration, thermal efficiency also depends upon the temperature ratio.

So, I leave it as an exercise for you to derive this expression, it can be derived in the same way as we have derived the simple Brayton cycle efficiency, only thing is here the heat added and heat rejected is different from what is was for this simple Brayton cycle analysis. So, from our discussion on regenerating Brayton cycle you should be able to derive an expression for the thermal efficiency of a regenerating Brayton cycle. Now I mentioned in the beginning, that there are other modifications possible for a simple Brayton cycle like inter cooling and regeneration something, we have discussed as well as reheating.

Now, inter cooling is something which occurs during the compression process reheating is something that can be applied for the expansion process and regeneration as we have seen is happening between the heat addition and heat rejection processes. So, these are other modification, that we are going to discuss that are to do with inter cooling and reheating.

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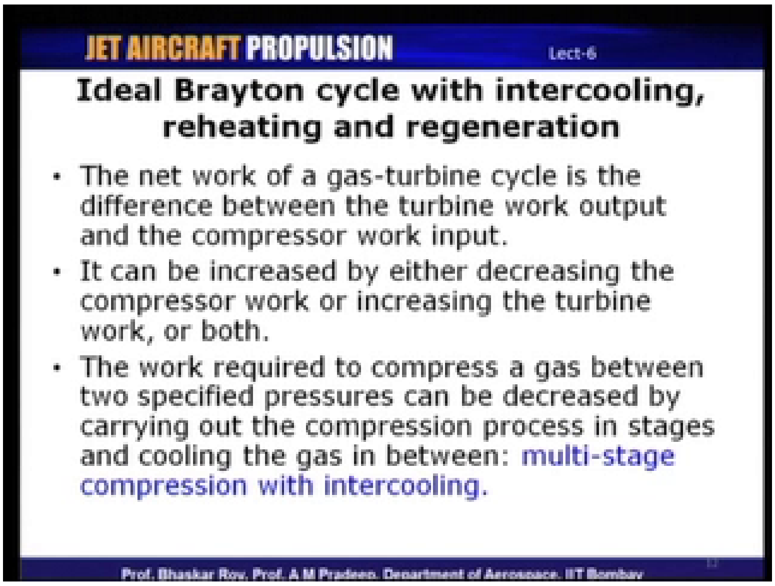

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**Ideal Brayton cycle with intercooling, reheating and regeneration**

- The net work of a gas-turbine cycle is the difference between the turbine work output and the compressor work input.
- It can be increased by either decreasing the compressor work or increasing the turbine work, or both.
- The work required to compress a gas between two specified pressures can be decreased by carrying out the compression process in stages and cooling the gas in between: multi-stage compression with intercooling.

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So, let us take a look at what we mean by inter cooling and reheating, so we know that the network of a gas turbine cycle is basically with the difference between the turbine work output and the compressor work input. So, this can be increased by either decreasing the compressor work or increasing the turbine work or both, that is you could either reduce the work required by the compressor or you could increase the work required or generated by the turbine or we could do both to get an improved efficiency.

And so, let us take a look at the compression process first, the work required to compress a gas between two specified pressures can be decreased by carrying out the compression in different stages and then cooling the gas in between. So, compression process can become more efficient if we want to cool the compression processes or we split the compression processes into different stages and in between the stages, we apply cooling and this is known as intercooling and if it is done for multi stages of the compressor it is known as multistage compression with intercooling.

So, multistage compression with intercooling is one of the options of improving the performance of an ideal Brayton cycle, that is by applying cooling basically, we split the compression process into different stages and then between these different stages, we apply cooling; so that for the subsequence stage it has to do lesser work, has compared to compression between a single compression between the entire pressure ranges. So, if you want to apply the compression for between states 1 and 2 as a single unit as compared to splitting that process into different stages and applying cooling, then the work required in the first case would be higher, than what it would be for the second case.

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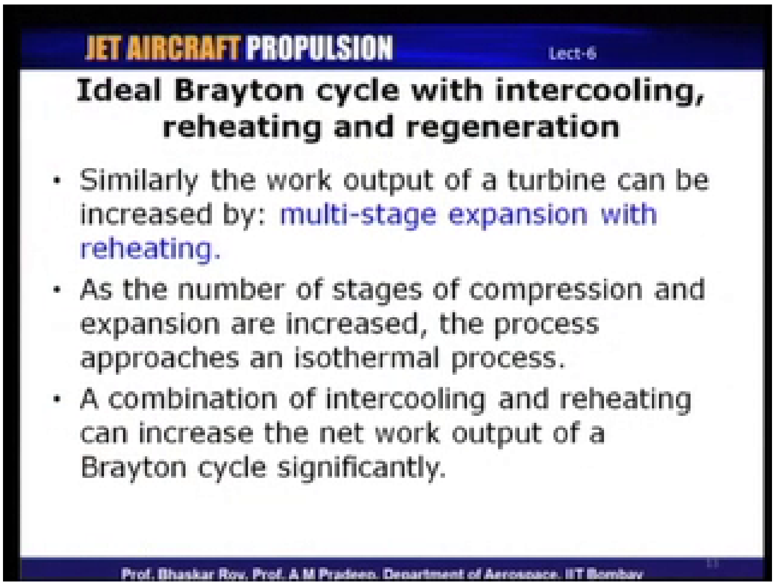

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**Ideal Brayton cycle with intercooling, reheating and regeneration**

- Similarly the work output of a turbine can be increased by: multi-stage expansion with reheating.
- As the number of stages of compression and expansion are increased, the process approaches an isothermal process.
- A combination of intercooling and reheating can increase the net work output of a Brayton cycle significantly.

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So, let us take a look at how it works, so as the number of stages of compression increases, basically the process will approach and isothermal process and ideally if we were to extend the Brayton cycle, an ideal Brayton cycle to have efficiencies approaching that of a carnot cycle, then, we can we need to ensure that the compression process and the expansion process, both these processes are isothermal and if we had regeneration, then comes an Ericsson cycle which is something you would have discussed during your you would have learn during thermodynamics.

So, infinite number of stages of intercooling compression processes makes it an isothermal compression infinite number of heating reheating of the turbine, makes it as an isothermal heat expansion process. And if you also have a regeneration taking place between the heat addition process and heat rejection processes, that is a cycle with number of intercooling stages of compression, number of stages of reheating and also regeneration taking place will represent an Ericsson cycle.

And if you recall Ericsson cycle has efficiency which is equal to that of a Carnot cycle efficiency, which is the maximum efficiency, that you can get and that will be; obviously, higher much higher than, what have a simple Brayton cycle generates. So, that is the advantage of having intercooling.

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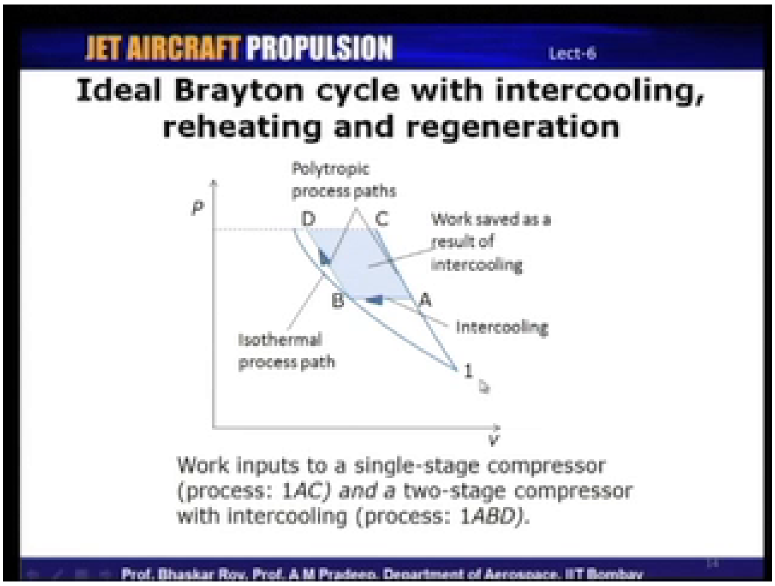

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Ideal Brayton cycle with intercooling, reheating and regeneration

Work inputs to a single-stage compressor (process: 1*AC) and a* two-stage compressor with intercooling (process: 1*ABD).*

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Let us, take a look at how intercooling works, now traditionally the process of compression takes place between states one and C, so this is the normal state of compression, that we are familiar with and we would like the compression process to take this path, which is shown here, which is an isothermal compression process which is what would be the process, which require the least amount of work and the way to do that is to split the compression process into several processes.

And let us say we split it into two stage compression with intercooling, that is process between state 1 and A, this is the first compression process, then we apply an intercooling for an ideal cycle that is at constant pressure and the second stage compression is between states B and D. So, what is shown here, by the shaded area is the amount of work that, we have saved as a result of intercooling; which means that if we had infinite number of these stages of intercooling, the area under this whole curve will be the amount of work that we would have saved as a result of intercooling.

And this is a tremendous amount of work that a work that can potentially be reduced by splitting the compression process into several stages and applying intercooling between them; and so, intercooling is one way in which we can increase the efficiency of cycle, by reducing the work required for a compression process, by trying to approximate a compression process to an isothermal process as much as possible.

Of course, it is also know that, you can known that you cannot have infinite number of stages of intercooling due to practical limitations but, even if you have to finite number of stages of intercooling; let us say one stage intercooling two stage and so on, it will still have a work requirement, which is lower than what an Ideal simple Brayton cycle requires.

So, intercooling is one way in which we can reduce the word required for compression and that is one of the ways of modifying a simple Brayton cycle, so as to get a better performance, what is the other way of doing it? As we have discussed it is reheating that is at the end of compression, well the third process which is the expansion process is basically an expansion in an turbine in a gas turbine engine, what we try to do is to split the expansion process into multiple stages; we have multiple stages of turbines and in between these two stages or several stages, we apply heating.

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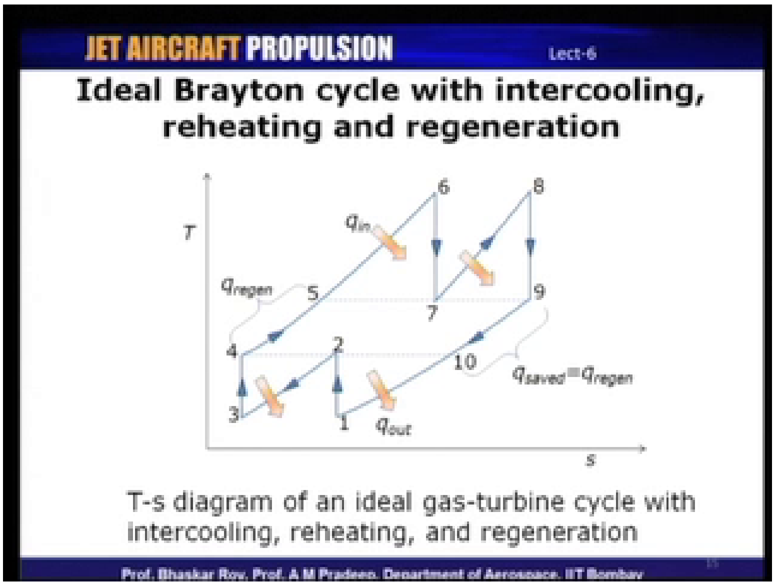

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Ideal Brayton cycle with intercooling, reheating and regeneration

T-s diagram of an ideal gas-turbine cycle with intercooling, reheating, and regeneration

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So, reheating between different stages of turbines also gives us an improved work output, let us take a look how that works in a two stage gas turbine ideal Brayton cycle, with intercooling reheating and let us say regeneration. Let us take a look at the compression process first this is two stage intercooling compression process, the compression as been split into two stages; so, this state 1 and 2 after that it is cooled that is the intercooling, where in heat is removed q out.

Now, consist of this as well and the second stage of compression between states three and four, after this there is a heating that is the heat addition process at the end of which there is expansion the first stage expansion taking place that is between states five as that is between states six and seven. And then the second stage of expansion taking place between states eight and nine, between these two stages of expansion we have a heat addition taking place, which is the reheat process.

So, we now, have two new heat exchange processes is taking place here, one is heat removal from this process during the intercooling and heat addition taking place during reheat process. We have also shown regeneration here an ideal regeneration were in this much amount of heat between states 9 and 10, it transferred to this process between states 4 and 5. So, that this is the heat regeneration, that is between states 4 and 5, so h 4 minus h 5 minus h 4 will be the q regenerated, which is basically equal to h 9 minus h 10 heat input has now, been reduced which is between states 5 and 6.

So, that would be a 6 minus h 5 plus h 8 minus h seven. So, these are the two stages of heat addition and what about heat rejection? Heat rejection between states ten and one that is q out as well as heat rejection during the intercooling process between h 2 or state 2, that and state 3 that is h 2 minus h 3; so heat rejected would be h 10 minus h 1 plus h 2 minus h 3 heat added would be h 6 minus h 5 plus h 8 minus h 7. So, this is a basically showing a Brayton cycle, which as two stages of intercooling and two stages of reheating, that is reheating between two stages of expansion and cooling between two stages of compression.

So, an intercooling and reheating process with regeneration is one of the ways of increasing the performance of Brayton cycle, substantially that is by making these modifications. So, thermodynamically it is very easy to implement, this in the sense that we can always split the compression process into several stages and say that the efficiency will be higher and so on, but there are practical limitations to how many stages can we actually do this, because as we increase the number of stages of either compression or expansion the mechanical complexity also substantially increases.

So, in terms of mechanical design and complexity weight and cost and so on, it does not make an economic sense to have infinite number of compression and expansion processes. So, normally what is say is that two to three stages of intercooling and reheat is probably the maximum that one could be using these principles, so that this whole thing is economically available. So, what we have discuss, so far is about the ideal cycles barrens of ideal cycle, which include regeneration intercooling reheat and so on.

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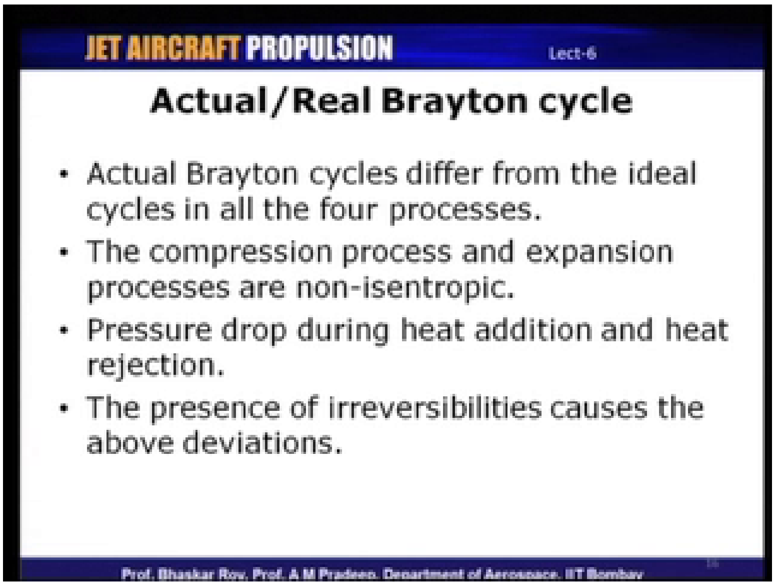

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## Actual/Real Brayton cycle

- Actual Brayton cycles differ from the ideal cycles in all the four processes.
- The compression process and expansion processes are non-isentropic.
- Pressure drop during heat addition and heat rejection.
- The presence of irreversibilities causes the above deviations.

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Let us, take a look at what would be an actual Brayton cycle or real Brayton cycle, how would be this different from an ideal cycle and how is that we can estimate or carry out a cycle analysis for that. So, an actual Brayton cycle or actual Brayton cycles, differ from ideal cycle in all these four processes, one of the basic assumption of an ideal cycle is that all the four processes are internally reversible actual processes are not and for example, the compression and expansion processes in an ideal cycle or assume to be isentropic an actual cycle, these processes are non isentropic.

And the heat addition, heat rejection processes were assume to be constant pressure in actual processes there will be a pressure drop take which takes place during heat addition and heat rejection. So, presence of these irreversibility's will cause a Brayton cycle, an actual Brayton cycle to be quite different from an ideal Brayton cycle.

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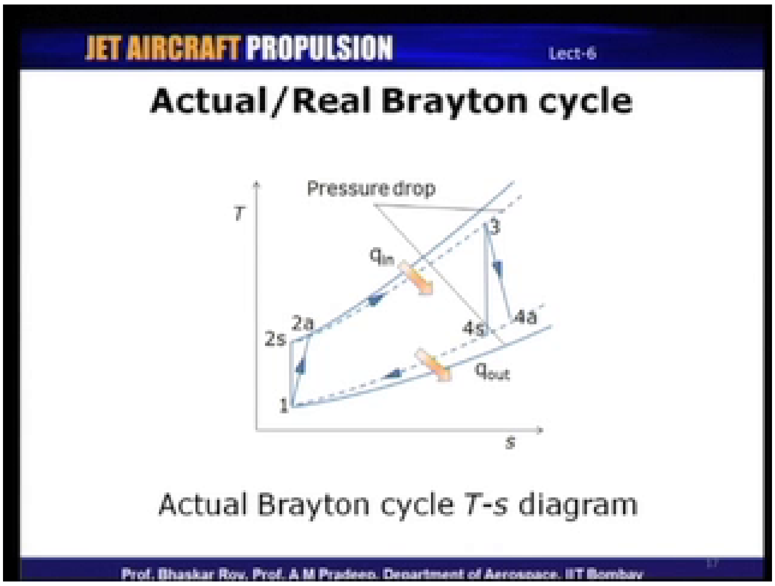

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Actual/Real Brayton cycle

Actual Brayton cycle *T*-*s* diagram

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So, this is how an actual Brayton cycle would be on T s diagram, so what is shown here between states 1 to 2 s, 2 s shows that the state represents an isentropic state. So, 1 to 2 s has is isentropic process, which is how it would have been if the process was ideal, but an actual process is non isentropic, there will be an increase entropy during the compression process.

So, two a is for the actual state actual process takes place between states 1 to 2 a and during this second process, there is as we can see there is a change in pressure it is not a constant pressure process, there is a pressure drop taking place during the heat addition process. And therefore, the temperature at the end of this process is three and the third process is an expansion process, again it is non isentropic, there will be an increase in entropy during this expansion process as well.

So, this would have been the ideal temperature at the end of this expansion process given by 4 s actual temperature is 4 a, again the last process is an expansion process is heat rejection process, during this which heat is rejected and there is pressure drop taking place as well during this process. So, an actual Brayton cycle as you can see consist of all the four processes, that is there is an expansion process, there is heat addition and compression and heat rejection and so on, but all the four processes are different from an ideal Brayton cycle.

So, basically the first two processes that is the compression and expansion processes are nonisentropic, heat addition and heat rejection processes do not take place at constant pressure, so these are the fundamental differences between an actual and a real Brayton cycle.

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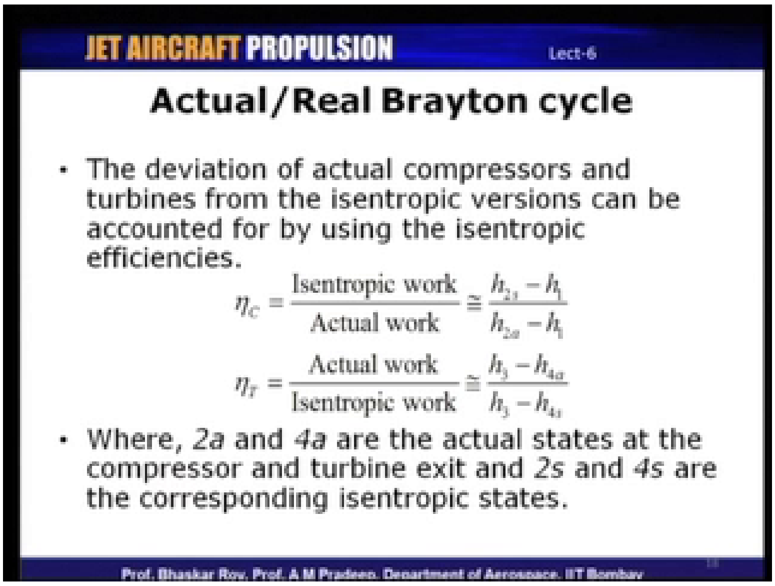

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## Actual/Real Brayton cycle

- The deviation of actual compressors and turbines from the isentropic versions can be accounted for by using the isentropic efficiencies.

$$\eta_C = \frac{\text{Isentropic work}}{\text{Actual work}} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{\text{Actual work}}{\text{Isentropic work}} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

- Where, *2a* and *4a* are the actual states at the compressor and turbine exit and *2s* and *4s* are the corresponding isentropic states.

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So, how do you account for these differences, now we know that there are the differences between an actual and an ideal Brayton cycle. Now one of the ways of accounting for the differences between is the deviation of actual compressors and turbines is by estimating or defining the efficiencies during the compression and expansion process. Now let us take a look at the compression for process first, now efficiency as we will define now as isentropic efficiency of the compression process, we will is basically the ratio of the isentropic work to the actual work.

Now, if you go back to the T s diagram I was showing in a compression process Ideally if the process work to be isentropic the work required would be lower than, what it would be for an actual process therefore, the efficiency the isentropic efficiency of the compressor would be equal to ratio of the isentropic work to the actual work. Now for a turbine it is the other way round, because the work output of an actual turbine will be lower than, the isentropic work output. Therefore, the isentropic efficiency of a turbine will be equal to the ratio of the actual work to the isentropic work, (Refer Slide Time: 41:03) it will be little more clear if you go back to the T-s diagram and take a look at these definition once again.

Now, this is the compression process, the ideal compression process between states 2 s and 1, the actual compression process between states 2 a and 1, so this difference is because of the presence of irreversibility's. So, h 2 s minus h 1 is the isentropic enthalpy difference h 2 a minus h 1 is the actual entropy difference enthalpy difference that is how it would define the efficiency of this process the compression process; similarly for the expansion process we have h 3 minus h 4 a the actual work divided by h 3 minus h 4 s as which is the isentropic work.

So, isentropic efficiency of a compressor would be equal to h 2 s, which is the a entropy at the enthalpy at the end of state 2 Isentropic process minus h 1 divided by h 2 a, which is enthalpy at the end of state the process, actual process that is state 2 minus h 1. For the turbine it would be equal to actual work by isentropic work, which is equal to h 3 minus h 4 a which is the actual work or enthalpy at end of the expansion process at state a divided by h 3 minus h 4 s, which is the enthalpy at state 4 for the isentropic process.

So, here 2 a and 4 a represents the actual state, which is corresponding to that of the compressor and the turbine exit and 2 s and 4 s are those corresponding to the isentropic states. So, using these isentropic efficiency definitions, one can estimate the deviation that an actual cycle would have as compared to an ideal cycle, so difference between an actual cycle and an ideal cycle can be in some sense by estimated using these efficiency definitions.

Now, the other processes where there are differences between the actual and ideal cycle is the pressure lose taking place during the heat addition process and heat rejection process. So, if we know the pressure lose that occurs between the heat addition process and the heat rejection process, one could also estimate the loses that would be occurring during that process.

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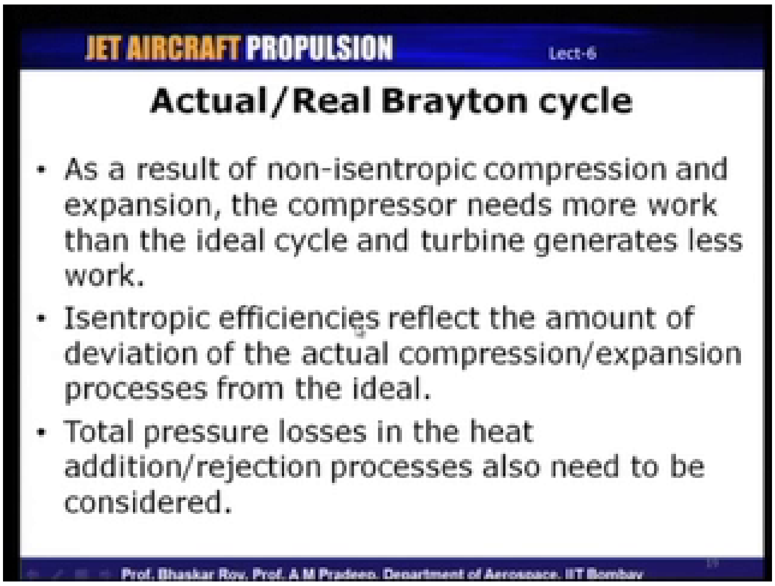

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## Actual/Real Brayton cycle

- As a result of non-isentropic compression and expansion, the compressor needs more work than the ideal cycle and turbine generates less work.
- Isentropic efficiencies reflect the amount of deviation of the actual compression/expansion processes from the ideal.
- Total pressure losses in the heat addition/rejection processes also need to be considered.

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So, as a result of this non isentropic compression expansion, the compressor of these needs more work than ideal cycle and the turbine generates less work than the ideal cycle.

So, isentropic efficiencies as we have defined it, now reflect the amount of deviation the actual or compression or a expansion processes have from the ideal and the total pressure losses in which occur in the heat addition or rejection processes, we will also have to be considered, so that, we can have an analysis of the cycle which is different from that of a ideal cycle.

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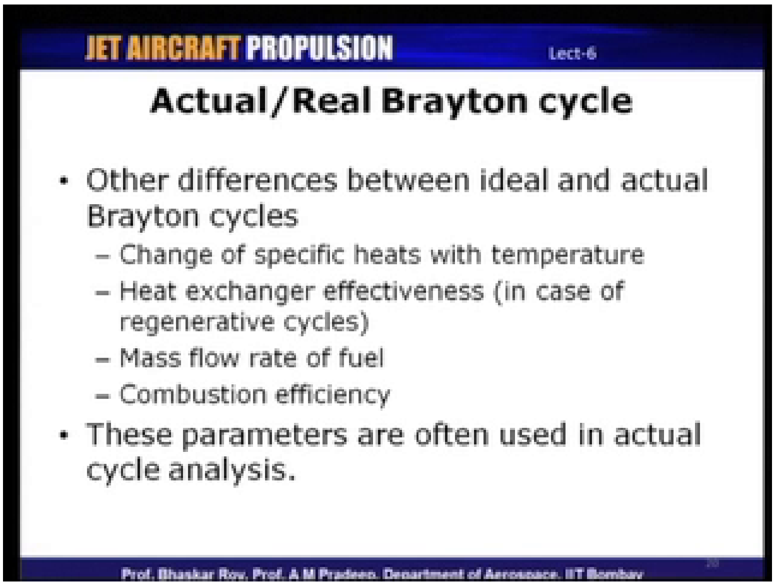

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## Actual/Real Brayton cycle

- Other differences between ideal and actual Brayton cycles
  - Change of specific heats with temperature
  - Heat exchanger effectiveness (in case of regenerative cycles)
  - Mass flow rate of fuel
  - Combustion efficiency
- These parameters are often used in actual cycle analysis.

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Now, there are also some other differences, which have which occur between ideal and actual cycles, which are sometimes used in cycle analysis one is the change of specific heats with temperature. Now, we have assumed in ideal cycle for cold air standard assumptions that specific heats do not change with temperature, which is not really true specific heat before combustion and after combustion could be substantially different.

So, there is a change in specific heat, which also could be consider, other parameter that could be consider is the heat exchanger or regenerator effectiveness if there is regeneration in the cycle, then the third parameter that sometimes is consider the mass flow rate of fuel; that is often of course, it is much its negligibly small quantity for aircraft engines at least, because mass flow rate of air is usually much higher many times higher than there of the fuel.

But, it sometimes considered in analysis and also the efficiency of the combustion process itself given by the combustion efficiency is yet another parameter, that is sometimes used. So, some of these parameters, which also show the deviation of actual cycles from the ideal cycles are sometimes used in the actual or real cycle analysis.

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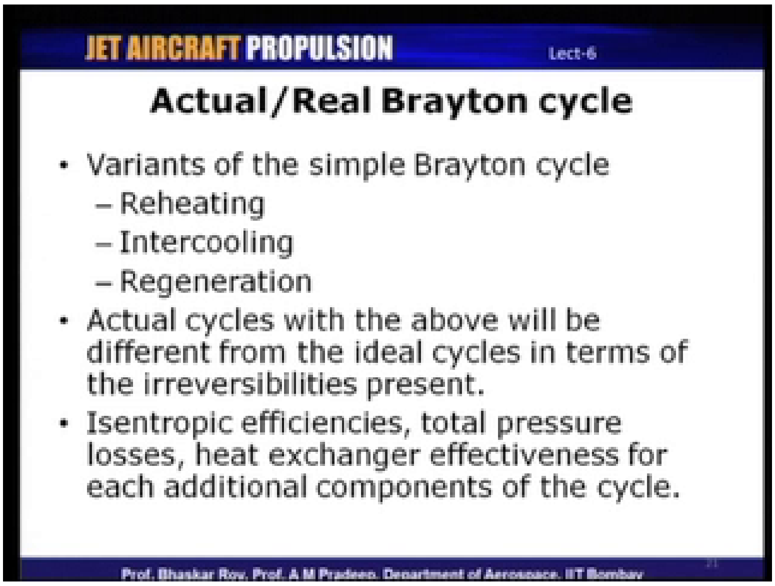

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## Actual/Real Brayton cycle

- Variants of the simple Brayton cycle
  - Reheating
  - Intercooling
  - Regeneration
- Actual cycles with the above will be different from the ideal cycles in terms of the irreversibilities present.
- Isentropic efficiencies, total pressure losses, heat exchanger effectiveness for each additional components of the cycle.

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Now, we have already discussed about variants of the simple Brayton cycle, the ideal cycle that could have reheating, intercooling or regeneration, now actual cycles with the above will be different from the ideal cycles in terms of the irreversibility's, that is an actual Brayton cycle with reheating will; obviously, be different from the real cycle, because there could be a loses taking place during the reheat process, there is there could be pressure losses in the reheat reheating may not take place at constant pressure.

Similarly, the isentropic efficiencies of individual stages of either reheating or intercooling, then the heat exchanger effectiveness, these are different parameters which will come into picture, when we have actual cycles actual Brayton cycles, which have some of these variants that is intercooling, reheat or regeneration which are quoting. So, simple Brayton cycle with all these individual components or a combination of these modification with reheat, intercool or regeneration, will need to have the isentropic efficiencies of individual components; the total pressure lose taking place during either the intercooling process or during the reheat process and in some cases, that could be heat exchanger effectiveness and so on.

So, these are some of the parameters which will have to be considered, when we have an actual Brayton cycle with these cycle modifications, so let us take a for example, an actual Brayton cycle with intercooling. Now actual Brayton cycle with intercooling would have intercooling taking place at different stages, so there would be isentropic efficiencies associated with each of these stages.

So, efficiency of each of these stages of intercooling is something, that will have to be considered the second parameter that will have to be considered is the heat exchanger effectiveness, between these two stages of or different stages of intercooling; let say we have a multi stage compression with intercooling.

So, each stage of compression will have it is own isentropic efficiency and intercooling, we will have some amount of heat exchanger effectiveness that will have to be considered. Now for Brayton cycle with let say reheating alone; that means that the expansion process or the turbine is split into multistage. So, multiple stages of expansion with reheat in between and therefore, each stage will have it is own efficiencies isentropic efficiency of expansion for each of these stages, with the amount of total pressure loss that is taken place during each of these stages of reheating.

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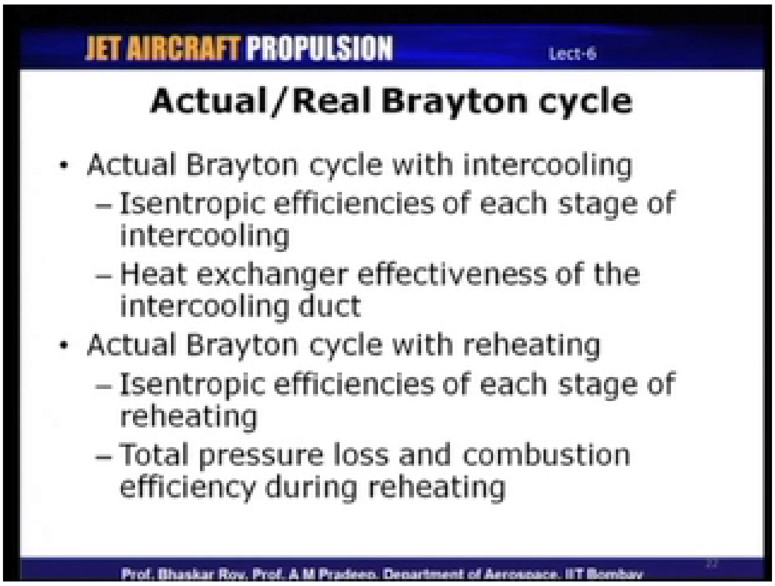

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Actual/Real Brayton cycle

- Actual Brayton cycle with intercooling
  - Isentropic efficiencies of each stage of intercooling
  - Heat exchanger effectiveness of the intercooling duct
- Actual Brayton cycle with reheating
  - Isentropic efficiencies of each stage of reheating
  - Total pressure loss and combustion efficiency during reheating

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So, total pressure loss and combustion efficiency, during reheat that would have to be consider for an actual cycle with reheat, for intercooling we consider isentropic efficiency of each stage and also the heat exchanger effectiveness of the intercooling. That with reheat, we have isentropic efficiencies of each of these stages of reheating and the second aspect would be, total pressure loss and combustion efficiency, which we will have to be consider during reheat.

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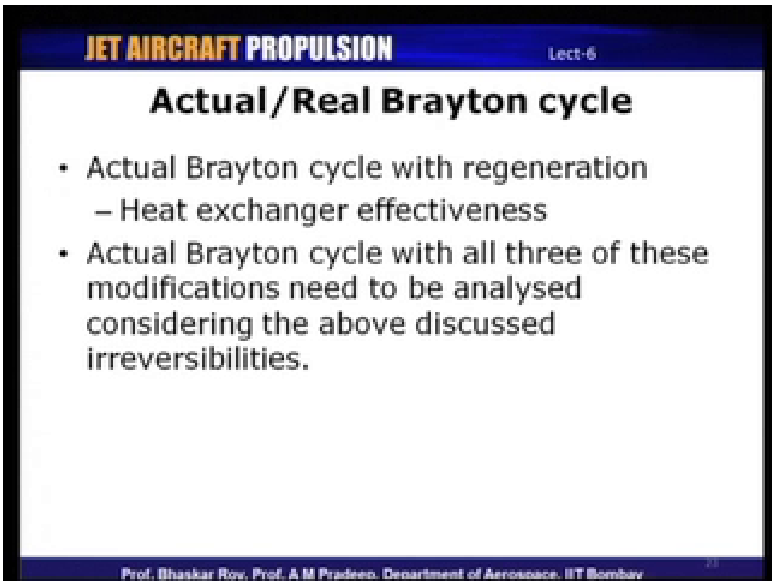

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## Actual/Real Brayton cycle

- Actual Brayton cycle with regeneration
  - Heat exchanger effectiveness
- Actual Brayton cycle with all three of these modifications need to be analysed considering the above discussed irreversibilities.

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Now, with regeneration, let us say the above cycles are being used with regeneration, regeneration as we know it is basically a heat transfer process, so heat exchanger effectiveness will also have to be considered during an actual Brayton cycle which operates with regeneration. So, an actual Brayton cycle with all these three modification will have to be considered or will have to be analyzed, while considering all these above irreversibility's.

Which pertain to efficiencies of the compression process and efficiencies of the expansion process and also pressure loses taking place, during either heat addition or heat removal or during reheat process. So, in an actual Brayton cycle, if all these irreversibility's are taken into account, one can actually estimate the net efficiency of such a cycle, compare that with the corresponding ideal cycle efficiency and then, we could basically have an estimate of where the loss in efficiency is taking place.

Because, if we were to have a Brayton cycle an actual Brayton cycle which has efficiencies approaching, that of an ideal Brayton cycle then basically the improvement in terms of reduced compressor, work increased turbine work output. And heat recovery from the exhaust these are some of the aspects that will have to be taken into an account, so has to improve the efficiency of an actual Brayton cycle.

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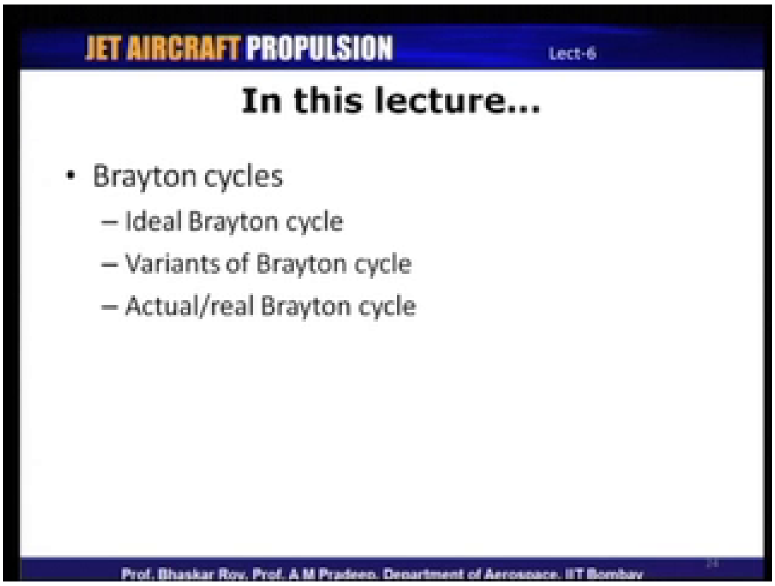

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In this lecture...

- Brayton cycles
  - Ideal Brayton cycle
  - Variants of Brayton cycle
  - Actual/real Brayton cycle

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So, let me summarize, what we have discussed in in today's lecture, we were discussing about Brayton cycles and we started how discussion with the ideal Brayton cycle the ideal simple Brayton cycle, which did not have any modifications. So, it just consisted of four processes a compression process, which was Isentropic, a constant pressure heat addition process, an Isentropic expansion process and a constant pressure heat rejection process.

So, these are the four different processes, which compared which constitute an ideal Brayton cycle, so this Brayton cycle can be operated with certain modifications or variation you could have intercooling in the compression process at is split the compression process into multiple stages with intercooling. So, as to reduce the net compressor work, we could split the expansion processes into multiple stages and apply reheating in between, so has to increase the expansion work and also use regeneration that is recover part of the heat, that is rejected transfer it to the heat transfer heat input process.

So, variation of the simple Brayton cycle and then, we also discussed about actual Brayton cycle or real Brayton cycles, variants none of the processes are idealize, there are none of the processes are internally reversible; for example, compression and expansion processes are non isentropic heat addition and heat rejection process do not take place at constant pressure.

So, if we include all these irreversibility's than the process becomes, what is known as an actual Brayton cycle, so these were some of the topics we have discussed during today's lecture.

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In the next lecture…

- Jet engine cycles for aircraft propulsion
  - Turbojet engine
  - Turbojet engine with afterburning
  - Turbofan and its variants
  - Turboprop and turboshaft engines

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And what will discuss in the next lecture would be basically to do with jet engine cycles, that is how a Brayton cycle can be used for a jet engine for aircraft propulsion, will discuss different version of the cycle, will start with the simple turbojet engine. Then will continue with turbojet engine with afterburning, then will take up turbofan and it is variants and also will discuss about turboprop and turbo shaft engines. So, the jet Brayton cycle for all these different forms of engines is something well, that will be discussing during the next lecture.