# Introduction to Aerospace Propulsion

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**Module No. # 01**

**Lecture No. # 14**

## Carnot cycle, Carnot principle, thermodynamic temperature scale

Hello, welcome to lecture 14 of this lectures series on introduction to aerospace propulsion. Over the last several lectures, we have been discussing some of the important aspects of thermodynamics including definition of certain basics terms of thermodynamics.

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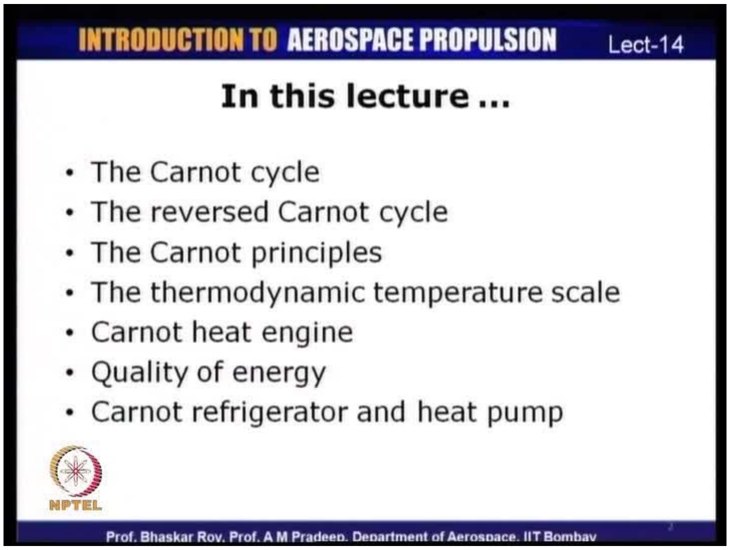

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

In this lecture ...

- The Carnot cycle
- The reversed Carnot cycle
- The Carnot principles
- The thermodynamic temperature scale
- Carnot heat engine
- Quality of energy
- Carnot refrigerator and heat pump

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We shall continue our journey in understanding basics of thermodynamics in today's lecture. What we are going to discuss today are the following: we shall be talking about one of the very basic fundamental cycles of thermodynamics, which is known as the Carnot cycle.

We shall be discussing about the Carnot cycle, which forms the basis of a very reversible cycle which has which we shall see in subsequent lectures slides today. This is a very fundamental cycle and we can define certain efficiencies based on that.

Then, we shall define what is known as the reversed Carnot cycle; followed by this we shall define Carnot principles and based on the Carnot principle we shall define the thermodynamic temperature scale. We have already defined thermodynamic temperature scale in earlier lectures, based on the constant volume thermometer and so on.

So, today we shall define a very fundamental much more fundamental aspect of the temperature scale based on the Carnot principle. We shall then talk about, what is known as the Carnot heat engine, which is a heat engine based on the Carnot cycle.

Then, we shall understand what is meant by quality of energy. We have already discussed about quantity associated with energy, but what we shall discuss today is that in addition to quantity, energy also has a certain quality associated with it. Towards the end of today’s lecture, we shall be talking about the Carnot refrigerator and heat pump.

These are some of the topics that we shall be discussing in today’s lecture. Over the last several lectures, what we have seen is that the efficiency of a thermodynamic cycle is affected or limited by lot of irreversibilities. That is, in actual processes the irreversibilities occur and therefore affect the efficiency of these cycles.

Also, we have discussed during our dissection of the reversible cycles or reversible processes that the efficiency of a cycle can be maximized, if we have a process which has reversible processes. So, in the presence of the reversible processes in a cycle can maximize the efficiency of a cycle.

So, it would be very nice if we have a certain cycle which can form a standard or basis which has all the processes, which are reversible. Therefore, we can compare all actual cycles with reference to the standard cycle. So, it is towards this effect that we shall be discussing about what is known as the Carnot cycle.

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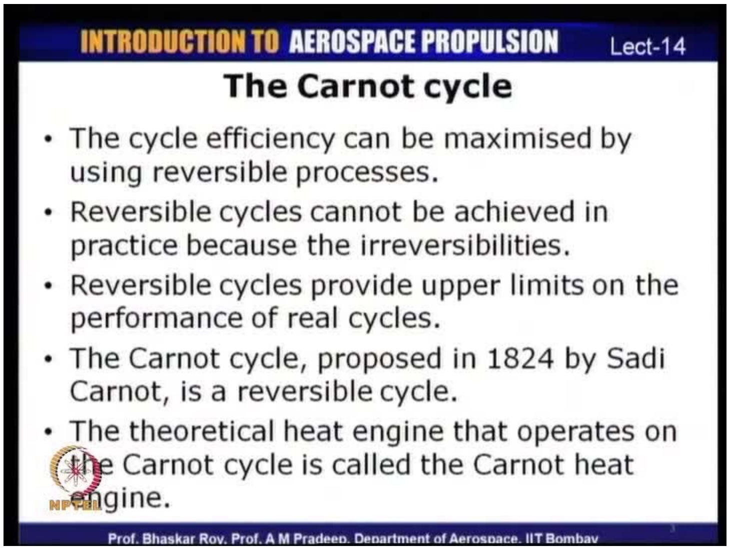

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### The Carnot cycle

- The cycle efficiency can be maximised by using reversible processes.
- Reversible cycles cannot be achieved in practice because the irreversibilities.
- Reversible cycles provide upper limits on the performance of real cycles.
- The Carnot cycle, proposed in 1824 by Sadi Carnot, is a reversible cycle.
- The theoretical heat engine that operates on the Carnot cycle is called the Carnot heat engine.

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This was way back in 1824s that a French scientist or French engineer named as Sadi Carnot defined, what is known as, or proposed a cycle which had all the processes which were reversible. So, cycle efficiency as we have discussed can be maximized, if we use reversible processes. Obviously, reversible cycles cannot be achieved in practice because of lot of irreversibilities that take place in reality.

If we have a certain cycle, which has lot of, or which comprises of reversible processes will provide an upper limit for the performance of the actual or real cycles. So, Sadi Carnot in 1824 proposed a cycle, which is known as the Carnot cycle.

Carnot cycle is basically a cycle which consists of all the processes which are reversible. The theoretical engine, which is based or which is operating on a Carnot cycle is known as a Carnot heat engine. This is what we discuss in today’s lecture; what is the significance of the Carnot cycle and Carnot heat engine and how is it that we can access the performance of real engines as compared to Carnot cycles?

Carnot cycle basically consists of 4 processes and all these 4 processes are reversible; 2 of these processes are reversible adiabatic processes and 2 of the other processes are reversible isotherms. So all the four processes being reversible, there are 2 isotherms and 2 adiabatic processes, which constitute a Carnot cycle.

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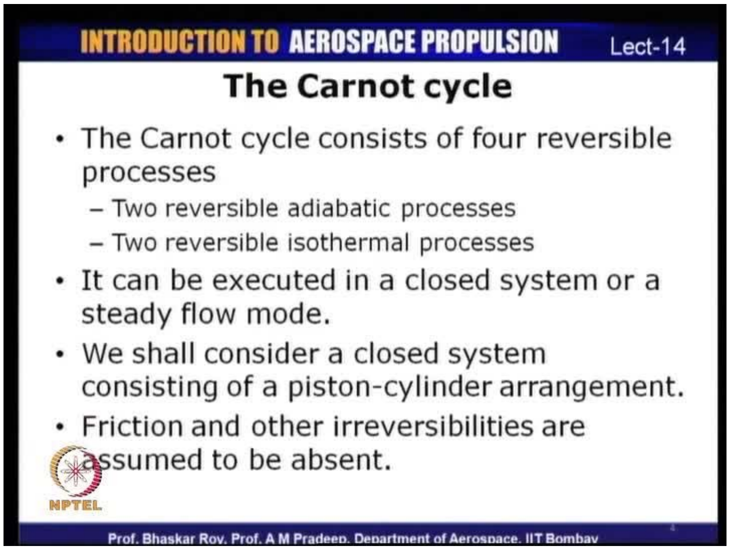

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## The Carnot cycle

- The Carnot cycle consists of four reversible processes
  - Two reversible adiabatic processes
  - Two reversible isothermal processes
- It can be executed in a closed system or a steady flow mode.
- We shall consider a closed system consisting of a piston-cylinder arrangement.
- Friction and other irreversibilities are assumed to be absent.

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A Carnot cycle can be executed either in a closed system form or in an open system or open cycle form. So, Carnot cycles can actually be operated in either modes. You can either have a closed system which operates on a Carnot cycle or an open system which operates on a Carnot cycle. We shall be discussing some more aspects of this, as we progress.

What we shall do initially is to derive an expression for defining some of the aspects of a Carnot cycle. So, before that let us understand how a Carnot cycle can be executed in a simple fashion.

For this we shall be considering a closed system, which consist of a piston cylinder arrangement as we have been discussing throughout the course and of course we shall be neglecting aspects like friction and other irreversibilities, because all these processes as we have discussed, have to be reversible.

If a process has to be reversible, all sources of irreversibilities must be absent and so we shall neglect the effects of friction and other irreversibilities. So, we shall first consider a piston cylinder arrangement.

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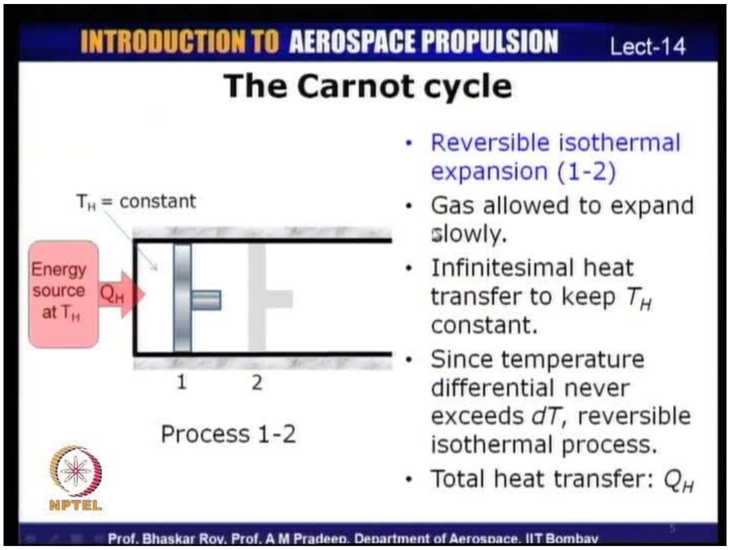

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## The Carnot cycle

Process 1-2

- Reversible isothermal expansion (1-2)
- Gas allowed to expand slowly.
- Infinitesimal heat transfer to keep $T_H$ constant.
- Since temperature differential never exceeds $dT$, reversible isothermal process.
- Total heat transfer: $Q_H$

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Depending upon what process is being executed, we shall be isolating or we shall be insulating one of the boundaries of the piston cylinder arrangement. So, what is shown in the slide here is the piston cylinder arrangement, which we were discussing.

On two of these boundaries, we can see that there is an insulation provided. So, this represents insulation on these walls but on these boundaries there in no insulation. So, it is possible that we can have an energy interaction or through heat transfer taking place through this boundary. So, the first process in the Carnot cycle is a reversible isothermal expansion.

During this process, we say that the system moves from its state 1 to state 2. During this process, the gas which is housed inside the piston cylinder arrangement is allowed to expand slowly and how does it expand? It expands basically because of the energy transfer heat transfer which is taking place from the energy source, which is a T H to the cylinder which is again at T H. Now, if this energy interaction has to take place reversibly, as we have seen that energy interaction through a finite temperature difference can lead to irreversibilities.

This temperature transfer and heat transfer which is taking place must be at a differential temperature, which does not exceed a value of d T. So, this makes it a reversible process and how is that isothermal? It is isothermal because as you transfer certain amount of heat to the cylinder, the piston moves slowly from in its state 1 proceeding towards final state 2. So, this process obviously takes place quasi statically that is the piston moves at an infinitesimal slow rate so that is in equilibrium at all instances of time. So, the piston moves at infinitesimal slow rate from state 1 to state 2.

This occurs because of an infinitesimal small heat transfer, which is taking place from the source which is at a temperature T H to the cylinder and such a way that the temperature difference differential never exceeds a value of d H. If it exceeds a value of d H then there is a heat transfer taking place through a fine temperature difference, which can lead to irreversibilities.

The total heat transfer which has taken place during this reversible isothermal process, let us quantify it by Q H. So, the first process is a reversible isothermal expansion process because it is an expansion process. We know that the volume has to increase which is what happened inside the piston cylinder arrangement.

So, the system has moved from its state 1 to state 2 through a process which is reversible. It is reversible because we assumed all other sources of irreversibilities to be absent and also that the heat transfer is taking place through a temperature differential of d T, which is an infinitesimally small temperature differential.

This ensures that the process is reversible. It also ensures that the temperature inside the cylinder remains a constant. So, this process can be qualified as an isothermal process.

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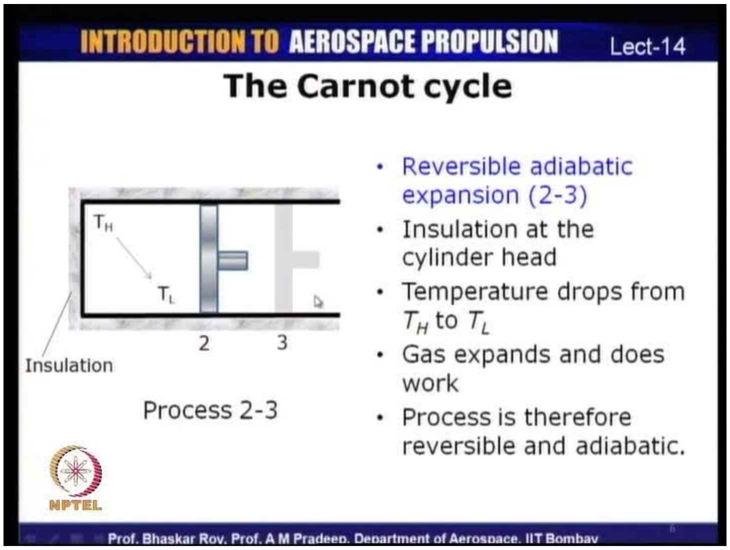

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## The Carnot cycle

- Reversible adiabatic expansion (2-3)
- Insulation at the cylinder head
- Temperature drops from $T_H$ to $T_L$
- Gas expands and does work
- Process is therefore reversible and adiabatic.

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The first process of the Carnot cycle is a reversible isothermal process. Now, the second process is basically a reversible adiabatic expansion process. During this process, the system moves from its state 2 to state 3. We know that it is an adiabatic process, which means that there cannot be any heat transfer taking place through the system boundaries.

We place insulation at the cylinder head to ensure that there is no heat transfer taking place across this system boundary. We have seen that there is already insulation on the other walls of the cylinder. During this reversible adiabatic expansion process from state 2 to state 3, the piston moves from the position which was at state 2 to a new position state 3 because it is an expansion process the volume has to increase. As this happens, the temperature within the cylinder drops from temperature T H to a temperature T L and so the gas expands. As we have seen, expanding gas does work on the movable boundary and so there is a p d v work during this process.

Now, why is the process reversible? It is reversible because we have assumed that frictional losses are negligible so irreversibilities are 0. It is also an adiabatic process because all the cylinder walls have insulation around them and so it makes the process reversible as well as adiabatic. So, this is the second process of the Carnot cycle, which is a reversible adiabatic expansion process.

So, the first two processes we have seen - first one was reversible isothermal expansion process and second process during which the system moves from state 2 to state 3 is an reversible adiabatic expansion process. Now, let us look at what is the third process in the Carnot cycle. The third process consists of a reversible isothermal compression process.

The next two processes as we shall see are the compression processes. So, the third process is a reversible isothermal compression process, during which the system move from its state 3 to state 4 and because it is a compression process we know that the volume inside the cylinder has to decrease. Now, again we remove the insulation which was placed at the cylinder head to enable heat transfer to take place from the system to the sink.

Now, the system was a temperature T L at the end of the second process and because this has to be isothermal process, temperature T L has to remain a constant.

How do we ensure that the temperature can remain a constant? It can be ensured, if as the piston moves quasi statically the temperature raises by an amount d T and at the same time if we are able to transfer this temperature d T from the system to the sink, which is again at the temperature T L. We can ensure that the process is reversible because the temperature differential is only d T and also that it is reversible because there are no other frictional or irreversibilities taking place.

Again, here the temperature differential between the system and the surroundings never exceed a value of d T. Therefore, it is a reversible isothermal process. So, let us quantify the heat transfer which has taken place between the processes by Q L. So, Q L represents the heat transfer which has taken place during this third process, which is a reversible isothermal compression process. It is isothermal because the temperature inside the cylinder is kept a constant at T L.

Last process probably you would have already guessed by now, is going to be a reversible adiabatic compression process because we have seen that they already been through expansion process and one compression process. Then, this is the last process in the Carnot cycle. It is a reversible adiabatic compression process, during which the system moves from state 4 to state 1. Now, because it is an adiabatic process, we reinstate the insulation at the cylinder head and because there is in insulation from all the sides, there cannot be any heat transfer between the system and the surroundings. So, it is an adiabatic process and it is a compression process, during which the piston moves from state 4 to state 1. So, as the piston moves from state 4 to state, it causes an increase of temperature from T L to T H.

There is an increase of temperature from T L to T H and so the temperature rises to where it was at the beginning of the process. Remember, we had started the Carnot cycle at a temperature of T H. We now have a cycle, in which all the processes are reversible and which consist of 2 expansions processes and 2 compression processes and the system comes back to its original state at the end of the process. So, this is a reversible cycle which is now known as the Carnot cycle. This was the cycle, which was proposed by Carnot way back in 1824 because Carnot felt that there is a need for defining cycle, which can form the basis for comparing real cycles with an ideal cycle. So, Carnot cycle is an ideal cycle and we would like all real life cycles to reach at some point, which is closer to the Carnot cycle.

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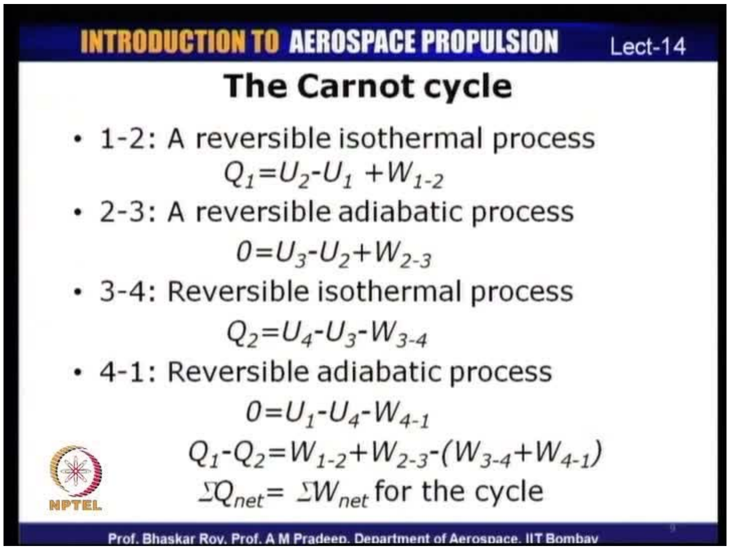

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## The Carnot cycle

- 1-2: A reversible isothermal process
  $Q_1=U_2-U_1+W_{1-2}$
- 2-3: A reversible adiabatic process
  $0=U_3-U_2+W_{2-3}$
- 3-4: Reversible isothermal process
  $Q_2=U_4-U_3-W_{3-4}$
- 4-1: Reversible adiabatic process
  $0=U_1-U_4-W_{4-1}$

$$Q_1-Q_2=W_{1-2}+W_{2-3}-(W_{3-4}+W_{4-1})$$

$\Sigma Q_{net}=\Sigma W_{net}$ for the cycle

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So that efficiencies can be very high and whereas we shall see little later Carnot cycles have the maximum possible efficiencies because Carnot cycle is a reversible cycle. In this 4 processes that we have seen consisting of 2 reversible adiabatics and 2 reversible isotherms, let us now look at the energy interactions, which have taken place between the systems and the surroundings. So, process 1 to 2 was a reversible isothermal process, during which let us say the initial system there was a heat transfer, which was equal to Q 1 and Q1 which is corresponding to the heat at the state 1 is equal to delta U plus W. This is as per the first law of the thermodynamics Q 1 is equal to U 2 minus U 1 plus W 1 2. So, W 1 2 correspond to the work done during the process 1 to 2. The second process is 2 to 3 which is a reversible adiabatic process, because it is adiabatic process, Q is equal to 0. So, 0 is equal to U 3 minus U 2 plus W 2 3, where W 2 3 is the work done during the process 2 3. The third process is 3 to 4, which is again a reversible isothermal process and here Q 2 will be equal to U 4 minus U 3 minus W 3 4. So, why is it minus W 3 4? Well it is minus W 3 4 because there is work done on the system. So, as per our definition for or as per our sign convention for work done on a system is taken as negative.

The last process is 4 1, which is a reversible adiabatic process and again Q is equal to 0 because it is a adiabatic process. 0 is equal to U 1 minus U 4 minus W 4 1, again work is negative because work is done on the system.

If you add up all this, because as we have seen for a cycle. First law for a cycle states that sigma Q net is equal to sigma W net. This is applicable for a cycle. So, if you add up all the work done all the energy interactions, the net heat transfer should be equal to the net work done, which is what you would get if you add up all the heat transfer done during the process that is sigma Q. If you add up all the right hand side which consisted of the internal energy and the work done, you would get sigma Q is equal to sigma W. So, for a cycle as we have seen sigma W should be equal to sigma Q. Now, what we shall do next is to plot the Carnot cycle on the common coordinates of plotting like pressure and volume as well as temperature and entropy. So, we will plot the Carnot cycle on P V and t s diagrams and we shall see how a Carnot cycle looks like.

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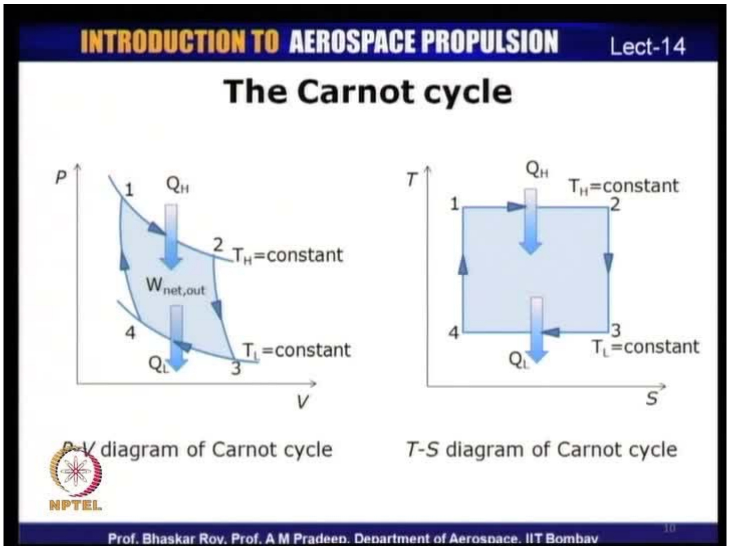

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The Carnot cycle

P-V diagram of Carnot cycle

T-S diagram of Carnot cycle

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Let us look at the P V diagram first. On a P V diagram, this is how the Carnot cycle would look like. Now, the process starts at state 1 and so we first have a reversible isothermal expansion. So, it is an expansion process, which means that the pressure has to drop and the volume has to increase, which is what you can see as the system moves from its state 1 to state 2 and temperature is a constant because it is an isothermal process.

T H is equal to constant here. At the end of the process 1 and during process 1 to 2, there is a heat transfer of Q H into the system. So, at the end of process one it is the system is at state 2, then there is a reversible adiabatic expansion, which causes the system to move from state 2 to state 3 with a drop in temperature from T H to T L. At the end of process 2, the system is at state 3.

Then, we begin our compression processes. The first process is a reversible isothermal compression, which means T L should be a constant and it is an isothermal process. There is a heat transfer taking place at Q L from the system to surroundings. At the end of process 3, we reach the state 4 and the last process is reversible adiabatic compression, taking the system back to its initial state, which was state 1 and the temperature of the system was T H. As we have already seen, the area under the curve in a P V diagram represents the net work output.

So, this is how a Carnot cycle would look like on a P V diagram. Let us also see, how it looks like on a T S diagram that is temperature and entropy diagram. On temperature entropy diagram, the first process is isothermal, T H is equal to constant and so we have a horizontal line, which corresponds to the isothermal process from state 1 to state 2.

During this process, there is a heat transfer Q H to the system. From state 2 to state 3, it is a reversible adiabatic process. If you recall during our earlier lectures, we had discussed that reversible adiabatic process is represented by

Is when I entropy remains at constant. So, reversible adiabatic process corresponds to an isentropic process and because it is an isentropic process, we have a vertical line meaning entropy remains constant. So, process 2 to 3 is a reversible adiabatic process, which is an isentropic process, where in entropy is a constant.

Process 3 to 4 is again an isothermal process. During which, Q L is transferred from the system to the surroundings and so again we have a horizontal line because temperature is a constant. Last process is a reversible adiabatic process and isothermal process and again it is a vertical line.

On a T S diagram, we can say that the Carnot cycle is basically represented by 2 horizontal lines, which correspond to isothermal process and 2 vertical lines, which correspond to isentropic processes. So, it is very important for us to remember how the Carnot cycle can be represented on P V and T S coordinates.

We shall be representing more of the real cycles, in a very similar fashion on P V and T S coordinates in later lectures. So, this is about the Carnot cycle and how we can understand the Carnot cycle in terms of the reversible processes involved and how we can represent a Carnot cycle on pressure, volume and temperature entropy coordinates.

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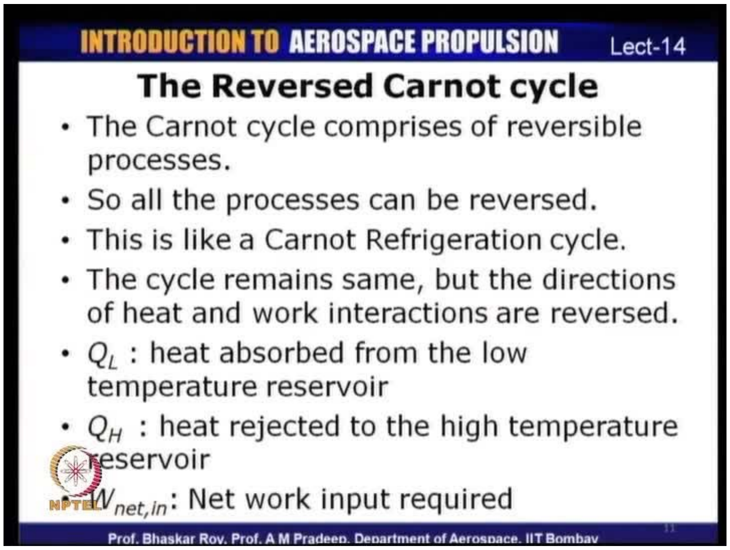

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The Reversed Carnot cycle

- The Carnot cycle comprises of reversible processes.
- So all the processes can be reversed.
- This is like a Carnot Refrigeration cycle.
- The cycle remains same, but the directions of heat and work interactions are reversed.
- $Q_L$ : heat absorbed from the low temperature reservoir
- $Q_H$ : heat rejected to the high temperature reservoir
- $W_{net,in}$: Net work input required

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What we shall see next is, how we can reverse a Carnot cycle because it is a reversible cycle, the reverse of the cycle also should be feasible. What we shall discuss about next is what is known as a reversed Carnot cycle. So, a reversed Carnot cycle will basically consist of processes which can be reversed.

All the processes, as we have seen a Carnot cycle can be reversed and so if we can reverse all the processes, we get what is known as or which is similar to what is known as a Carnot refrigeration cycle. The cycle remains exactly the same but the directions of heat and work interactions are reversed because it is a reversed Carnot cycle.

Which means that Q L will now correspond to the heat, which is absorbed from the low temperature reservoir and Q H will correspond to the heat rejected to the high temperature reservoir and W net in will be the net work required to carry out the cycle because for refrigeration cycle, we have seen that there is work required work input required to ensure that there is heat transfer from a low temperature source to a high temperature sink.

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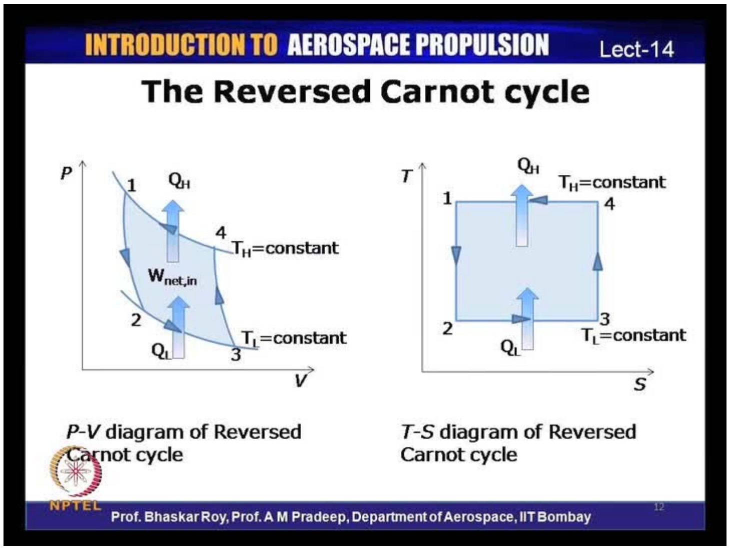
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The Reversed Carnot cycle

*P-V* diagram of Reversed Carnot cycle

*T-S* diagram of Reversed Carnot cycle

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So, a reversed Carnot cycle will consist of process which can be reversed and the cycle remains the same. All the processes will remain exactly the same, as what it was previously but just that the directions of heat and work interactions will be reversed. So, if you were to plot the reversed Carnot cycle on P V and T S diagrams, they would look exactly similar to what it was for the normal Carnot cycle, just that the directions of heat and work interactions will be reversed. Let us look at, what the reverse Carnot cycle would look like. Reverse Carnot cycle, as I mentioned looks exactly the same as the previous one but just that the direction of heat interaction, a work interaction has been reversed. Here, we have a heat transfer from low temperature T L towards a high temperature T H taking place.

This obviously will require a work input and the direction of the heat and work interactions are reversed, so the whole cycle is now reversed. The process begins at one and goes in this fashion and it will look exactly the same as it was in the previous case. So, the same cycle has now been represented on the T S diagram as well. Here, again process is exactly the same just that there heat and work interactions have been reversed.

This is basically reversed Carnot cycle, which is kind of used to represent refrigeration cycles and as we shall see later on in today’s lecture. We are going to use the Carnot cycle to define what is known as Carnot heat engine and we shall use the reverse Carnot cycle to define the Carnot refrigeration and heat pump cycles or heat engines.

We shall be comparing, this will form the basis for comparing actual cycles with something which is ideal and something which has the maximum efficiency.

Now, that we have understood what is meant by what is basically a Carnot cycle. We shall now define or understand what are the principles of Carnot or Carnot principle as they are known as. We have seen that as a consequence of the second law of thermodynamics, there are theoretical limits to the efficiencies which an ideal cycle can have in fact obviously all real cycles also have theoretical limits for their maximum efficiencies. So, Carnot cycle basically forms the basis for defining for which maximum limit of any heat engine that the efficiency of a heat engine can take.

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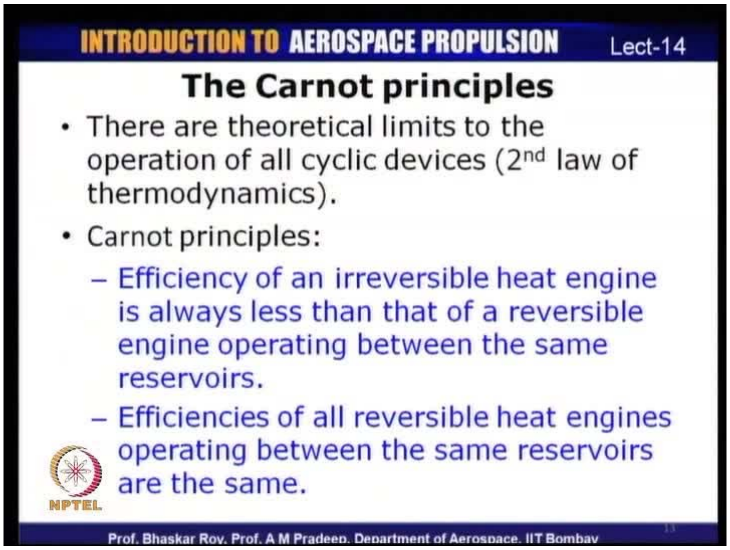

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**The Carnot principles**

- There are theoretical limits to the operation of all cyclic devices (2nd law of thermodynamics).
- Carnot principles:
  - Efficiency of an irreversible heat engine is always less than that of a reversible engine operating between the same reservoirs.
  - Efficiencies of all reversible heat engines operating between the same reservoirs are the same.

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So, based on the Carnot cycle and Carnot principles, Carnot defines certain principles and these are known as Carnot principles. So, Carnot principles basically state that the efficiency of an irreversible heat engine is always less than that of a reversible engine operating between the same reservoirs.

The first Carnot principle, this is the basically the first Carnot principle; first Carnot principle states that, the efficiency of an irreversible heat engine is always less than that of the reversible engine is they are operating between the same temperature reservoir.

Which means that, all real life cycles which are irreversible will have efficiencies, which are less than that of a reversible engine which is operating between the same temperature reservoirs. The second Carnot principles states that efficiencies of all reversible heat engines operating between the same reservoirs are the same. So, the second Carnot principles states that all reversible heat engines which operate between the same temperature source and sink will have the same efficiency. So, the first Carnot principle states that a reversible heat engine has the maximum efficiency, which means that it is impossible for any irreversible engine to have efficiencies which are higher than that of a reversible engine, if both of them are operating between the same temperature reservoirs or same temperature differential reservoirs.

The second Carnot principle states that, if you look at a number of reversible heat engines, which are operating between the same source and sink, all of them will have the same efficiencies. As a consequence of the Carnot principles, Carnot principle basically puts an upper limit on the efficiency of all irreversible heat engines as well as on all reversible engines because reversible engine will have the maximum efficiency. All irreversible engines will have efficiency which is obviously less than that of a Carnot cycle or Carnot heat engine.

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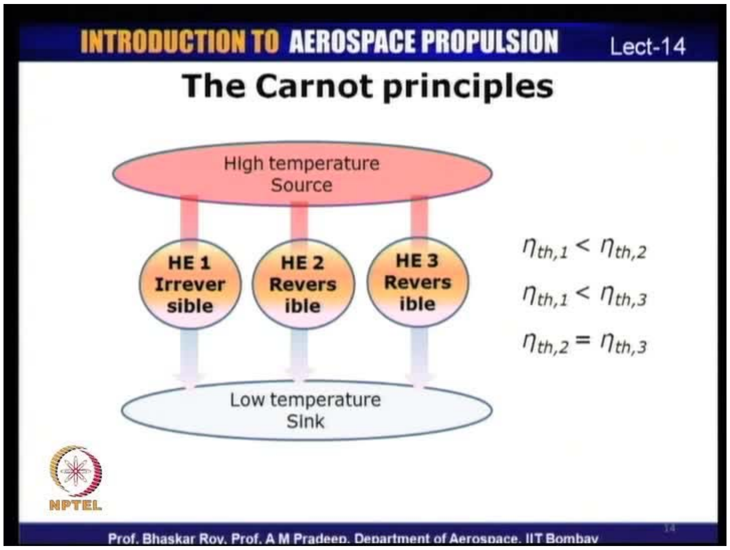

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## The Carnot principles

$\eta_{th,1} < \eta_{th,2}$

$\eta_{th,1} < \eta_{th,3}$

$\eta_{th,2} = \eta_{th,3}$

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To illustrate this point, let us take a look at this illustration here, where we have 3 different heat engines operating between the same high temperature source and the same low temperature sink.

The first heat engine, which is heat engine 1 is an irreversible heat engine and the second and the third engines are reversible heat engines. So, heat engine 2 and heat engine 3 are reversible heat engines, where as heat engine 1 is an irreversible heat engine. As a consequence of Carnot principle, the thermal efficiency of heat engine 1 should be less that the thermal efficiency of heat engine 2.

At the same time, thermal efficiency of heat engine 1 should also be less than thermal efficiency of heat engine 3. This is because heat engine 1 is irreversible, where as 2 and 3 are reversible.

As a consequence of the second Carnot principle, we have thermal efficiency of 2 is equal to the thermal efficiency of 3, that is the efficiency of all heat engines operating between the same temperature source and sink are the same.

So, this is just to illustrate the Carnot principles, the 2 Carnot principle - the first Carnot principle states that irreversible heat engine efficiency is always less than a reversible heat engine and that the efficiency of all reversible engines operating between the same temperature source and sink are the same. Now, as we have discussed for the second law of thermodynamics, where we had Kelvin-Planck and the Clausius statements both the statements are negative statements and you cannot really prove a negative statements. You can only argue out the negative statements saying that if you violate one of those statements, the other statement is also automatically violated and vice versa and that there has not been any violations of these statements, which have been shown to be exist in actual practice. Similarly, Carnot principles are also negative statements in that sense and it is not really possible to exactly prove the Carnot cycle mathematically but of course you can argue out that if you have a violation of the Carnot principle, it can lead to violation of the second law of thermodynamics.

So, what we shall do next is to try and prove the Carnot principles by showing that if you violate the Carnot principle; you are also going to violate the second law of thermodynamics. Therefore, violation of a Carnot principle is not permitted.

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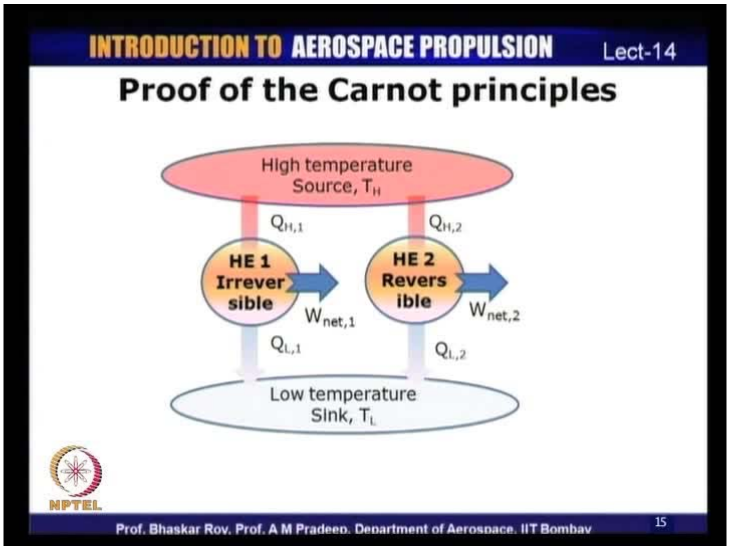

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## Proof of the Carnot principles

High temperature Source, $T_H$

$Q_{H,1}$

$Q_{H,2}$

**HE 1 Irreversible**

**HE 2 Reversible**

$W_{net,1}$

$W_{net,2}$

$Q_{L,1}$

$Q_{L,2}$

Low temperature Sink, $T_L$

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Let us look at, how we can prove or argue out the prove for the Carnot principle. Now, here we have 2 heat engines operating between the same temperature source, which is at T H and a low temperature sink, which is the T L.

Now, one of the heat engines that is heat engine 1 is an irreversible heat engine and the second heat engine that is heat engine 2 is a reversible heat engine. So, heat engine 1 being irreversible and heat engine 2 is reversible. So, heat engine 1 transfers heat at the rate of Q H 1 generates a net work output of W net 1 and transfers balance heat to the sink at Q L 1. Heat engine 2 on the other hand, which is reversible transfers Q H 2 from the source generates a net work output W net 2 and transfers the balance heat Q L 2 to the sink.

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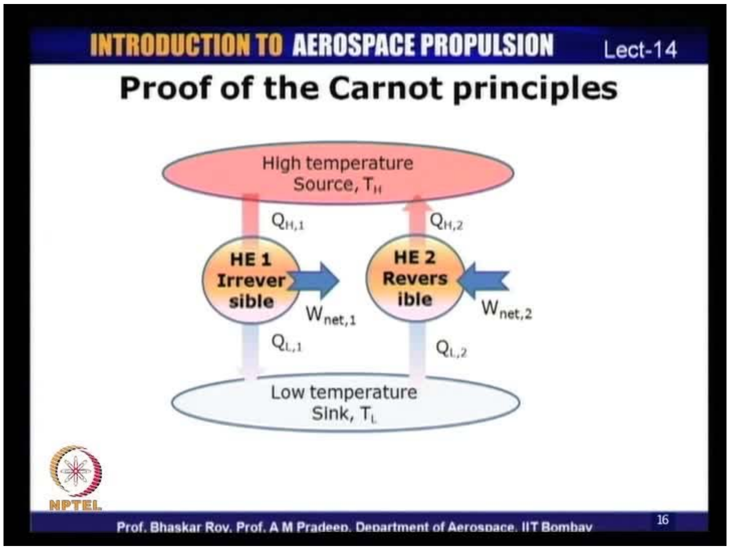

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

**Proof of the Carnot principles**

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Now because the second heat engine is a reversible heat engine, the reverse of this heat engine should also be perfectly possible, which is what is happening here now. So, what we have done now here is that, we have reversed the heat engine 2, which means that the heat engine 2 is now transferring heat, which is operating like a reversed Carnot cycle transferring heat from low temperature sink T L to a high temperature source Q, which is at T H which means that it requires a network input. So, here there is a W net 2 which is required to drive the reversible heat engine.

This reversible heat engine is operating in a manner that it is transferring heat from low temperature sink to a high temperature source because it was a reversible heat engine.

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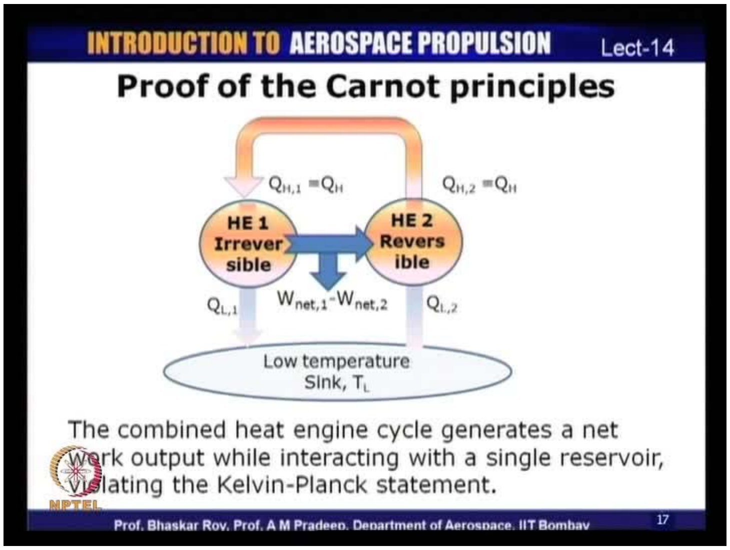

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## Proof of the Carnot principles

The combined heat engine cycle generates a net work output while interacting with a single reservoir, violating the Kelvin-Planck statement.

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Now, we have heat engine which is now transferring heat to high temperature source; it should be possible for us to transfer heat from the reversible heat engine to the irreversible heat engine, which is what is done here. If you combine the heat engine 1 and the heat engine 2, heat engine 1 of course being an irreversible heat engine and heat engine 2 being reversible heat engine, the output of the reversible heat engine which was Q H 2. Let us say, it is equal to Q H can be used as an input to the irreversible heat engine, which is again Q H. So, the combined heat engine cycle can be assumed to operate in this fashion that is you transfer heat from the reversible engine, transfer it to the irreversible engine which means that you can remove.

You can now get away with the temperature source or the high temperature source you do not need this anymore. You can transfer the output of the reversible engine to the irreversible one, which means that there is a net work output from this system, which is equal to W net 1 minus W net 2.

What we have now is that the combined heat engine cycle, which consist of an irreversible engine and a reversible engine will generate a net work output. At the same time, it is transferring or in fact generating net work output by interacting with single reservoir, which is basically a clear violation of the Kelvin-Planck statement of the second law, because Kelvin-Planck statement states that, it is impossible for a heat engine which can generate a network output by interacting with a single reservoir, which is exactly what is happening here. You have a network output from system or a combination of heat engines generating a net work output and transferring heat with a single reservoir. This is assuming that the efficiency of heat engine 1 is equal to heat engine 2 that is if the efficiencies were same that means that 1 minus Q L by Q H is the same for heat engine 1 and heat engine 2, then obviously this can be proved that you will end up with the system, where in the combined heat engines will generate a network output by interacting with the single reservoir.

This means that it is impossible for an irreversible heat engine to have the same efficiency as that of reversible heat engine. So, this proves that if you were to have a heat engine, which is the irreversible and which has an efficiency which is higher or equal to that of a reversible engine then you end up violating the second law of thermodynamics.

Which means that the first Carnot principle which states that you cannot have efficiency of an irreversible engine equal to or exceeding that of a reversible heat engine. This basically proves that the Carnot cycle is again a fundamental principle as an outcome of the second law of thermodynamics. If you were to violate the Carnot principle, you will also end up violating the second law of thermodynamics, basically the Kelvin-Planck statements of the second law of thermodynamics.

So, that was one of the ways of arguing out a proof or the Carnot principle and as I mentioned that it is not possible to mathematically prove some of the statements because these are negative statements. You cannot really prove them mathematically but you can argue out that if you were to violate these statements, it can also lead to the violation of the fundamental laws of the thermodynamics.

So, that was our discussion on the Carnot principles and what we shall discuss next is a temperature scale, which we can derive based on the Carnot principles. What we shall discuss, we have already derived temperature scale during our initial lectures, where we were talking about temperature scale based on constant volume thermometer and Celsius scale and so on and also we had some discussion on the Kelvin scale.

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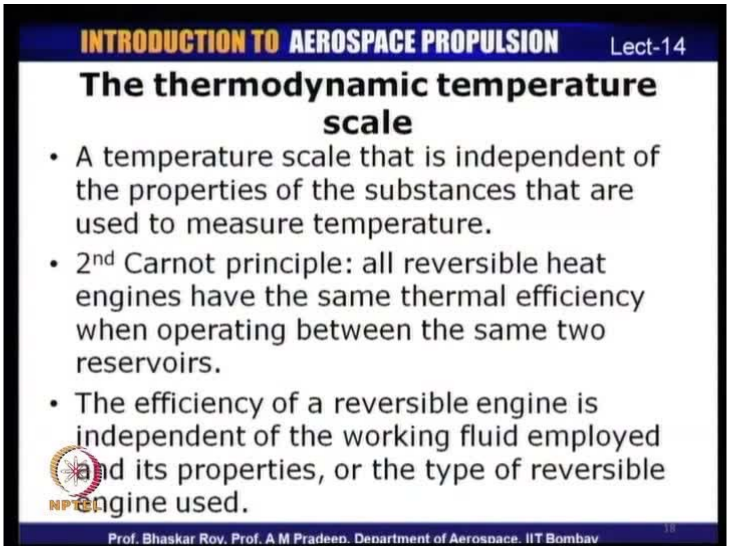

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## The thermodynamic temperature scale

- A temperature scale that is independent of the properties of the substances that are used to measure temperature.
- 2nd Carnot principle: all reversible heat engines have the same thermal efficiency when operating between the same two reservoirs.
- The efficiency of a reversible engine is independent of the working fluid employed and its properties, or the type of reversible engine used.

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We shall discuss some more fundamental aspects of how you can derive the Kelvin scale, the way Lord Kelvin had derived long ago, when he defined the Kelvin scale. The basis for temperature scale is coming from the Carnot principle itself. Now, as we had discussed that the ideally we would like to have a temperature scale that is independent of the properties of the substance, which are used to measure temperature because if you have a scale which depends upon the properties then it is not possible to reproduce these characteristics under different conditions. So, a temperature scale that is ideal should be basically independent of the properties of the substance itself. Now, the second Carnot principle that we discussed basically was that all reversible heat engines have the same thermal efficiency, when operating between 2 reservoirs which are the same 2 reservoirs.

So, the efficiency of a reversible engine is independent of the working fluid, which is employed it is properties of the type of engine which is used because all reversible engines should have the same efficiency if they are operating between the same temperature limits. Which means that it does not depends on what kind of engine you have or what properties are used for the cycle and so on all the cycles should have the same efficiency. This means that such a cycle will have properties, which are independent of what is going on inside the cycle as long as they are all reversible. So, that forms the basis for defining at the temperature scale because we have now a cycle which does not depend upon what is the working fluid and all cycles obviously will have the same efficiency. Based on this, you can actually define the temperature scale which is something that would be ideal; it does not depend upon the working fluid or the type of heat engine and so on.

This temperature scale, which is independent of the nature of the working fluid is what will be used for defining the temperature scale, which is known as the thermodynamic temperature scale. So, to define the thermodynamic temperature scale, let us take the property of the reversible cycles and also try and define the efficiency associated with these cycles.

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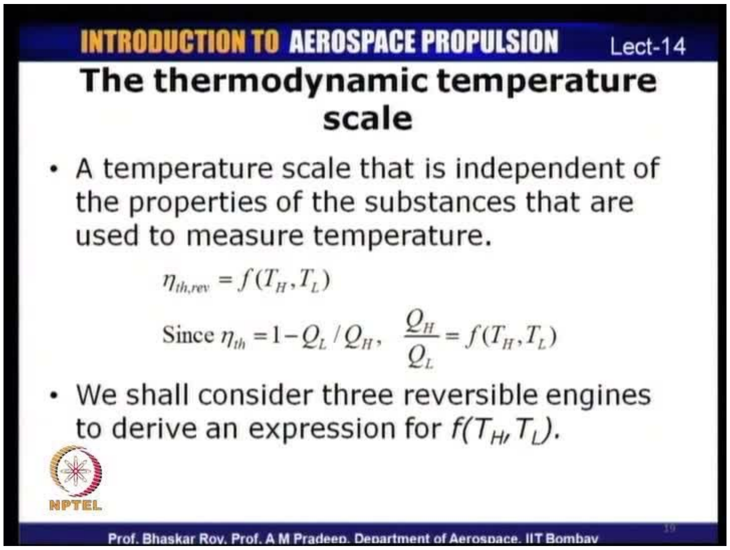

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## The thermodynamic temperature scale

- A temperature scale that is independent of the properties of the substances that are used to measure temperature.

$$\eta_{th,rev} = f(T_H, T_L)$$

$$\text{Since } \eta_{th} = 1 - Q_L / Q_H, \quad \frac{Q_H}{Q_L} = f(T_H, T_L)$$

- We shall consider three reversible engines to derive an expression for $f(T_H, T_L)$.

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As we have seen, the efficiency of a reversible cycle basically depends upon or is a function of the 2 temperatures T H and T L that is the 2 temperature limits of the source and the sink, thermal efficiency is a function of these 2. We already seen that thermal efficiency is equal to 1 minus Q L by Q H. Therefore, Q H by Q L should be a function of T H by T L. So, this is a property which comes from the efficiency definition and so we shall consider for defining the temperature scale and also to derive an expression in terms of T H and T L.

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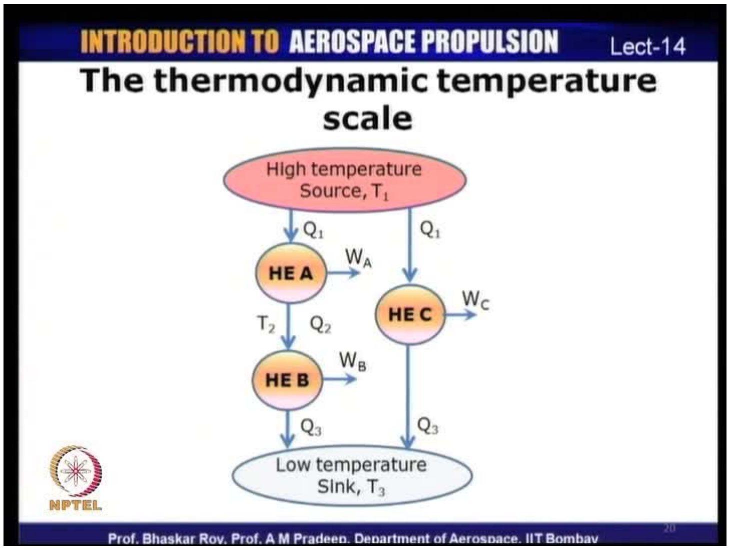

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## The thermodynamic temperature scale

High temperature Source, $T_1$

$Q_1$

$Q_1$

HE A

$W_A$

$T_2$

$Q_2$

HE C

$W_C$

HE B

$W_B$

$Q_3$

$Q_3$

Low temperature Sink, $T_3$

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Let us now consider 3 reversible engines, which are operating in this fashion. These are the 3 reversible engines that we are talking about heat engine A, heat engine B and heat engine C. These are operating between high temperature source at T 1 and low temperature sink at T 3. Now, heat engine A transfers heat at the rate of Q 1 transfers it at the rate Q 2 to heat engine B and heat engine B transfers heat at the rate of Q 3 to the low temperature sink. So, heat engine A generates a network output of W A, heat engine B generates a network output of W B and heat engine C on the other hand transfer heat at Q 1 from the source generates a net work output of W C transfer heat to the Q 3 to the sink.

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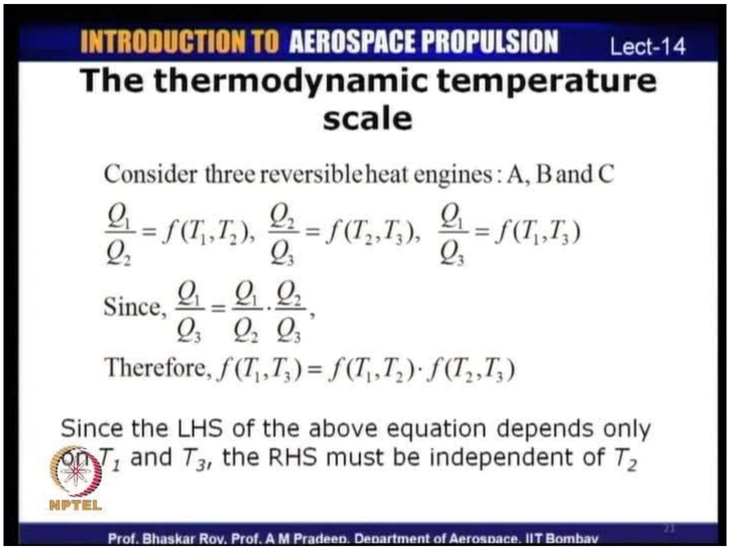

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## The thermodynamic temperature scale

Consider three reversible heat engines : A, B and C

$$\frac{Q_1}{Q_2} = f(T_1, T_2),\ \frac{Q_2}{Q_3} = f(T_2, T_3),\ \frac{Q_1}{Q_3} = f(T_1, T_3)$$

Since, $\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} \cdot \frac{Q_2}{Q_3}$,

Therefore, $f(T_1, T_3) = f(T_1, T_2) \cdot f(T_2, T_3)$

Since the LHS of the above equation depends only on $T_1$ and $T_3$, the RHS must be independent of $T_2$

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All these 3 heat engines are reversible in nature. So, there are 3 heat engines obviously 2 of them are operating in some form series operations. A and B are operating in series, in the sense that the output of heat engine A is driving the input of heat engine B generating a network output W B.

Now, these 3 engines are reversible heat engines A B and C and therefore for heat engine A Q 1 by Q 2 should be a function of T 1 and T 2. Similarly, for heat engine B Q 2 by Q 3 is a function of T 2 and T 3 and for heat engine C Q 1 by Q 3 is a function of T 1 and T 3. So, we can express this ratio Q 1 by Q 3 as Q 1 by Q 2 multiplied by Q 2 by Q 3. Therefore, function T 1 T 3 Should be equal to function T 1 T 2 multiplied by function of T 2 and T 3.

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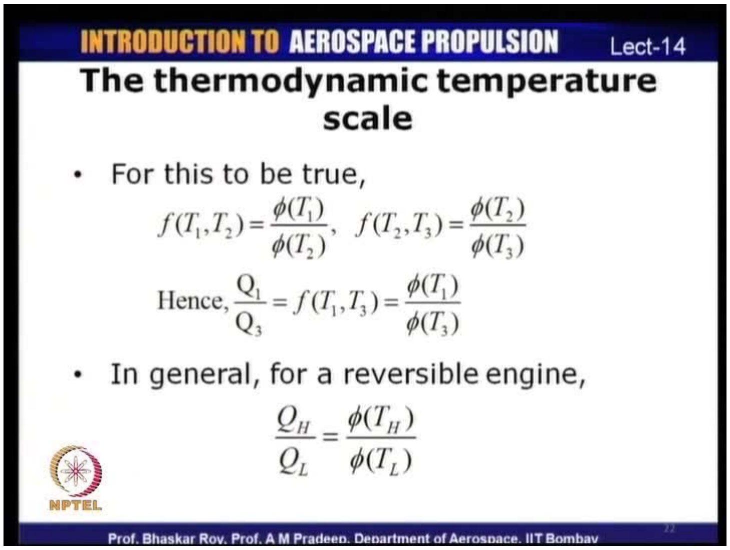

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## The thermodynamic temperature scale

- For this to be true,

$$f(T_1,T_2)=\frac{\phi(T_1)}{\phi(T_2)},\quad f(T_2,T_3)=\frac{\phi(T_2)}{\phi(T_3)}$$

$$\text{Hence, }\frac{Q_1}{Q_3}=f(T_1,T_3)=\frac{\phi(T_1)}{\phi(T_3)}$$

- In general, for a reversible engine,

$$\frac{Q_H}{Q_L}=\frac{\phi(T_H)}{\phi(T_L)}$$

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Now, if we look at closely at the left hand side of this equation, which is f of T 1 and T 3 this depends only on T 1 and T 3. Therefore, this means that the right hand side must be independent of temperature T 2 because the left hand side depends only on T 1 and T 3. It follows that the right hand side should also depend only on T 1 and T 3 and therefore it should be independent of T 2. So, if this is to be true then f of T 1 T 2 should be equal to phi function of T 1 divided by function of T 2 because that is a function of Q 1 and Q 2. Similarly, f of T 2 T 3 is equal to phi of T 2 by phi of T 3. Therefore, the ratio of heat transfer Q 1 by Q 3 should be equal to f of T 1 T 3 which is again equal to phi T 1 divided by phi T 3.

For a reversible cycle in general, we can write that Q H by Q L is equal to phi of T H divided by phi of T L. This means that the ratio of heat transfer from the high temperature source to the sink is basically a function of the ratio of the corresponding temperatures from the high temperatures source to the sink. So, this is a property which comes up as a consequence that we were looking at 3 different reversible heat engines. In general, you can have n number of heat engines, you will still end up getting the same that is the ratio of the heat transfer from the high temperature source to the heat transfer to the sink Q H by Q L should be a function of corresponding temperatures. So, Lord Kelvin proposed that this phi can be represented in terms of temperature scale that is phi of T can be equated to T, if we have certain temperature scale. So, that temperature scale is now referred to as the Kelvin scale of temperature, where in start at temperature of 0 which various between 0 to infinity. Temperature on a Kelvin scale can vary from 0 to infinity. So, 0 kelvin is the lowest temperature that is possible and we already seen the third law of thermodynamics stating that that at 0 kelvin, which is absolute 0 entropy becomes 0.So, you cannot have a temperature which is lower than 0 kelvin.

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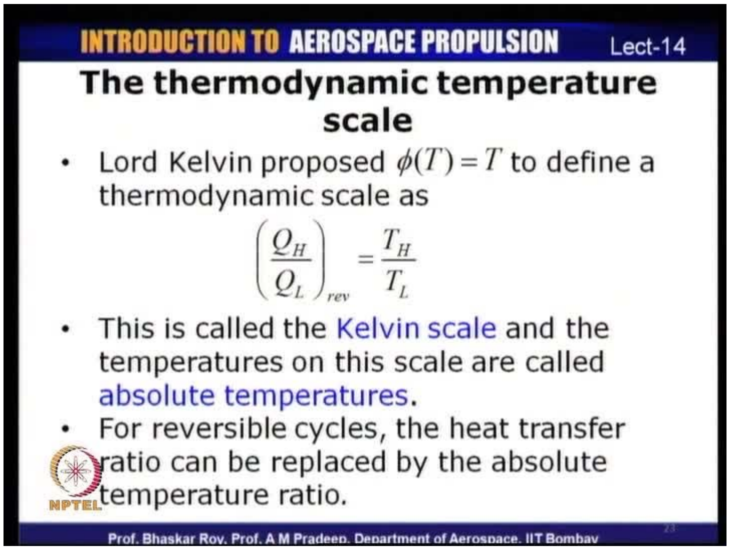

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

**The thermodynamic temperature scale**

- Lord Kelvin proposed $\phi(T) = T$ to define a thermodynamic scale as

$$\left(\frac{Q_H}{Q_L}\right)_{rev} = \frac{T_H}{T_L}$$

- This is called the Kelvin scale and the temperatures on this scale are called absolute temperatures.
- For reversible cycles, the heat transfer ratio can be replaced by the absolute temperature ratio.

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So, Lord Kelvin proposed that phi of T can be equated to T and therefore for a reversible cycle Q H by Q L should be equal to T H by T L. This scale is basically known as the Kelvin scale and the temperatures on the Kelvin scale are known as absolute temperature.

This means that for reversible cycles, the heat transfer ratio can be replaced by the temperature ratio. So, absolute temperature ratios can actually replace the heat transfer rates on as long as the cycle is reversible.

For reversible cycle, you can actually replace the heat transfer rates by the corresponding absolute temperature. So, please remember that the temperatures that are going to be used will be the absolute temperature on the Kelvin scale. Kelvin scale was basically in the 19th century well 20th century 1953 I guess it was defined that. We shall define the triple point of water on a Kelvin scale as 273.16 kelvin. So, 273.16 kelvin, which is on the Celsius scale equal to 0.01 degree Celsius is the temperature corresponding to the triple point of water. So, this is something we have already discussed earlier as well.

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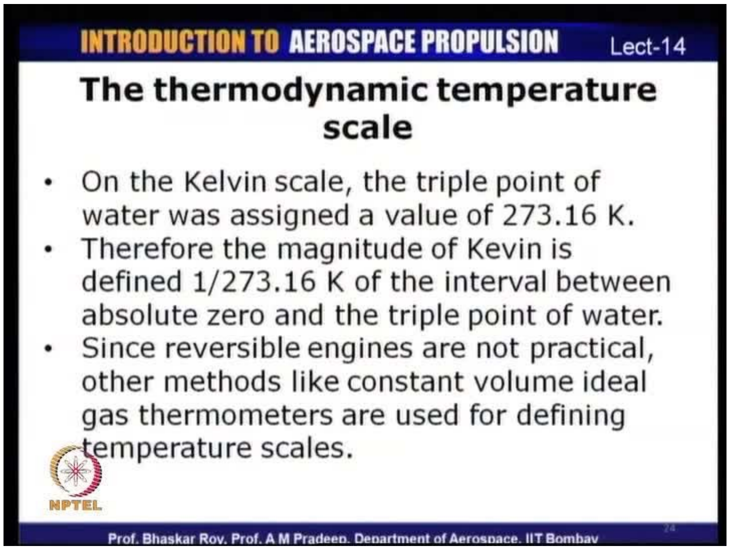

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## The thermodynamic temperature scale

- On the Kelvin scale, the triple point of water was assigned a value of 273.16 K.
- Therefore the magnitude of Kevin is defined 1/273.16 K of the interval between absolute zero and the triple point of water.
- Since reversible engines are not practical, other methods like constant volume ideal gas thermometers are used for defining temperature scales.

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The magnitude of Kelvin is defined as 1 by 273 of the interval between absolute 0 and the triple point of water. So, to define what is meant by 1 kelvin on a Kelvin scale it is equal to 1 by 273 times the interval between absolute 0 and the triple point of water. Now, you may wonder that reversible cycles are something which is ideal you cannot really realize a reversible cycle. So, how do you define an actually thermodynamic temperature scale, if you cannot actually create a reversible cycle and because reversible engines are not practical. We use other methods like the constant volume ideal gas temperature thermometer for defining the ideal gas temperature scale or the thermodynamic temperature scale. We use some these techniques to define the temperature scale and not really a reversible cycle because you cannot actually have reversible cycle and therefore generated temperature scales. So, we use something which is an approximation of that at the ideal gas constant volume thermometer, which is used to define the thermodynamic temperature scale.

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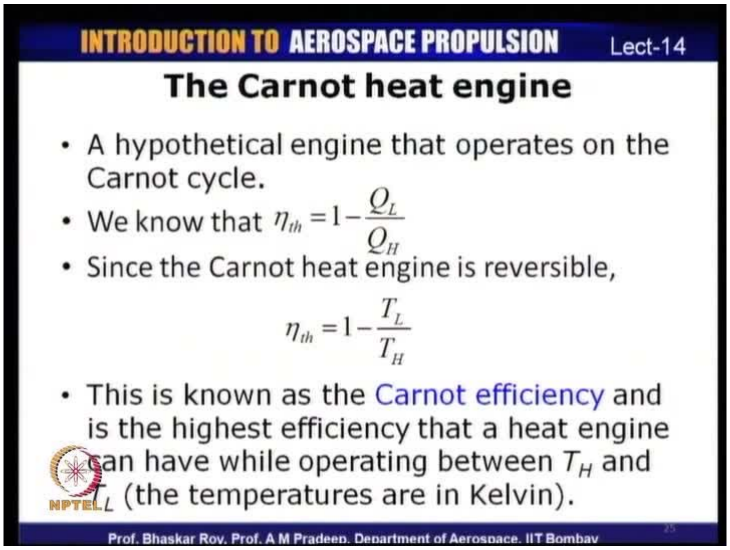

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## The Carnot heat engine

- A hypothetical engine that operates on the Carnot cycle.
- We know that $\eta_{th} = 1 - \frac{Q_L}{Q_H}$
- Since the Carnot heat engine is reversible,

$$\eta_{th} = 1 - \frac{T_L}{T_H}$$

- This is known as the Carnot efficiency and is the highest efficiency that a heat engine can have while operating between $T_H$ and $T_L$ (the temperatures are in Kelvin).

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We have now defined the thermodynamic temperature scale and also the Carnot principle and the Carnot cycles. We will now look at, what is Carnot heat engine? A Carnot heat engine is a heat engine, which is based on the Carnot cycle. So, a heat engine which is obviously hypothetical and that operates based on the Carnot cycle is known as the Carnot heat engine. We have defined already thermal efficiency, which is 1 minus Q L by Q H and since the Carnot heat engine is reversible thermal efficiency for a reversible engine will be 1 minus T L by T H.

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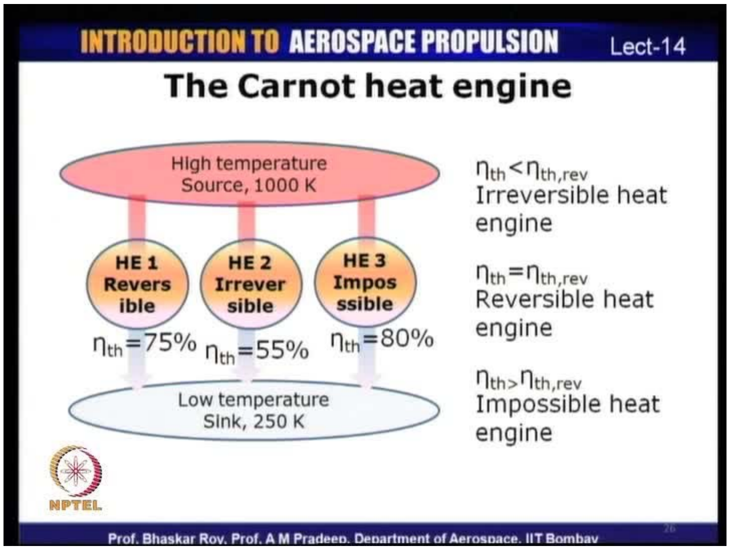

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## The Carnot heat engine

High temperature Source, 1000 K

HE 1 Reversible $\eta_{th} = 75\%$

HE 2 Irreversible $\eta_{th} = 55\%$

HE 3 Impossible $\eta_{th} = 80\%$

Low temperature Sink, 250 K

$\eta_{th} < \eta_{th,rev}$ Irreversible heat engine

$\eta_{th} = \eta_{th,rev}$ Reversible heat engine

$\eta_{th} > \eta_{th,rev}$ Impossible heat engine

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This is basically known as Carnot efficiency and this is the highest efficiency that a heat engine can have, while operating between temperature T H and T L. These temperatures are in Kelvin; if you use celsius temperature, you will get grossly erroneous values. Make sure that when you are calculating efficiencies use the Kelvin scale for temperatures.

So, for all reversible engines the thermal efficiency is basically a function of the temperature ratios. So, thermal efficiency will be 1 minus T L by T H. So, to illustrate this, if we look at 2 temperature sources and a sink temperature source; let us say, source is 1000 kelvin and sink 250 kelvin. For a reversible cycle, the efficiency will be 1 minus T L by T H, which is 1 minus 250 by 1000 and therefore it is 75. Let us say, there are 3 heat engines are operating here, heat engine 1, 2 and 3.

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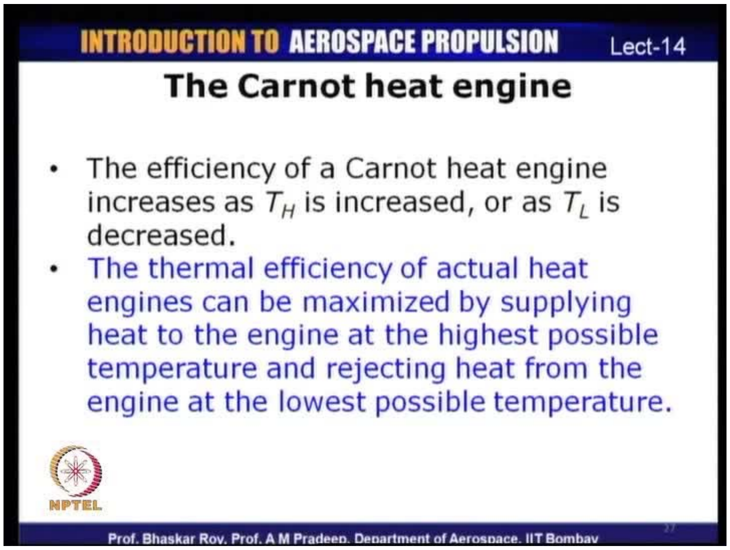

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## The Carnot heat engine

- The efficiency of a Carnot heat engine increases as $T_H$ is increased, or as $T_L$ is decreased.
- The thermal efficiency of actual heat engines can be maximized by supplying heat to the engine at the highest possible temperature and rejecting heat from the engine at the lowest possible temperature.

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Heat 1 is reversible and therefore it is efficiency is 75 percent, which is 1 minus T L by T H. An irreversible engine should have efficiency, which is lower than that of a reversible engine. As a consequence of the first Carnot principle, let us say the efficiency is 55 percent. So, that is a possible engine and an impossible engine is one, which has an efficiency higher than that of the Carnot efficiency let us say 80 percent, So that is an impossible engine. So, thermal efficiency less than the reversible thermal efficiency is an irreversible heat engine, if the thermal efficiency is equal to that of the thermal efficiency for reversible cycle it is a reversible heat engine and if thermal efficiency exceeds the reversible cycle efficiency it is an impossible heat engine. So, the efficiency as you can see of a Carnot heat engine increase as T H increases or as T L is decreased. Thermal efficiency of actual heat engines can actually be maximized by supplying heat to the engine at highest possible temperature and rejecting heat from the engine at the lowest possible temperatures. As you increase the temperature differential between the source and the sink, you can maximize the efficiency of these heat engines.

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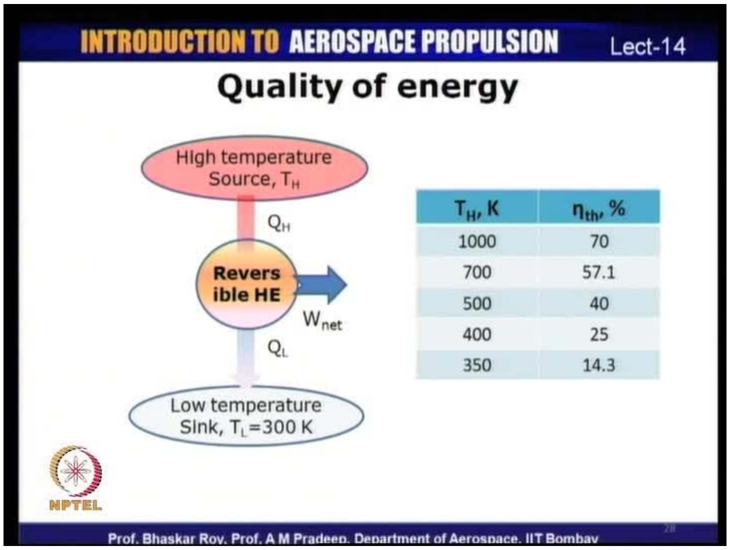

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

Quality of energy

| $T_H$, K | $\eta_{th}$, % |
|---|---|
| 1000 | 70 |
| 700 | 57.1 |
| 500 | 40 |
| 400 | 25 |
| 350 | 14.3 |

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Let us look at this point a little more detail from this example, where we have a high temperature source let us say, at temperature T H and there is a reversible heat engine operating between source of T H and let us say, we fix this temperature of the sink at 300 kelvin. As you change the temperature of the source let us say, it was 1000 kelvin then we get efficiency of 70 percent, which is 1 minus 300 by 1000 which is 70.7 that is 70 percent. Now, if the temperature of the source is instead of 1000 it is seven 700, we get a corresponding efficiency of 57.1 and so on. So, what we see is that as you reduce the temperature of the source from 1000 to let us say, 350 there is a drastic reduction in the efficiency of the cycle, which means that there is a certain amount of quality associated with the energy which is transferred from the source to the sink. As the temperature of the source decreases, the quality of the energy also decreases because you can see that the efficiency associated with that process also decreases.

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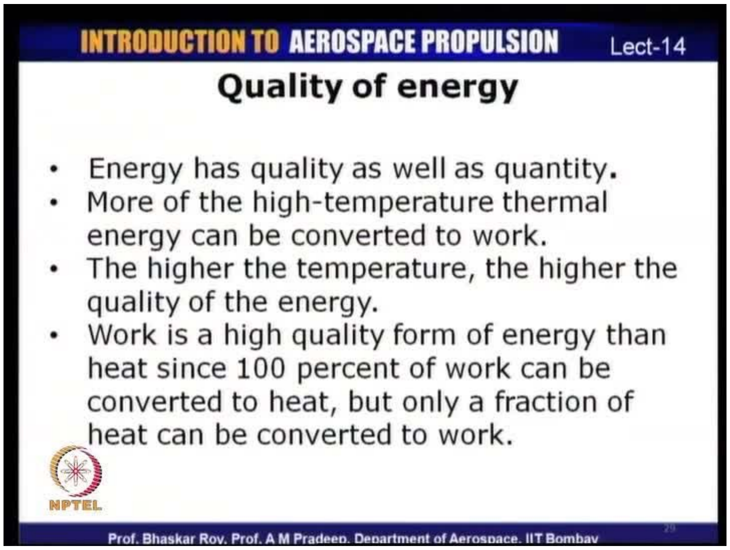

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## Quality of energy

- Energy has quality as well as quantity.
- More of the high-temperature thermal energy can be converted to work.
- The higher the temperature, the higher the quality of the energy.
- Work is a high quality form of energy than heat since 100 percent of work can be converted to heat, but only a fraction of heat can be converted to work.

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So, this gives us an idea that there is certain quality associated with energy and energy has a certain quality in addition to quantity. We have already defined quantity for energy and in addition to quantity; we also have a certain quality associated with energy. More of the high temperature thermal energy can be converted to work, if the temperature is higher, higher the temperature higher is the quality of energy. As we shall see later on as well, work is a high quality form of energy and it is possible to convert 100 percent of work into heat but on the other hand heat is the low quality energy, you cannot transfer heat 100 percent into work. So, quality of energy is something that is very important and we should understand that energy has a certain quality in addition to quantity.

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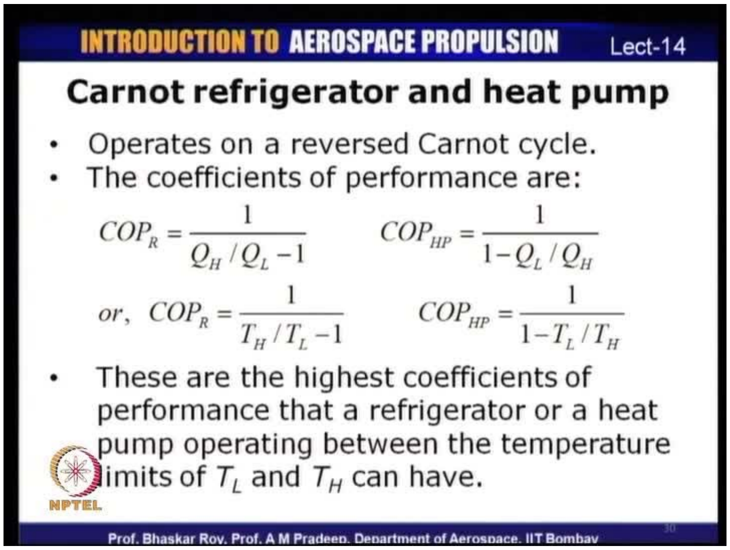

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## Carnot refrigerator and heat pump

- Operates on a reversed Carnot cycle.
- The coefficients of performance are:

$$COP_R = \frac{1}{Q_H / Q_L - 1} \qquad COP_{HP} = \frac{1}{1 - Q_L / Q_H}$$

$$or, \quad COP_R = \frac{1}{T_H / T_L - 1} \qquad COP_{HP} = \frac{1}{1 - T_L / T_H}$$

- These are the highest coefficients of performance that a refrigerator or a heat pump operating between the temperature limits of $T_L$ and $T_H$ can have.

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Now, we have already defined the reverse Carnot cycle and based on the reverse Carnot cycle, we can also define Carnot refrigerator and a heat pump which basically function based on the reversed Carnot cycle. Carnot refrigerator and heat pump operates on reverse Carnot cycle. You can also define the coefficient of performance for refrigerator and heat pump as we already defined this for all refrigerators and heat pump. C O P refrigerator is 1 minus Q H by Q L minus 1, for a heat pump it is 1 by 1 minus Q L by Q H. Since, these are reversible C O P of refrigerator is 1 by T H by T L minus 1 C O P of heat pump is 1 by 1 minus T L by T H.

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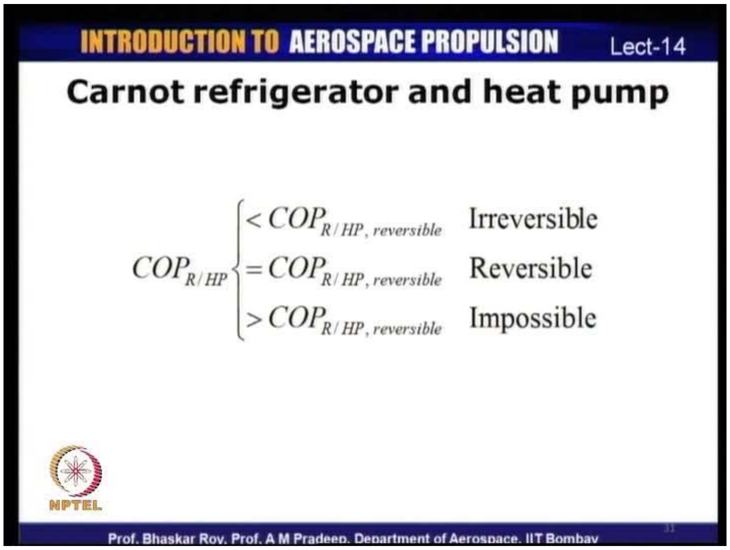

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

## Carnot refrigerator and heat pump

$$COP_{R/HP} \begin{cases} < COP_{R/HP,\, reversible} & \text{Irreversible} \\ = COP_{R/HP,\, reversible} & \text{Reversible} \\ > COP_{R/HP,\, reversible} & \text{Impossible} \end{cases}$$

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These are the highest coefficients of performance that a refrigerator or a heat pump can have, if they are operating between temperatures T L and T H. These define the limits for the coefficient of performance that heat pumps and refrigerators can have. It means that C O P of a refrigerator or heat pump, if it is less than that of a reversible one it is irreversible refrigerator of heat pump, C O P equal to the C O P of reversible process is a reversible refrigerator or heat pump, C O P greater than that of refrigerator heat pump it is an impossible refrigerator or a heat pump.

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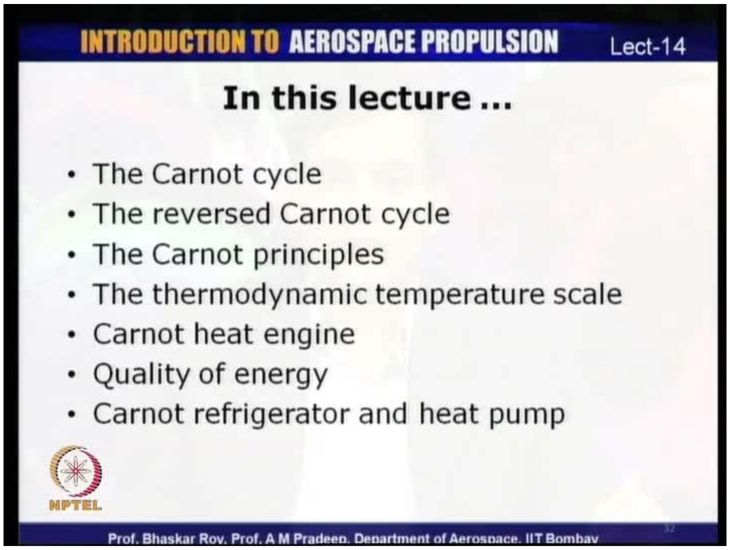
INTRODUCTION TO AEROSPACE PROPULSION Lect-14

In this lecture ...

- The Carnot cycle
- The reversed Carnot cycle
- The Carnot principles
- The thermodynamic temperature scale
- Carnot heat engine
- Quality of energy
- Carnot refrigerator and heat pump

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So, let me now wind up what we have discussed during this lecture. During this lecture, we have been discussing about the Carnot cycle, what is the basis of Carnot cycle, how you can define a Carnot cycle based on reversible processes and then we also discussed about the reversed Carnot cycle, which is the basic Carnot cycle operating in a reverse manner that is all heat and work interactions are reversed.

We also define the Carnot principles, which defines the maximum efficiencies that heat engines can have as compare to the reversible engines and that the efficiency of all reversible engines are the same, if they are operating between the same temperature differential. Based on this, we define the thermodynamic temperature scale and also the origin of the Kelvin scale. Though, we have discussed this in the earlier lectures, it is now that we have actually looked at how this Kelvin scale was developed by Lord Kelvin. Then, we define the Carnot heat engine which is operating on the Carnot cycle, efficiency of a Carnot engine and Carnot heat engine basically gives the maximum efficiency that any heat engine can have. We also discussed about the quality of the energy that is in addition to quantity energy also has a quality, higher the temperature higher is the quality.

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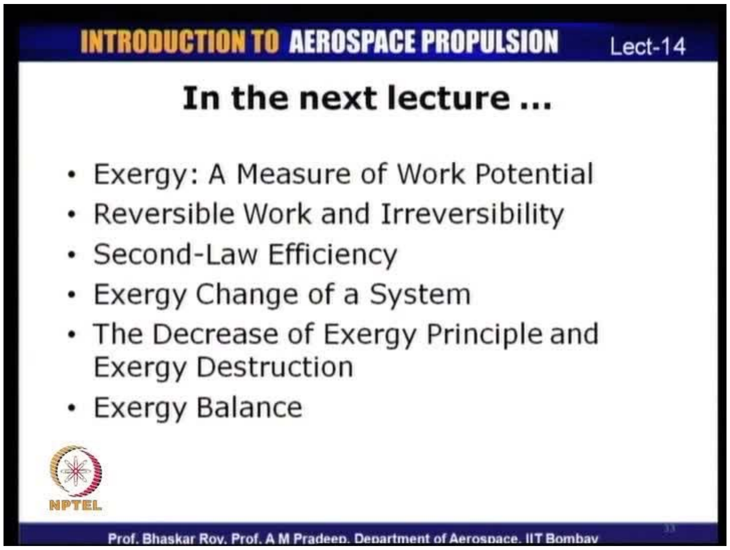

INTRODUCTION TO AEROSPACE PROPULSION Lect-14

**In the next lecture …**

- Exergy: A Measure of Work Potential
- Reversible Work and Irreversibility
- Second-Law Efficiency
- Exergy Change of a System
- The Decrease of Exergy Principle and Exergy Destruction
- Exergy Balance

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Towards the end of the lecture, we were discussing about Carnot refrigerator and heat pump, which operates on the basic reversed Carnot cycle. In the next lecture, we shall be discussing about a new concept which is known as Exergy, which is the measure of the work potential and we shall then talk about reversible work and irreversibility. Then, we shall discuss about second law efficiency and Exergy Change of a System. We shall then define, what is meant by the decrease of Exergy Principle and Exergy Destruction and towards the end of the next lecture, we shall discuss about the Exergy Balance. So, these are some of the topics that we shall be discussing in the next lecture which would be lecture 15.