1. Details of Module and its structure

Module Detail	
Subject Name	Physics
Course Name	Physics 02(Physics Part 2, Class XI)
Module Name/Title	Unit 8, Module 4, Second law of Thermodynamics Chapter 12, Thermodynamics
Module Id	keph_201204_eContent
Pre-requisites	First law of thermodynamics, reversible and irreversible thermodynamic processes, isothermal process, adiabatic process, isochoric process and isobaric process.
Objectives	After going through this module, the learners will be able to: • Understand that spontaneous processes have a certain direction, and that this direction cannot be reversed. • Appreciate irreversibility on the basis of second law of thermodynamics • Relate to Heat engines and their efficiency. • Know about the constraints imposed on the efficiency of a heat engine by the second law of thermodynamics. • Understand the Carnot engine as an ideal heat engine.
Keywords	Heat engine, efficiency of heat engine , Carnot engine, entropy, second law of thermodynamics

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1. UNIT SYLLABUS

Unit 8: Thermodynamics

Chapter 12: Thermodynamics
Thermal equilibrium and definition of temperature (zeroth law of thermodynamics), heat, work and internal energy. First law of thermodynamics, isothermal and adiabatic processes. Second law of thermodynamics: reversible and irreversible processes, Heat engine and refrigerator.

2. MODULE WISE DISTRIBUTION OF UNIT SYLLABUS 6 Modules

The above unit is divided into six modules for better understanding.

Module 1	• **Thermal equilibrium** • **Heat exchange** • **Zeroth law of thermodynamics** • **Daily life observations**
Module 2	• **Relation between work and internal energy** • **Work on solids, liquids & gas** • **Relation between heat and internal energy** • **Molecular nature of heat and work**
Module 3	• **First law of thermodynamics** • **Relation between internal energy work and heat absorbed or released by a body** • **Relevance of first law to gases** • **P-V indicator diagram** • **Thermodynamically processes Isothermal, adiabatic, isobaric, isochoric, reversible and irreversible**
Module 4	• **Second law of thermodynamics**

	• **Heat engines** • **Carnot cycle** • **Efficiency of engines**
Module 5	• **Refrigerator** • **Heat machines -devices that produce heat geyser, toaster, stove –devices that operate on using internal energy**
Module 6	• **Understanding the thermal effect of heat and thermodynamics** • **Problem solving in thermodynamics**

MODULE 4

3. WORDS YOU MUST KNOW

Three states of matter: solid liquid gas

Thermodynamic system: Part of the universe that is under consideration.

Surroundings: everything in immediate or in far environment of the system.

Boundary: surface separating the system from surroundings

Open system: system that can exchange matter and energy with the surroundings

Closed system: system that can only exchange energy with the surroundings

Isolated system: system that can exchange neither energy nor matter with the surroundings

Adiabatic wall: boundary that prevents heat exchange

Diathermic wall: boundary that allows heat exchange

Equilibrium state: a thermodynamic system is in equilibrium state if all the macroscopic variables that describe the system do not change in time and space.

Temperature: the fundamental property of every system which directs heat flow between any two systems.

Internal energy: Sum of the potential and kinetic energies of molecules of the system, assuming centre of mass of the system to be at rest

Thermodynamic work: work that brings a change in the random motion of the molecules of a thermodynamic system and hence can change its internal energy.

Heat: energy in transit which is transferred due to temperature difference, without the need for any bulk movement of the system or its parts.

Entropy: a thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system. lack of order or predictability; gradual decline of order into disorder.

Zeroth law of thermodynamics: states that 'two systems in thermal equilibrium with a third system separately are in thermal equilibrium with each other'.

First law of thermodynamics:

The change in internal energy of a system is equal to the difference in the heat given to the system and the work done by the system. Basically it is the law of conservation of energy.

Isothermal process: A thermodynamic process in which the temperature of the system remains constant.

Isobaric process: A thermodynamic process in which the pressure of the system remains constant.

Isochoric process: A thermodynamic process in which the volume of the system remains constant.

Adiabatic process: A thermodynamic process in which there is no exchange of heat energy between the system and the surroundings.

Reversible process: The system remains in thermodynamic equilibrium at every stage and it can be made to retrace the path to reach back the initial thermodynamic state.

Irreversible process: The system cannot be made to retrace its path.

Cyclic process: A process which returns back to its initial state through a series of steps.

4. INTRODUCTION

You have learnt about the relation between internal energy and heat in the previous modules of this unit. Let us now see how the thermodynamical processes are involved in daily life.

Consider these

1) **A hot cup of tea left outside on a cold day gives heat to the surroundings and becomes cold.**

Have you seen a cold cup of tea becoming hotter by drawing heat from the cold surrounding on its own? Never!

2) **If we drop a cup made of china glass accidentally, it shatters into many tiny pieces**.

Have you ever seen the shattered pieces come together on their own and join themselves to make the cup again? Never!

3) **If we open a nozzle of a helium gas balloon in a room, the helium gas molecules will spread into the room and the balloon will deflate.**

Have you ever seen the balloon inflating on its own due to the helium gas in the room returning back into the balloon? Never!

Why are the above seemingly innocent situations impossible?

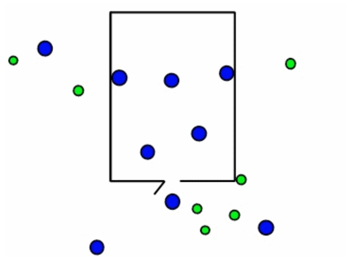
What prevents their occurrence?

Which law of physics is being violated?

THINK ABOUT THESE

We note that in all possible processes quoted above, we are moving towards a more disordered state. The disorder of the system and the universe increases

- In situation 1, when the heat goes from the hot body to cold surroundings.
- In situation 2, when the cup shatters into many pieces
- In situation 3, when the helium gas from the balloon diffuses into the room.



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For the reverse process in the above given situations, we would be moving towards a more ordered state of the system and the universe. And we have seen that the processes quoted above never happen in the reverse direction.

An important observation: The process in which the net disorder of the system plus universe increases is favourable and hence it occurs spontaneously. On the other hand, the reverse process in which the net disorder of the system and universe

decreases is not favourable and therefore it does not occur on its own (or spontaneously). This disorder is referred to as the entropy.

5. SECOND LAW OF THERMODYNAMICS

The First Law of Thermodynamics is the principle of conservation of energy. Common experience shows that there are many conceivable processes that are perfectly allowed by the First Law and yet are never observed. For example, nobody has ever seen a book lying on a table jumping to a height by itself. But such a thing would be possible if the principle of conservation of energy were the only restriction. The table could cool spontaneously, converting some of its internal energy into an equal amount of mechanical energy of the book, which would then hop to a height with potential energy equal to the mechanical energy it acquired. But this never happens. Clearly, some additional basic principle of nature forbids the above, even though it satisfies the energy conservation principle. This principle, which disallows many phenomena consistent with the First Law of Thermodynamics is known as the Second Law of Thermodynamics

Second law of thermodynamics states that the entropy of the system and surroundings either increases or remains same in any process. It never decreases.

The gas molecules leaving the chamber will never collect back into the chamber again as it will decrease the total entropy

EXAMPLE

Stated below are some situations. Point out the ones which violate the second law of thermodynamics

a. Boulders from a mountain falling down and breaking into many smaller stones. (Landslide)

b. Mixing of two gases inside a chamber when the partition between them is removed

c. The mixture of gases separating on their own and returning back to their side of the chamber.

d. A box sliding on a plane rough surface becoming warm.

e. A box takes heat from the surroundings and starts sliding on a plane surface.

SOLUTION: **3 and 5** (because the system and universe are moving towards a more ordered state)

6. HEAT ENGINES AND THEIR EFFICIENCY

Many scientists have given their own statements for the Second law of thermodynamics to explain this law. These statements are mainly related to the heat engine and refrigerator.

To understand them let us consider a very simple situation. If we rub our hands together on a cold day, our hands become warm. In this process we have converted mechanical work into heat. If we rub our hands more vigorously, larger amount of heat will be generated. So we can convert work into heat. In fact, all of the work done can be converted into heat. Joule did many experiments in which he converted all the work into heat and also measured the amount of heat generated.

A heat engine on the other hand involves the reverse process. **A heat engine is a device which converts heat energy into mechanical energy in a cyclic process**. From time immemorial many intellectuals wanted to create a heat engine which has a hundred percent efficiency. Such a heat engine means that its system which is working in a cyclic process is capable of converting all the heat (taken from some heat reservoir) into work. They spent years and years in trying to design such an engine. They thought that if it was possible to convert all the work into heat then nature should allow them to convert all the heat into work in a heat engine.

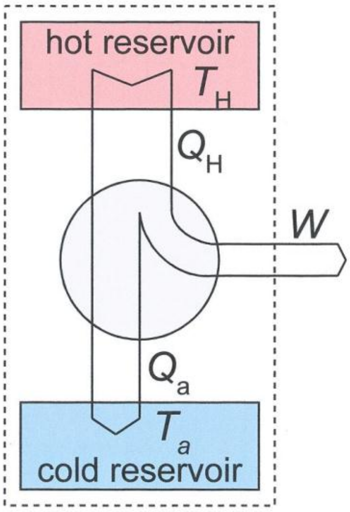
Eventually they realized that creating such a heat engine was an impossible task. This realization gives rise to the Second law of thermodynamics.

Kelvin Statement Of The Second Law Of Thermodynamics:

A process whose only net result is to transfer energy as heat from a cooler object to a hotter one is impossible.

This simple statement is the reason why we cannot have hundred percent efficient heat engines. To appreciate this statement in its totality let us understand the working of the heat engine.

Schematic diagram of heat engine



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- **System takes heat Q_H from the hot reservoir maintained at the temperature T_H.**
- **It converts some of this heat into work W**

  and
- **rejects the rest of the heat Qa to the cold reservoir maintained at the temperature T_a**

  and
- **returns to its initial state.**
- **Then the process continues again.**

$W = Q_H - Q_a$

Efficiency of the heat engine η

$$\frac{\text{Output}}{\text{Input}} = \frac{\text{Work done by the system}}{\text{Heat absorbed from the hot reservoir}}$$

$$= 1 - \left(\frac{Q_a}{Q_H}\right)$$

A hundred percent efficiency means that the output is equal to input and it is possible only if no heat is rejected to the cold reservoir (i.e. Qa = 0). This again means that the system is capable of converting all the heat it takes from the hot reservoir into work. But according to the second law of thermodynamics this is impossible. So it can be concluded that

No heat engine working in a cyclic process can have a hundred percent efficiency

Point to be noted:

In the statement given above, **the word cyclic process is very important.**

For example, a gas which is undergoing a isothermal process takes heat from its surrounding and converts the whole of it into work. But after the process of isothermal expansion, the gas is not in its original thermodynamic state. To bring it back to its original state, some work has to be done on it and in this process some heat will be rejected by the gas.

This means that without a cold reservoir to reject some amount of heat we cannot design a heat engine.

EXAMPLE:

A heat engine absorbs 200J of heat from the hot reservoir and rejects 150J of heat to the cold reservoir in each cycle. What is the efficiency of the heat engine?

SOLUTION:

Heat absorbed from the hot reservoir (Q_1) = 200J

Heat rejected to the cold reservoir (Q_2) = 150J

Useful work done (W) = $Q_1 - Q_2$ = 50J

Efficiency (η) = W/ Q_1 = 50/200 = 0.25 or **25%**

STEAM ENGINES:

The earliest heat engines were steam engines.

In the steam engine

- **Water is heated at a very high pressure and converted into steam.**
- **Heat required in this process is Q_{in}.**
- **The steam produced pushes a piston to do work (W).**
- **In the process the steam cools down.**
- **It is made to exit the chamber at a much lower temperature.**
- **The steam is further cooled by the condenser where it rejects the heat (Q_{out}) and liquefies.**
- **The water thus produced is again made to go made to go through the boiler to produce steam. Thus the whole process begins all over again.**
- **The efficiency of the best steam engine is only around 40% (Efficiency (η) = W/ Q_{in}).**

'The question which arises is 'If we cannot make a heat engine with 100% efficiency then what is the maximum possible efficiency attainable in a heat engine'

The answer to this was found by 'Sadi Carnot'. He conceptualized a reversible heat engine which had efficiency greater than any other heat engine. This was stated as the Carnot theorem

'No engine working between two given heat reservoirs can be more efficient than the Carnot's reversible engine working between those two reservoirs'

7. CARNOT ENGINE:

Carnot's engine was a reversible engine. To understand and appreciate this engine, we need to look at the conditions required to make a reversible engine.

Heat always goes from a hot object to a cold object, this process is irreversible.

Similarly,

heat lost in a process due to friction and other dissipative forces is irrecoverable. This process is also irreversible.

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Moreover

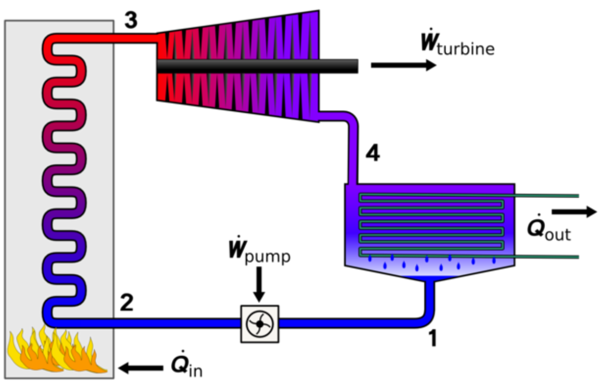
if the system goes through non-equilibrium states due to sudden changes then it cannot be made to retrace its path i.e. the process again becomes irreversible.

Hence we see that if want a process to be reversible, the above mentioned constraints should be factored.

Keeping the above in mind, we list certain conditions under which a process is reversible:

(a) **Thermal energy transfer is between two objects which are at the same temperature (or have negligible temperature difference).**

(b) **Dissipative forces like friction, viscous forces are absent.**



(c) **System is made to go through quasi-static process in which the system always passes through its equilibrium states**.

In practical life, creating these conditions is almost impossible. Here we are talking of ideal conditions.

Therefore, a reversible process is also an idealized concept.

In fact, Carnot engine itself is an idealized concept.

Carnot never made such an engine. It is a perfect engine which cannot be made.

We can approach it by refining the designs of our heat engines but we will never really reach it.

The components of the Carnot engine consist of

a) Hot reservoir always maintained at a temperature T_1. Its temperature does not change even when heat is drawn from it

b) Working substance: It consists of an ideal gas in a cylinder with a piston. Frictional forces are completely absent in it. So when the piston moves, there is no dissipation of energy.

c) Cold reservoir always maintained at temperature T_2. Its temperature does not change even when heat is given to it.

The working of the Carnot engine involves four reversible and quasi-static processes.

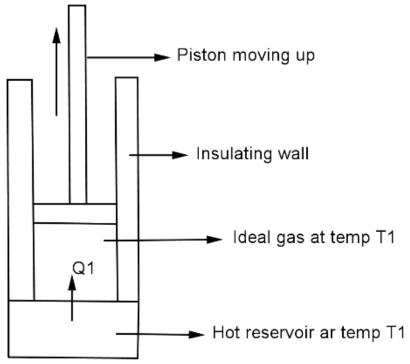
By **quasi-static** we mean that the gas in the working system is always in its equilibrium state. **This is made possible by making all the processes; that the gas goes through, a very-very slow (infinitesimally slow) process.**

The four processes are-

- **i) Isothermal expansion of the gas**
- **ii) Adiabatic expansion of the gas to a lower temperature T_2**
- **iii) Isothermal compression of the gas which involves an isothermal exhaustion of heat to the cold reservoir at temperature T_2**
- **iv) Adiabatic compression of the gas to a higher temperature T_{1T}**

The four processes of the Carnot cycle are illustrated below:

Step 1: Isothermal expansion: This process involves an isothermal absorption of heat from the hot reservoir at temperature T_1. The cylinder having the ideal gas is placed over the hot reservoir. Then the piston of the cylinder is pulled up very slowly which results in Q_1 amount of heat being absorbed from the hot reservoir. Heat can only be transferred into the cylinder through the upper wall of the hot reservoir which is perfectly conducting. The piston is pulled up very slowly so that the temperature of the gas and reservoir remain T_1 throughout the process.



Isothermal expansion

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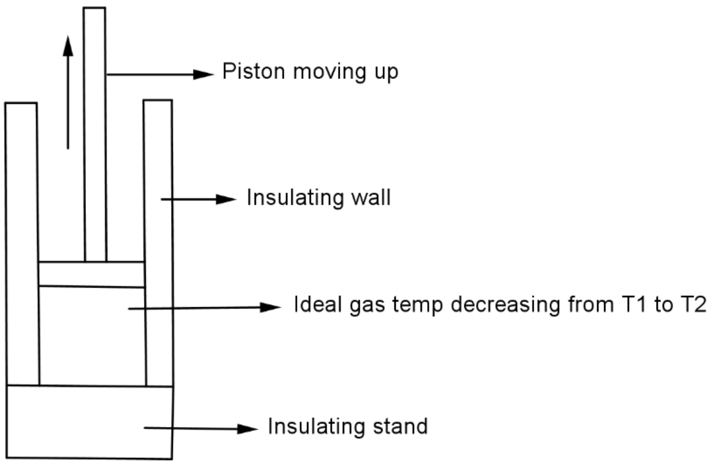
Step 2: Adiabatic expansion: The cylinder with the gas is now placed on an insulating stand and the piston is moved up slowly. Since the boundary walls of the cylinder are completely insulated, no heat exchange takes place between the gas and the surroundings. In the expansion, work is being done by the gas at the cost of its internal energy, hence the internal energy of the gas decreases which in turn causes the temperature of the gas to drop. This temperature is made to drop from the initial temp T_1 to the final temp T_2



Adiabatic expansion

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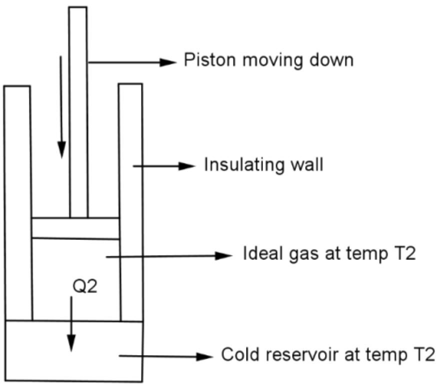
Step 3: Isothermal compression: This process involves an isothermal exhaustion of heat to the cold reservoir at temperature T_2. The cylinder having the ideal gas is placed over the cold reservoir. Then the piston of the cylinder is pushed down slowly which results in Q_2 amount of heat being rejected to the cold reservoir. The upper wall of the cold reservoir is perfectly conducting. The piston is pushed down very slowly so that the temperature of the gas and reservoir remain T_2 throughout the process



Isothermal compression

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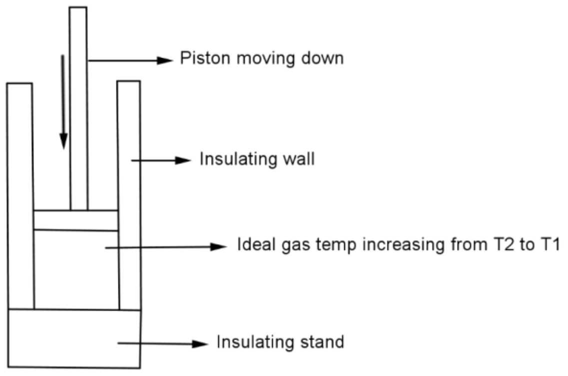
Step 4: Adiabatic compression: The cylinder with the gas is again placed on an insulating stand and the piston is moved down slowly. Since the boundary walls of the cylinder are completely insulated, no heat exchange takes place between the gas and the surroundings. In the compression, work is being done on the gas, hence the internal energy of the gas increases which in turn causes the temperature of the gas to rise. This temperature is made to rise from the initial temp T_2 to the final temp T_1.



Adiabatic compression

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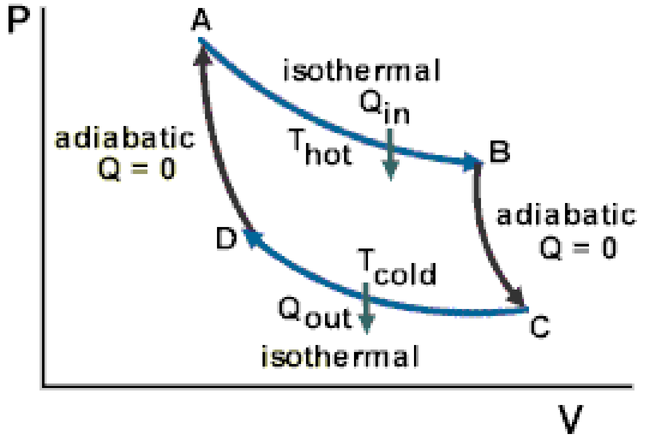
PV indicator diagram of the Carnot cycle

The four processes of the Carnot cycle can be depicted in a PV indicator diagram. In every step, the initial thermodynamic variables P, V and T (Pressure, Volume and temperature) change to a new set of thermodynamic variables. Area enclosed by the PV diagram is equal to the total work done by the Carnot engine.



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Isothermal expansion is depicted by the curve AB.

- The thermodynamic state of the gas at A is given by P_1, V_1 and T_1 while the final thermodynamic state of the gas at the end of this process of isothermal expansion shown at B is given by P_2, V_2 andT_1. Temperature of the gas is maintained at T_1 throughout this process.
- Since the gas is an ideal gas, total internal energy of the gas is only due to the total kinetic energy of the gas molecules. If there is no change in temperature the total kinetic energy remains constant, so there is no change in the internal energy of the gas.
- Here all the heat absorbed by the gas from the hot reservoir (Q_{in} or Q_1) is converted into work (by the first law of thermodynamics)
- **Work done in this process**

$$\mathbf{W_{AB} = nRT_1 In\left(\frac{V_2}{V_1}\right) = Q_1 = heat\ absorbed\ from\ the\ source}$$

(Where n = number of moles, R = Gas constant)

Adiabatic expansion is depicted by the curve BC.

- The final thermodynamic state of the gas at C is given by P_3, V_3, T_2 at the end of this process.
- Since there is no heat exchange with the surroundings, the work done in expansion is at the expense of the internal energy. So the temperature drops down from T_1 to T_2 in this process.
- **Work done in this process**

$$\mathbf{W_{BC} = \frac{nR(T_1 - T_2)}{\gamma - 1}}$$

(Where γ = ratio of the two molar specific heats of gas Cp/Cv)

Isothermal compression is depicted by the curve CD.

- The final thermodynamic state of the gas at D is given by P_4, V_4, and T_2 at the end of this process. The temperature of the gas is maintained at T_2 throughout this process

- Again there is no change in internal energy of the gas, so the work done in this process of isothermal compression is equal to the heat rejected (Q_{out} or Q_2)to the cold reservoir(sink)
- **Work done in this process**

$$W_{CD} = nRT_2 In\left(\frac{V_4}{V_3}\right) = Q_2 = \text{heat rejected to the sink}$$

Adiabatic compression is depicted by the curve DA

- At the end of this process, the gas returns to its initial thermodynamic state at A which is given by P_1, V_1, andT_1.
- Since there is no heat exchange with the surroundings, the work done in compression increases the internal energy of the gas. So the temperature rises from T_2 to T_1 in this process.
- **Work done in this process**

$$W_{DA} = \frac{nR(T_2 - T_1)}{\gamma - 1}$$

Total work done in one complete cycle of Carnot engine = Sum of the work done in each process

$$W = W_{AB} + W_{BC} + W_{CD} + W_{DA}$$

$$= nRT_1 \ln(V_2/V_1) + nRT_2 \ln(V_4/V_3) \qquad (\text{Since } W_{BC} = -W_{DA})$$

$$= nRT_1 \ln(V_2/V_1) - nRT_2 \ln(V_3/V_4)$$

Now since the curve BC and DA represent adiabatic curves, they will follow the adiabatic equation-

So for the adiabatic BC $\quad T_1V_2^{\gamma-1} = T_2V_3^{\gamma-1}$ -------------------- (i)

& for the adiabatic DA $\quad T_2V_4^{\gamma-1} = T_1V_1^{\gamma-1}$ --------------------- (ii)

From (i) $\quad T_1 / T_2 = V_3^{\gamma-1} / V_2^{\gamma-1}$

From (ii) $\quad T_1 / T_2 = V_4^{\gamma-1} / V_1^{\gamma-1}$

$$(V_3/V_2)^{\gamma-1} = (V_4/V_1)^{\gamma-1}$$

Therefore $V_3 / V_2 = V_4 / V_1$

OR $V_3 / V_4 = V_2 / V_1$

So the total work done will be $W = nRT_1 \ln (V_2/V_1) - nRT_2 \ln (V_2 / V_1)$

$$W = nR (T_1 - T_2) \ln (V_2/V_1)$$

Efficiency η= Output / input = W/ Q_1 = Total work done / heat absorbed from the source

$$= \quad nR (T_1 - T_2) \ln(V_2/V_1) / \; nRT_1 \ln(V_2/V_1)$$

$$\eta = (T_1 - T_2) / T_1$$

Points to be noted:

- **The efficiency of a Carnot engine depends only on the temperature of source and sink.**
- **A hundred percent efficiency means that, the temperature of the sink should be absolute zero (0K) or the temperature of the source should be infinite. Both situations are practically impossible. So even a Carnot engine cannot have a cent percent efficiency.**

EXAMPLE:

A Carnot engine works between two heat reservoirs at temperatures T_1= 300 K and T_2= 200 K. (a) what is its efficiency? (b) If it absorbs 100 J from the hot reservoir during each cycle, how much work does it do? (c) How much heat does it give off during each cycle?

SOLUTION:

(a) Efficiency = $(T_1 - T_2) / T_1$ = 300 – 200/ 300 = 1/3

(b) Efficiency = Work done per cycle/ heat absorbed from source

So work done = 1/3 x 100 = 33.3 J

(c) Heat rejected = Heat absorbed – work done = 100 – 33.3 = 66.66 J

Tabulated below are the various efficiencies of a Carnot engine having different source and sink temperatures

S.N.	Temperature of source (in K)	Temperature of sink (in K)	Efficiency of Carnot engine (η)
1	500	350	0.3
2	500	300	0.4
3	500	250	0.5
4	500	200	0.6
5	500	150	0.7
6	550	250	0.54
7	600	250	0.58
8	650	250	0.61
9	700	250	0.64
10	750	250	0.66

Interpreting the table:

- **When the temperature of the source is fixed (S.N. 1--5) and the temperature of the sink is decreased by 50K the efficiency goes up by 0.1 in every such decrement**.
- When the temperature of the sink is fixed (6 – 10) and the temperature of the source is increased by 50K, the efficiency goes up but not as much as 0.1. Also the increase is not uniform.
- **So it can be concluded that decreasing the temperature of the sink is more effective than increasing the temperature of source by the same amount in increasing the efficiency of the Carnot engine.**

FOUR STROKE CAR ENGINE

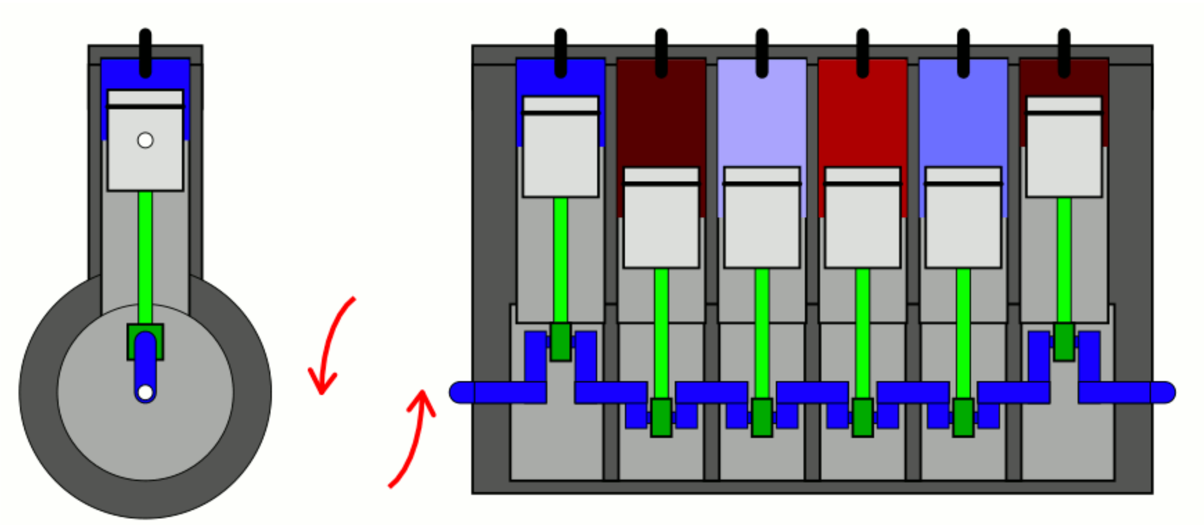
These are internal combustion engines. the fuel (gas) is burnt inside the cylinder. this expands and pushes the piston.

Internal combustion means just what it says: that fuel is burned inside the engine.

In a car engine, petrol is burned inside the engine, which ignites the petrol vapour and releases energy that moves the car.

There are also other methods of internal combustion, such as diesel engines and CNG gas engines. Internal combustion is an efficient system that requires a relatively small engine to create motion.

It is also more fuel efficient than external combustion engines, such as an old-fashioned steam engine.



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you could also see the video just for information , the video shows history of automobile engines .

https://auto.howstuffworks.com/engine.htm

or

https://www.youtube.com/watch?time_continue=205&v=KQ8J6CN5gAs

8. SUMMARY:

Second law of thermodynamics:

1. The total entropy of the universe never decreases. It can either remain same or increase in any process
2. The efficiency of a heat engine can never be 100%

Carnot engine:

- Carnot engine is an ideal reversible heat engine. It is only a concept.
- There are no dissipative forces during the working of the engine.
- The working substance is an ideal gas working between the hot and cold reservoir.
- The Carnot cycle consists of four processes in which the gas absorbs heat from the hot reservoir, does some work, rejects some heat to the cold reservoir and then returns back to its initial state to complete the cycle.
- The gas is always in its equilibrium state at every step

Efficiency of the Carnot engine (η): It depends only on the temperature of the source (hot reservoir) T_1 and the sink (cold reservoir) T_2 and it is equal to

$$\eta = (T_1 - T_2) / T_1$$

Carnot theorem:

'No engine working between two given heat reservoirs can be more efficient than the Carnot's reversible engine working between those two reservoirs.'