Basics of Mechanical Engineering-3

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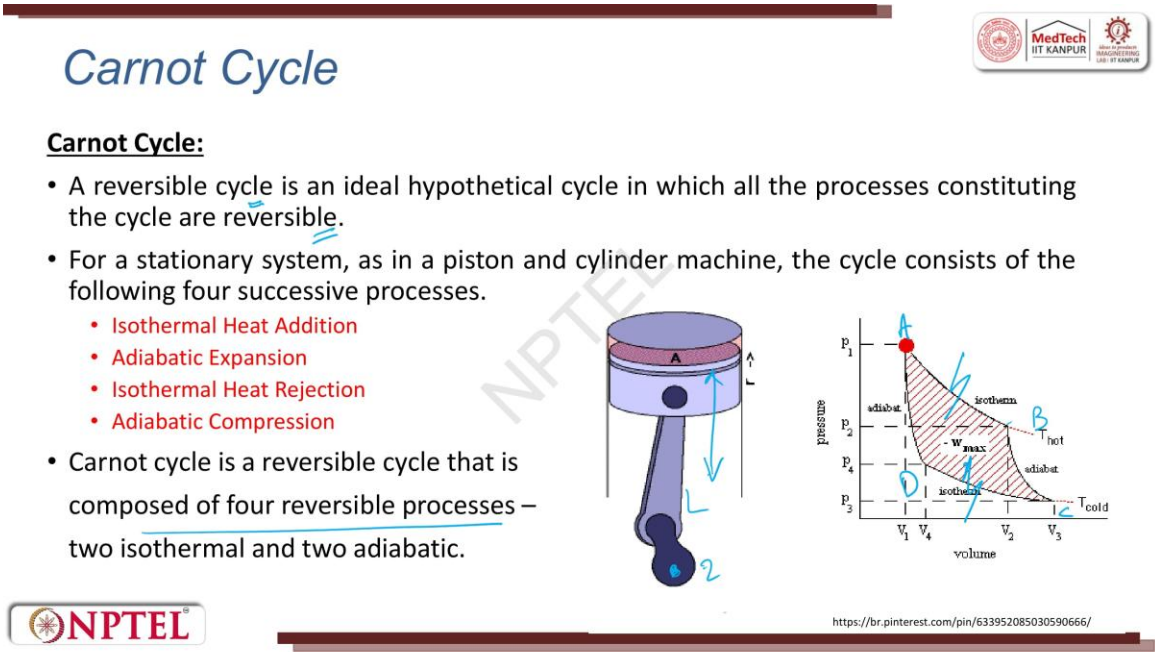
Week 02

Lecture 09: Basic Laws of Thermodynamics Part 4 of 5

Well, friends, welcome to the fourth part of the Basic Laws of Thermodynamics.

In this, we will try to explore the Carnot Cycle. How do you calculate the COP of the Carnot Cycle, Refrigerator, Reversible Engines, and finally, Entropy? In the second law of thermodynamics, we said there is randomness introduced. That randomness is entropy. We will see that in detail.



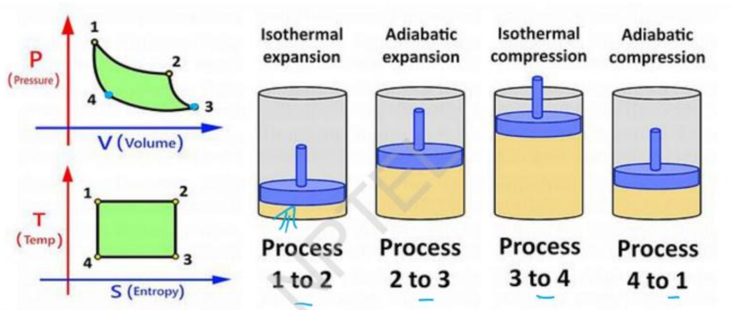
The Carnot Cycle is a reversible cycle. It is an ideal hypothetical cycle in which all the processes constituting the cycle are reversible. So, when we draw a PV diagram, we will see A, B, C, and D: AB, BC, CD, DA. AB is isothermal, BC is adiabatic, CD is isothermal, and DA is adiabatic.

So, here there is heat in, and here there is heat out. For a stationary system, as in a piston-cylinder machine, in a piston-cylinder machine, you will have a cylinder. You will have a piston. This piston will move up and down. So here, we are attaching it to a lever.

And then, that in turn is attached to a smaller one. So, let us make it as link 1 and link 2. And then, it is attached to a point. So now, when this rotates, it can transfer. It can rotate a shaft or it can transfer energy.

For a stationary system, as in a piston and cylinder machine, the cycle consists of four steps. As I told you, isothermal heat addition, isothermal heat rejection, adiabatic expansion, and adiabatic compression. Four cycles happen. The Carnot cycle is a reversible cycle that is composed of four reversible processes. So, what happens in isothermal expansion? We are seeing an animation here. I have divided it into four parts.

Carnot Cycle



The four processes in a Carnot Cycle are:

1. Process 1 - 2 (Reversible Isothermal Heat Addition)
2. Process 2 – 3 (Reversible Adiabatic Expansion)
3. Process 3 – 4 (Reversible Isothermal Heat Rejection)
4. Process 4 – 1 (Reversible Adiabatic Compression)

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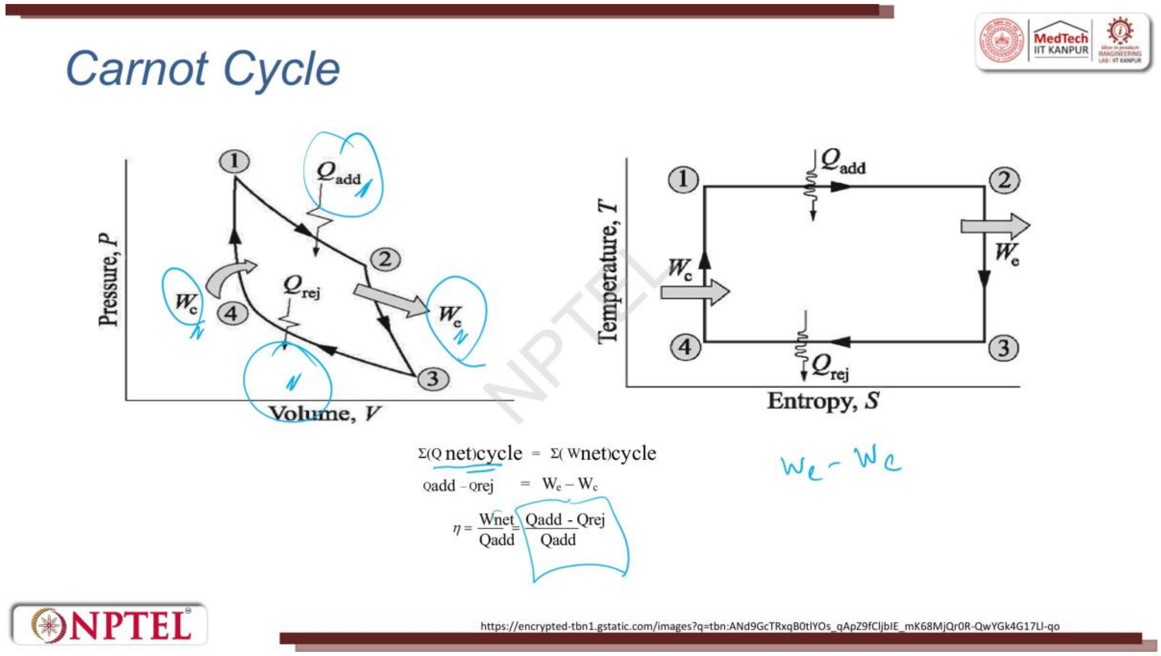
So, in the isothermal expansion, when it moves from 1 to 2, you can see that the piston is trying to expand. It is trying to go up. And when it goes from 2 to 3, it is adiabatic expansion.

So, still the piston is expanding. So, then 3 to 4 is isothermal compression which happens from 3 to 4. Isothermal compression happens and from 4 to 1, you can see that adiabatic compression happens. So, when there is a heat which is given, there is an expansion happening and once the expansion is saturated, then the weight is there. This weight is trying to push it down once again.

When it is trying to push it down, it is trying to compress. So, 1 to 2, 2 to 3, 3 to 4 and 4 to 1. The four processes in a Carnot cycle are 1 to 2 is reversible isothermal heat addition. 2 to 3 is reversible adiabatic expansion. 3 to 4 is reversible isothermal heat rejection. And 4 to 1 is going to be reversible adiabatic compression. If you see the TS diagram, it looks like a simple rectangle.



The same thing what we have dealt in the previous slide; add, reject, work e, work c. W_e is work in exhaust or expansion. And then, here it is of compression, volume change, compression. So,

$$\Sigma(Q_{net})_{cycle} = \Sigma(W_{net})_{cycle}$$

$$Q_{add} - Q_{rej} = W_e - W_c$$

$$\eta = \frac{W_{net}}{Q_{add}} = \frac{Q_{add} - Q_{rej}}{Q_{add}}$$

So, if you want to calculate the efficiency, it is going to be work net. So, what is work net? Work net is going to be W_e - Wc. Work net is this, and then you will have the heat.

Carnot Cycle

- $\eta = 1 - \frac{Q_{rej}}{Q_{add}}$

From T-S diagram:

$$\eta = 1 - \frac{T_2(\Delta S)}{T_1(\Delta S)}$$

$$\eta = 1 - \frac{T_2}{T_1}$$

Carnot's Cycle (some more insights):

1.The efficiency of an irreversible heat engine is always less than efficiency of a reversible one operating between the same two reservoirs.

2.The efficiencies of all reversible heat engines operating between the same reservoirs are the same.

3.Since the efficiencies of all reversible heat engines operating between the same heat reservoirs are the same, the efficiency of a reversible engine is independent of the nature or amount of the working substance undergoing the cycle.

NPTEL

So, if you are looking for the efficiency, it is going to be

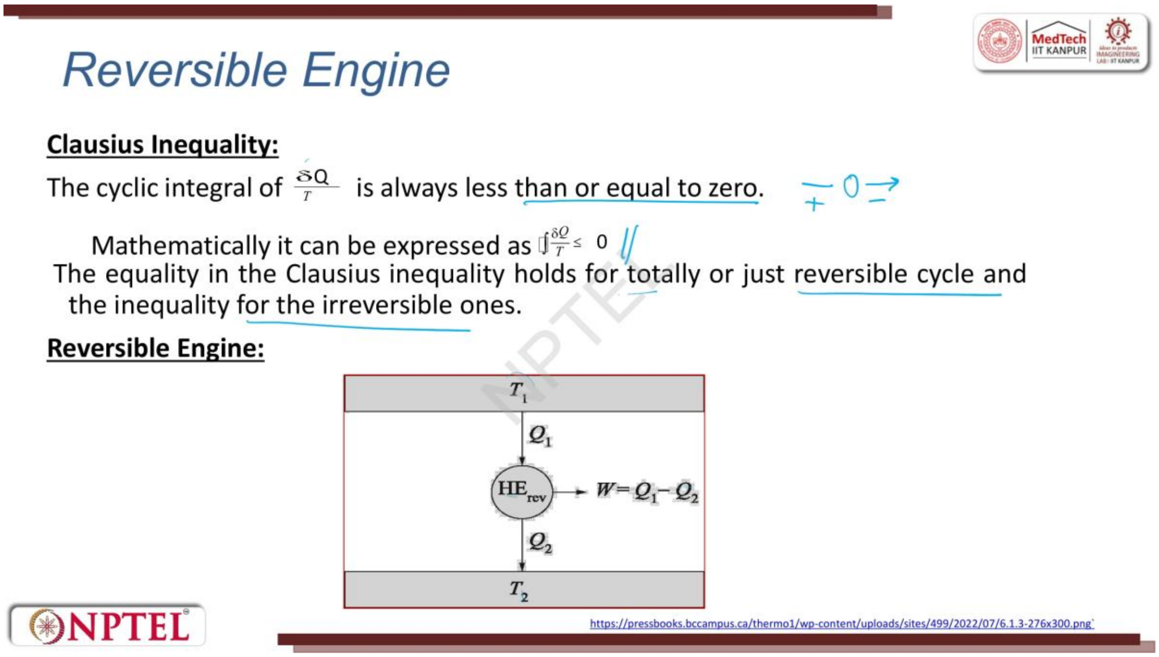
- $\eta = 1 - \frac{Q_{rej}}{Q_{add}}$

From T-S diagram:

$$\eta = 1 - \frac{T_2(\Delta S)}{T_1(\Delta S)}$$

$$\eta = 1 - \frac{T_2}{T_1}$$

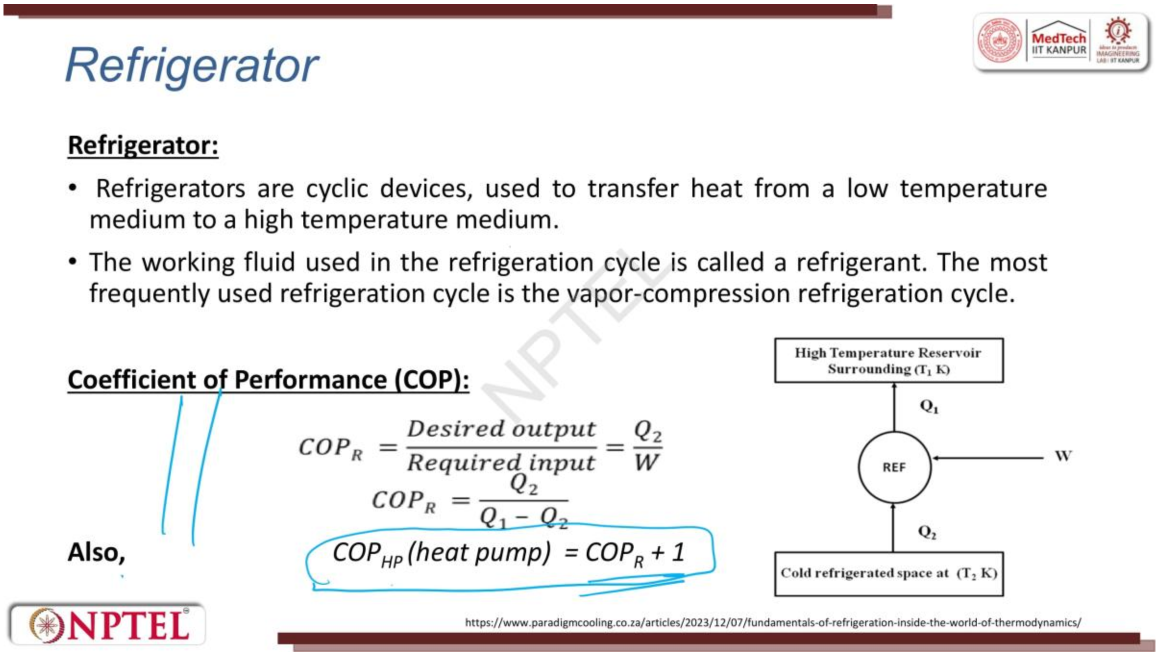
So, the Carnot cycle. Which gives you a little more insight: the efficiency of an irreversible heat engine is always less than that of a reversible engine. The efficiency of all reversible heat engines operating between the same reservoirs is the same.



Since the efficiency of all reversible heat engines operating between the same heat reservoirs is the same, the efficiency of the reversible engine is independent of the nature or the amount of working substance undergoing the cycle. So, please note it down. So, this can be a question asked in the examination. The efficiency of a reversible engine is independent of the nature or the amount of working substance undergoing the cycle.

Clausius' inequality, which is also an important thing you should understand. The cyclic integral of dQ/T is always less than or equal to 0. So, if you take a positive minus, right. So, mathematically, it can be represented as the cyclic integral of dQ/T, which is less than or equal to 0. The equality—we are talking about inequality.

The equality in quasi-static processes holds for totally or just reversible cycles, and the inequality for irreversible cycles. So, this is a reversible engine. T is the temperature, Q1 is the heat that goes to the heat engine, which is reversible. Q2, which is after doing work, comes out and goes to the sink.



Let us look at a refrigerator. Refrigerators are also cyclic devices used to transfer heat from a lower-temperature medium to a higher-temperature medium. The working fluid used in the refrigeration cycle is called a refrigerant.

So, if you go back and see, we have said that in a Carnot reversible heat engine operating between the same heat reservoirs, the conditions are the same. The efficiency of a reversible engine is independent of the nature or state of the working fluid. The most frequently used refrigeration cycle is the vapor compression refrigeration cycle. You will see this vapor compression refrigeration cycle later. COP is an important terminology used—the coefficient of performance.

The Coefficient of Performance for a refrigerator is always defined as desired output divided by required input. Desired output will be

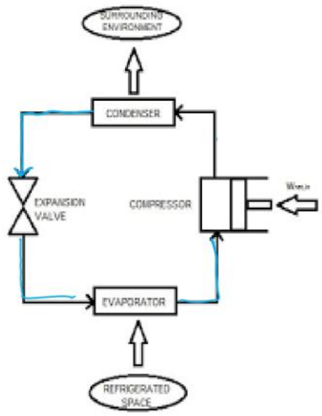
$$COP_R = \frac{Desired\ output}{Required\ input} = \frac{Q_2}{W}$$

$$COP_R = \frac{Q_2}{Q_1 - Q_2}$$

$$COP_{HP}\ (heat\ pump) = COP_R + 1$$

Refrigerator

- A refrigerator is a heat pump device that operates on the principle of transferring heat from a low-temperature region to a high-temperature region.
- Unlike a heat engine, which converts heat into work, a refrigerator consumes work (usually electrical energy) to remove heat from a space that must be kept cool (such as the interior of a refrigerator or an air-conditioned room) and rejects it to the warmer surrounding environment.
- This process seemingly goes against the natural flow of heat, which is from hot to cold, and is only made possible by doing external work, as explained by the Second Law of Thermodynamics.



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A refrigerator is a heat pump device that operates on the principle of transferring heat from a lower-temperature region to a higher-temperature region. Unlike heat engines, which convert heat into work, a refrigerator consumes work to remove heat from the space that must be kept cool and rejects it to the warmer surrounding environment. So, this is the expansion valve. We have seen this in the previous lecture itself. You have a compressor where pressure and temperature increase.

Then you have an evaporator. So, then from the evaporator, it goes to the refrigerator sink or space. Then from there, you can see that expansion happens, and then it goes to the condenser. So, you can try to take it this way: condenser to the expansion valve, expansion valve to the evaporator, evaporator to the compressor, compressor, and then this gets. So, once the air is compressed, it moves to a compressor, right? From a compressor, it tries to expand. Why does it do that?

Because it has to take heat and then give the cold air. This process seemingly goes against the natural flow of heat, which is from a hot body to a cold body. Now, we are moving from a cold body to a hot body. So, which is from hot to cold, and is only made possible by doing external work, as explained by the second law of thermodynamics. So, a refrigerator works, and this is how it is.

Refrigerator

A typical refrigerator works on a **vapor-compression refrigeration cycle**, which consists of four key components:

- **Compressor**: Compresses the refrigerant gas, raising its pressure and temperature.
- **Condenser**: The high-pressure hot gas flows through the condenser coils, where it loses heat to the surroundings and condenses into a high-pressure liquid.
- **Expansion Valve/Capillary Tube**: The high-pressure liquid refrigerant passes through this valve, which reduces its pressure rapidly and causes partial evaporation.
- **Evaporator**: The low-pressure liquid absorbs heat from the inside of the refrigerator and evaporates, cooling the space. The cycle then repeats.

S – L – G

So, a typical refrigerator works on vapor compression. Vapor compression. So, you use vapor and compress it in a refrigeration cycle. Compressor: It compresses the refrigerant gas, raising its pressure and temperature. The compressor compresses the refrigerant gas.

When it compresses, the pressure increases, and the temperature increases. So, then that leads to vapor, which comes here. The condenser: The high-pressure hot gas flows through a condenser coil, where it loses heat to the surroundings and condenses into a high-pressure liquid. So, high-pressure hot gas flows through the condenser coil, where it loses heat to the surroundings and condenses into a high-pressure liquid. So, the temperature goes up, high-pressure liquid.

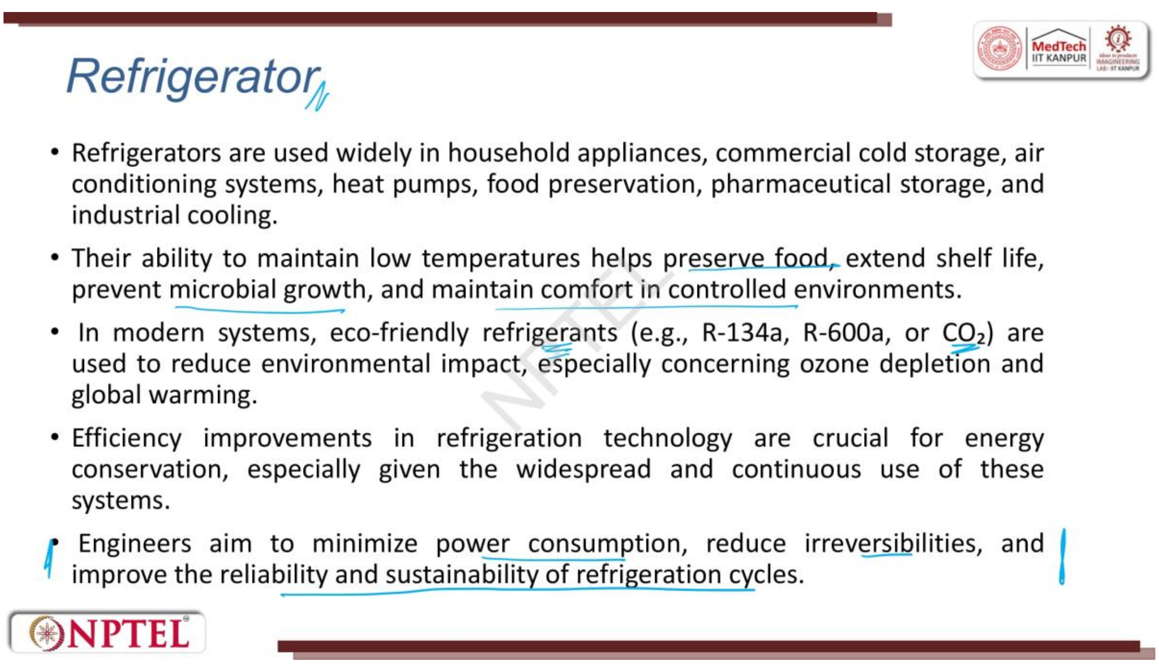
So, the expansion and capillary tube: The high-pressure liquid refrigerant passes through this valve, and it reduces the pressure. Expansion means it is reducing the pressure. Pressure rapidly drops and causes partial evaporation. This partial evaporation, whatever is there, the low-pressure liquid absorbs heat from the inside of the refrigerator and evaporator, cooling the space. The cycle then repeats. So, compressor, condenser, expansion valve, capillary tube, and evaporator.

There are four things which are there in a refrigerator. It follows a vapor condenser. Vapor is solid, liquid, gas. Vapor comes in this phase. Solid, liquid, vapor phase.

So, we also saw the latent vapor in the beginning lectures. We saw the fundamentals. So, here it is very simple. Compressor, where there is a liquid or a compressed gas. So, it is compressed.

So, when the gas is compressed, pressure and temperature go high. Once it is compressed, what happens? It cannot be kept on compressing. Then, it condenses. The high-pressure hot gas flows through a condenser coil where heat is lost because the vapor loses heat to the surroundings and condenses into a high-pressure liquid.

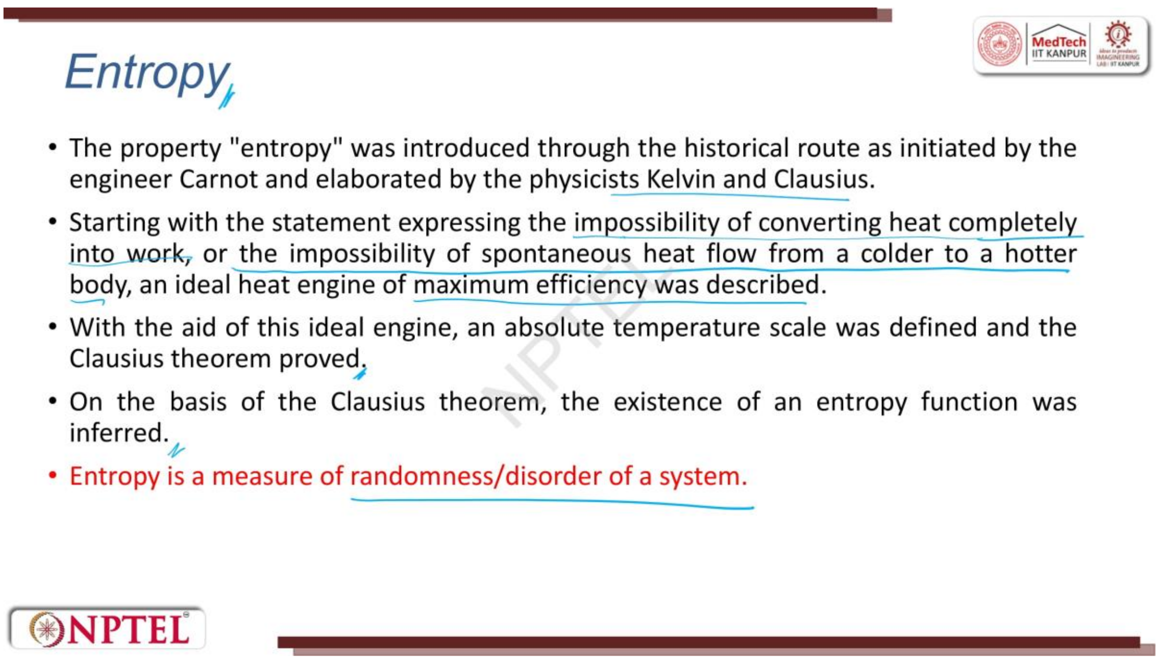
The vapor that was there gets converted into a liquid. Now, that liquid refrigerant passes through a valve which reduces its pressure rapidly and causes partial evaporation. So, the evaporator: The low-pressure liquid absorbs heat from the inside of the refrigerator and evaporates, cooling the space. The cycle then repeats, right?



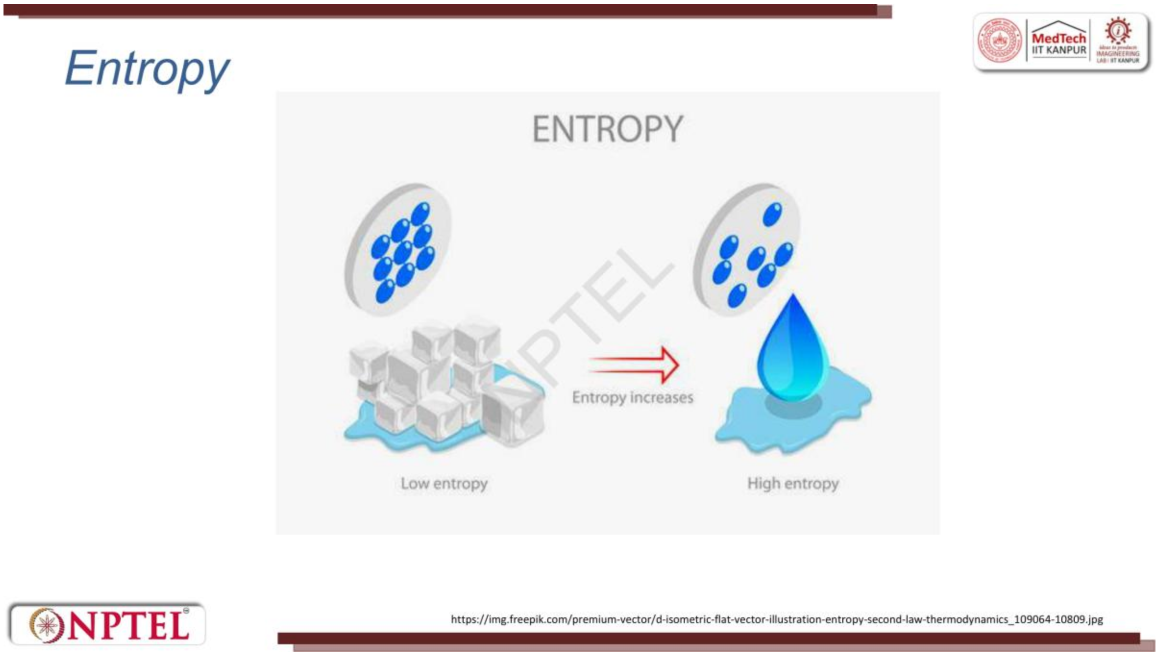
So, these are all little examples which talk about the refrigerator because as an engineer, you should understand how the refrigerator works. So, the refrigerator is widely used in homes as an appliance where it is used, as we have said here. This ability to maintain low pressure helps preserve foods, extend shelf life, prevent microbial growth, and maintain all these things. So, what is happening? You try to take the heat out and keep the cold in. In modern systems, eco-friendly refrigerants are used.

CO2 is also used, which reduces the environmental impact. The efficiency improvements in refrigeration technology are crucial for energy conversion. Engineers aim to minimize power consumption, reduce irreversibility, and improve the reliability and sustainability of the refrigerant cycle. So, this is our goal. I repeat, engineers aim to minimize power consumption, reduce irreversibility, and improve the reliability and sustainability of the machine.

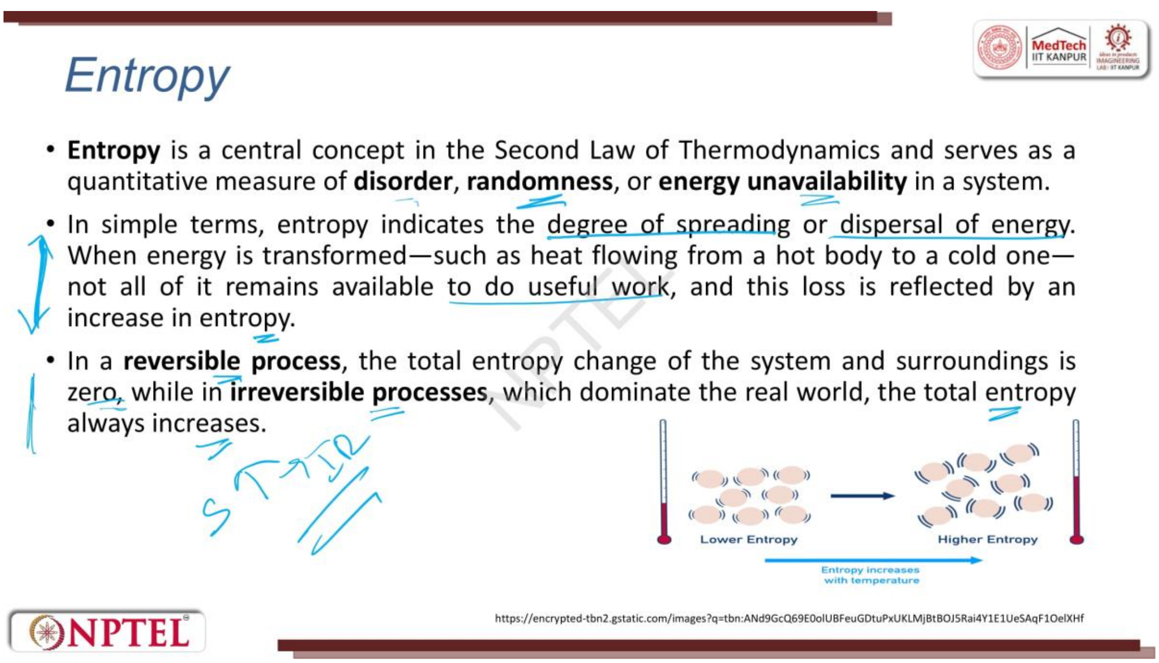
So, this is a refrigerator. So, in a crude sense, a refrigerator is different from heat engines. Unlike heat engines, which convert heat into work, the refrigerator consumes work to remove heat from the space that must be kept cold and rejects it to the warmer surrounding environment.



The last topic in the second law of thermodynamics is entropy. The property of entropy was introduced through the historical route, initiated by an engineer, Carnot, and elaborated by physicists Kelvin and Clausius. Starting with the statement expressing the impossibility of converting a heat completely into work, or impossibility of spontaneous heat flow from a colder to a hotter body, an ideal heat engine of maximum efficiency was described. With the aid of its ideal engine, an absolute temperature scale was defined and Clausius theorem proved it. On the basis of Clausius theorem, the existence of entropy function was inferred. Entropy is a measure of randomness or disorder of a system.



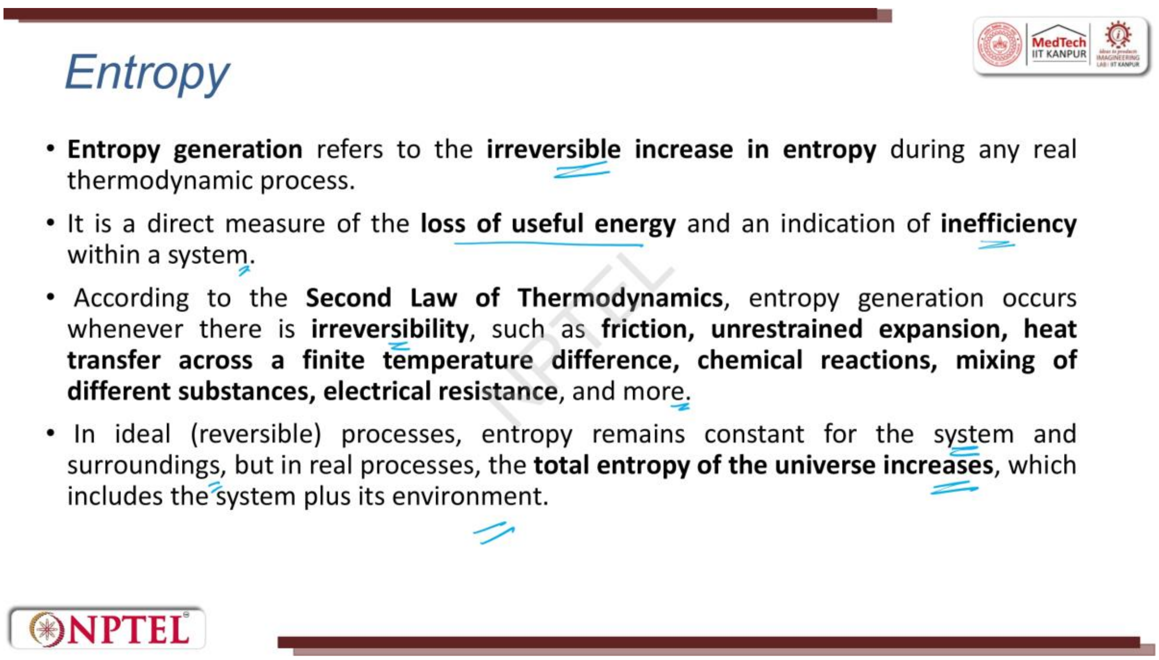
So, this is low entropy material will be, this will be high entropy material will be. The entropy increases as and when you apply energy to it.



Entropy is a central concept in the second law of thermodynamics and serves as a quantitative measure of disorder, randomness and energy unavailability in a system. In simple terms, entropy indicates the degree of spreading or dispersal of energy. It indicates the degree of spreading and dispersal of energy. When energy is transformed such as heat flowing from a hot body to a cold one, not all of it remains available to be useful work.

And, this loss is reflected by an increase in entropy. So, when does or how does an entropy increase? Entropy indicates the degree of spreading or dispersal of energy. When energy is transformed such that the heat flowing from a hot body to a colder one, not all of its remaining available to be useful work. In the reversible process, the total entropy change of a system and the surrounding is 0 in the reversible.

But whereas in irreversible process, the total entropy always increases. S increases when it is irreversible. So, this is low entropy. When the temperature is applied, there is a high entropy.



Entropy generation refers to irreversible increase in entropy during a real-time thermodynamics. In a direct measurement of loss of useful energy and indicate inefficiency within a system is increase in entropy. According to the second law of thermodynamics, entropy generation occurs whenever there is irreversibility, such as friction, unrestrained expansion, heat transfer across a finite temperature difference, chemical reaction, mixing of different substances, electrical substances, or more. In ideal process, entropy remains constant for the system and surrounding. In ideal process, the entropy remains constant for a system and surrounding. But in real world, the total entropy of the universe increases which includes system plus its environment.

Entropy

- The **mathematical expression** for entropy change including generation is:

$$\Delta S_{total} = \Delta S_{system} + \Delta S_{surroundings} = S_{gen} \geq 0$$

Where:

ΔS_{total} = Total entropy change of system + surroundings

S_{gen} = Entropy generation

$S_{gen} > 0$ for real (irreversible) processes

$S_{gen} = 0$ for ideal (reversible) processes

$S_{gen} < 0$ is impossible and violates the Second Law

So, if you want to mathematically express entropy, it is entropy $dS_{total} = dS_{system} + dS_{surrounding} = S_{gen}$ which is greater than equal to 0. So, if the S gen is entropy generation, if S gen is greater than 0 for a real process, if generation is equal to 0, it is an ideal process. If it is less than 0, it is impossible or a violation of second law. This is the entropy.

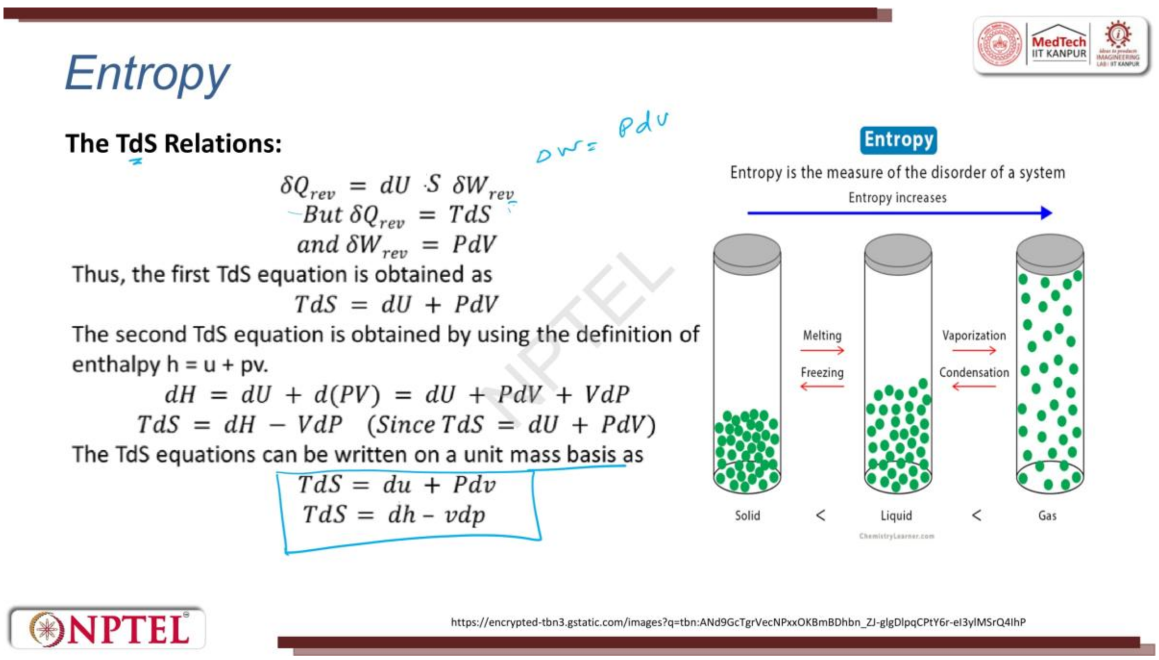
Entropy

Entropy generation is essential for understanding:

- Irreversibilities in real processes
- Limits of performance (no device can be 100% efficient)
- Wasted energy and where it occurs
- Design improvements by pinpointing inefficiencies
- Environmental impact, as higher entropy generation often corresponds to higher fuel consumption and emissions
- Entropy generation acts as a **thermodynamic cost** of performing any process in the real world. By minimizing it, we approach the ideal reversible process and achieve **maximum efficiency**.

So, the entropy generation is essential for understanding. Irreversibility in real processes can be determined by entropy. The limit of performance is also present. Waste energy and where it occurs can also be identified when studying entropy. Design improvements by pinpointing inefficiencies are achieved when understanding the concept of entropy. Environmental impact, as high entropy generation often corresponds to higher fuel consumption and emissions, is also present.

Entropy generation acts as the thermodynamic cost of performing any real-world process. By minimizing it, we approach the ideal reversible process and achieve maximum efficiency.



The thermodynamic system (TdS) relationship shows that entropy is a measure of a system's disorder, increasing from solid to liquid to gas. When melting occurs, a solid turns into a liquid, and applying more heat leads to vaporization. Vaporization to liquid is condensation.

If you refer back to the vapor cycle used in refrigerators, it involves vapor compression. The vapor compresses into a liquid, then the liquid freezes and becomes solid. This is a cycle. Here, you can observe how entropy increases.

$$\delta Q_{rev} = dU \cdot S\ \delta W_{rev}$$
$$But\ \delta Q_{rev} = TdS$$
$$and\ \delta W_{rev} = PdV$$

Thus, the first TdS equation is obtained as

$$TdS = dU + PdV$$

The second TdS equation is obtained by using the definition of enthalpy h = u + pv.

$$dH = dU + d(PV) = dU + PdV + VdP$$

$$TdS = dH - VdP \quad (Since\ TdS = dU + PdV)$$

The TdS equations can be written on a unit mass basis as

$$TdS = du + Pdv$$

$$TdS = dh - vdp$$

Entropy

- **Entropy change of an ideal gas**

The entropy change between two states of an ideal gas can be obtained from the ideal gas equation and the combined equation of the first and second laws.

$$TdS = du + Pdv$$

But, $S_2 - S_1 = c_v \ln[T_2 / T_1]$, $du = c_v\, dT$ and $P = (RT)/v$

Therefore, $TdS = c_v\, dT + [\frac{RT}{v}]\, dv$ or $\int dS = \int (c_v \frac{dT}{T}) + \int (R \frac{dv}{v})$

$\therefore S_2 - S_1 = c_v \ln[T_2 / T_1] + R \ln[v_2 / v_1]$

Again, $TdS = dh - vdP$

Now, $dh = c_p\, dT$ and $v = (RT)/P$

$$dS = c_p\, [dT/T] - [RT/PT]\, dP$$

$$\int dS = \int (c_p\, dT/T) - R \int (dP/P)$$

$$\therefore S_2 - S_1 = c_p \ln[T_2 / T_1] - R \ln[P_2 / P_1]$$

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So, the entropy change in an ideal gas: The entropy change between two states of an ideal gas can be obtained from the ideal gas equation and combined equation of the first and second laws.

$$TdS = du + Pdv$$

But, $S_2 - S_1 = c_v \ln[T_2 / T_1]$, $du = c_v\, dT$ and $P = (RT)/v$

Therefore, $TdS = c_v\, dT + [\frac{RT}{v}]\, dv$ or $\int dS = \int (c_v \frac{dT}{T}) + \int (R \frac{dv}{v})$

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Again, $TdS = dh - vdP$

Now, $dh = c_p\, dT$ and $v = (RT)/P$

$$dS = c_p\, [dT/T] - [RT/PT]\, dP$$

$$\int dS = \int (c_p\, dT/T) - R \int (dP/P)$$

$$\therefore S_2 - S_1 = c_p \ln[T_2 / T_1] - R \ln[P_2 / P_1]$$

Entropy - Applications

Applications of Entropy:

- The principle of increase of entropy is one of the most important laws of physical science. It is the quantitative statement of the second law of thermodynamics.
- Every irreversible process is accompanied by entropy increase of the universe, and this entropy increase quantifies the extent of irreversibility of the process.
- The higher the entropy increase of the universe, the higher will be the irreversibility of the process.
- The entropy principle helps engineers:

➢Validate the **possibility** of processes

➢Assess **efficiency and losses**

➢Guide the **design of sustainable systems**

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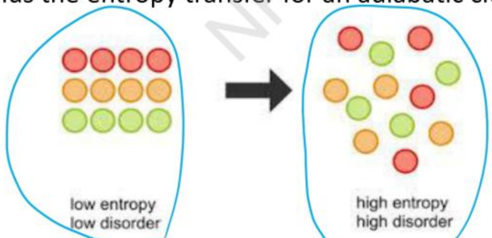
So, the application of entropy: where do we use it? So, the principle of increase in entropy is one of the most important laws of physical sciences. It has the equal quantitative statement of the second law of thermodynamics as the application of entropy. Every irreversible process is accompanied by an entropy increase of the universe.

The higher the entropy increase of the universe, the higher is the irreversibility of the process. Higher is the entropy increase, the higher the level. The entropy principle helps engineers to find out the possibility of a process, the efficiency or the loss of a process, and serves as a guide for sustainable systems. So, these are the principles where entropy is used for an engineer.

Entropy

- Entropy can be transferred to or from a system in two forms: heat transfer and mass flow.
- In contrast, energy is transferred by work also.
- Entropy transfer is recognized at the system boundary as entropy crosses the boundary, and it represents the entropy gained or lost by a system during a process.
- The only form of entropy interaction associated with a fixed mass or closed system is heat transfer, and thus the entropy transfer for an adiabatic closed system is zero.



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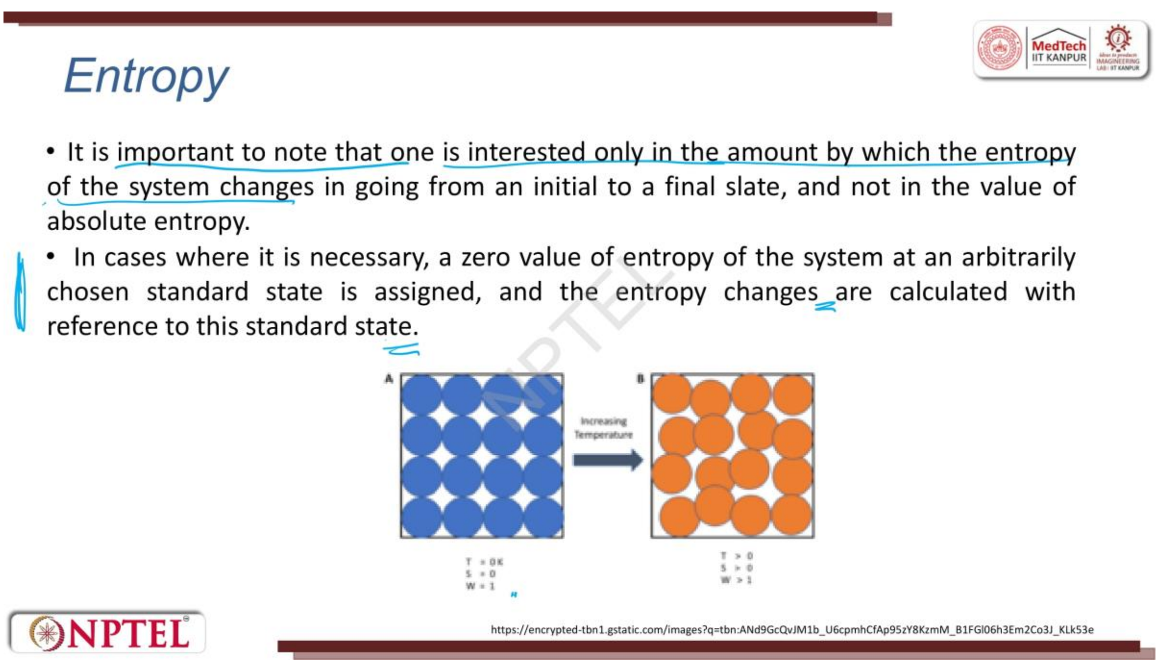
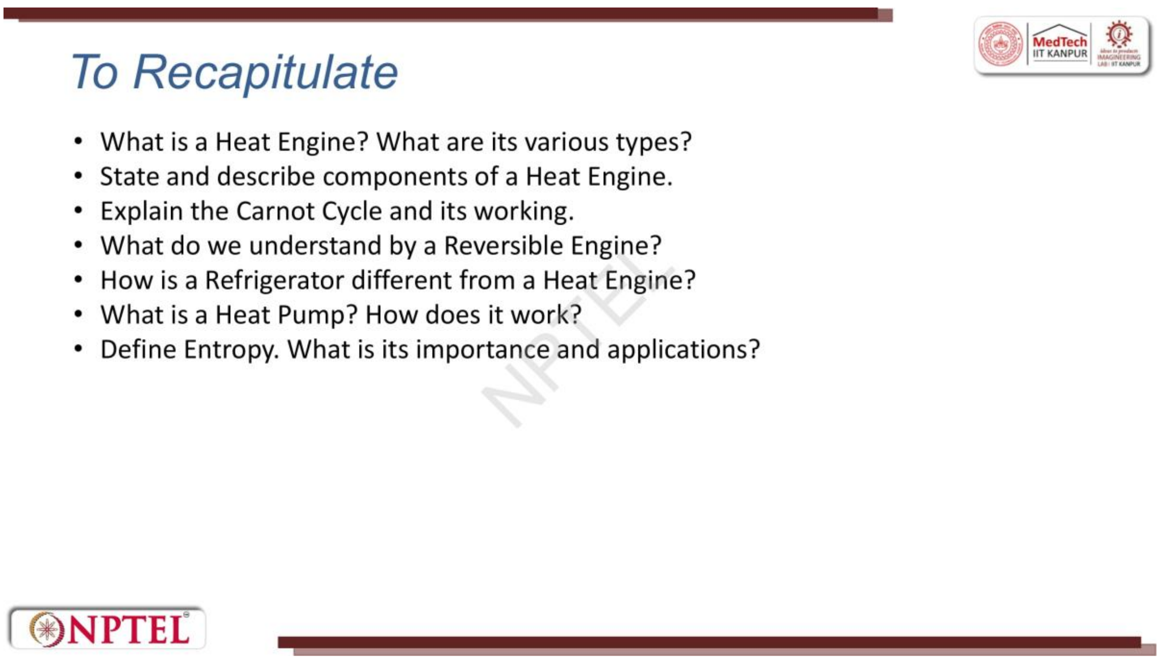
The entropy can be transferred to or from your system in two forms. Either it transfers heat or it transfers mass. So, heat transfer and mass flow can happen in the entropy. In contrast, the energy is transferred by work. But entropy is transferred by two forms, heat transfer and mass flow. In energy, it is transferred as only work.

Entropy transfer is recognized as a system boundary as entropy crosses the boundary and it represents the entropy gained or lost by the system during the process. This statement is also very important. Entropy transfer is recognized at the system boundary as entropy crosses the boundary, and it represents the entropy gained or lost by the system during the process. The only form of entropy interaction associated with a fixed mass or closed system is heat transfer. And, thus the entropy transfer for an adiabatic closed system is zero.

Important. The only form of entropy interaction associated with its fixed mass or closed system is heat transfer. When it goes to adiabatic, of an adiabatic closed system is 0. So, low entropy, low disorder, this is high entropy and high disorder.



It is important to note that one is interested only in the amount of the entropy of the system changes is going from initial to final and not its value. In cases where it is necessary, a zero value of entropy for a system at an arbitrarily chosen standard state is assigned, and the entropy changes are calculated with reference to that standard state. So, this is also important. These two are very important in cases where it is necessary: a zero value of entropy for a system at an arbitrarily chosen standard state is assigned, and entropy changes are calculated with reference to its standard state. So, here we will try to cover all those things. This is what it is. So, what happens to these things when the temperature increases? So, you can see this very clearly: what happens to temperature, what happens to work, and what happens to entropy.



Friends, in this chapter, we saw what a heat engine is, what its various types are, and described the components of a heat engine. Then, we looked into the Carnot cycle and its working. We understood reversible engines. Then, we explored how a refrigerator works and how it differs from a heat engine. What is a heat pump?

How does it work? And finally, we understood entropy, its importance, and its applications.

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These are the references, and thank you very much.