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 5, Refrigerator Chapter 12, Thermodynamics
Module Id	keph_201205_eContent
Pre-requisites	Thermal equilibrium, Zeroth law of thermodynamics, internal energy, first law of thermodynamics, second law of thermodynamics ,heat engine, Carnot engine and Carnot theorem
Objectives	After going through this module, the learners will be able to: • Understand the working of refrigerators and their coefficient of performance • Know about the constraints imposed on the coefficient of performance by the second law of thermodynamics • Apply laws of thermodynamics to mechanical work and heat related devices
Keywords	Refrigerator, coefficient of performance, second law of thermodynamics

2. Development Team

Role	Name	Affiliation
National MOOC Coordinator (NMC)	Prof. Amarendra P. Behera	Central Institute of Educational Technology, NCERT, New Delhi
Programme Coordinator	Dr. Mohd. Mamur Ali	Central Institute of Educational Technology, NCERT, New Delhi
Course Coordinator / PI	Anuradha Mathur	Central Institute of Educational Technology, NCERT, New Delhi
Subject Matter Expert (SME)	Smita Fangaria,	Physics PGT Developer Anvishika Amity International School, Noida
Review Team	Prof. V. B. Bhatia (Retd.) Associate Prof. N.K. Sehgal (Retd.) Prof. B. K. Sharma (Retd.)	Delhi University Delhi University DESM, NCERT, New Delhi

TABLE OF CONTENTS:

1. UNIT SYLLABUS

Unit 8: Thermodynamics

Syllabus

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 5

3. WORDS YOU MUST KNOW

Thermodynamic system: Part of the universe that is center of attentions

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

Boundary: surface separating the system from surroundings

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

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

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.

Path function: Quantity whose magnitude depends on the path between the initial and final points/ states.

State Function: quantity whose magnitude depends only on the initial and final points/states and not on the path.

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: Measure of disorder in a system.

Second law of thermodynamics in relation to entropy: Total entropy of the universe never decreases in a process.

Heat engine: A device which converts heat energy into mechanical energy in a cyclic process.

Second law of thermodynamics in relation to heat engine: No heat engine working in a cyclic process can have a hundred percent efficiency.

Carnot engine: An ideal, reversible engine in which there are no dissipative forces. The ideal gas used as a working substance is always in equilibrium as it goes through the four processes of isothermal expansion, adiabatic expansion, isothermal compression and adiabatic compression and returns back to its initial state to complete the cycle.

Efficiency of the Carnot engine (η):

It depends only on the temperature of the source (hot reservoir) $\mathbf{T_1}$ and the sink (cold reservoir) $\mathbf{T_2}$ and it is equal to

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

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'

4. INTRODUCTION

We have learnt in the earlier modules about thermodynamics, the movement of heat

The distinction between mechanics and thermodynamics is worth bearing in mind. In mechanics, our interest is in the motion of particles or bodies under the action of forces and torques. Thermodynamics is not concerned with the motion of the system as a whole. It is concerned with the internal macroscopic state of the body. When a bullet is fired from a gun, what changes is the mechanical state of the bullet (its kinetic energy, in particular), not its temperature. When the bullet pierces a wood and stops, the kinetic energy of the bullet gets converted into heat, changing the temperature of the bullet and the surrounding layers of wood.

Temperature is related to the energy of the internal (disordered) motion of the bullet, not to the motion of the bullet as a whole.

In dealing with heat engine, a device by which a system is made to undergo a cyclic process that results in **conversion of heat to work**.

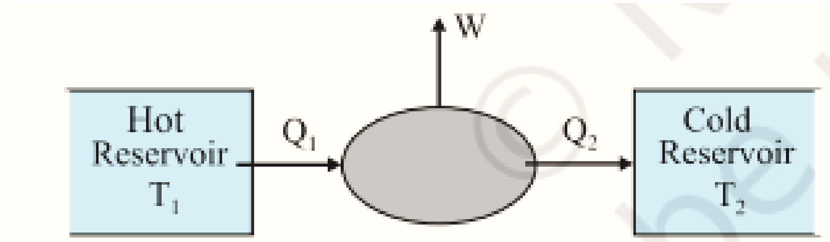
(1**) It consists of a working substance–the system. For example, a mixture of fuel vapour and air in a gasoline or diesel engine or steam in a steam engine are the working substances**.

(2) **The working substance goes through a cycle consisting of several processes. In some of these processes, it absorbs a total amount of heat Q_1 from an external reservoir at some high temperature T_1.**

(3) **In some other processes of the cycle, the working substance releases a total amount of heat Q_2 to an external reservoir at some lower temperature T_2.**

(4) The work done (W) by the system in a cycle is transferred to the environment via some arrangement (e.g. the working substance may be in a cylinder with a moving piston that transfers mechanical energy to the wheels of a vehicle via a shaft).

The basic features of a heat engine are schematically represented in figure



Schematic representation of a heat engine. The engine takes heat Q_1 from a hot reservoir at temperature T_1, releases heat Q_2 to a cold reservoir at temperature T_2 and delivers work W to the surroundings.

The cycle is repeated again and again to get useful work for some purpose. The discipline of thermodynamics has its roots in the study of heat engines. A basic question relates to the efficiency of a heat engine. The efficiency (η) of a heat engine is defined by

$$\eta = \frac{W}{Q_1}$$

where Q_1 is the heat input i.e., the heat absorbed by the system in one complete cycle

and W is the work done on the environment in a cycle. In a cycle, a certain amount of heat (Q_2) may also be rejected to the environment. Then, according to the First Law of Thermodynamics, over one complete cycle

$$W = Q_1 - Q_2$$

The mechanism of conversion of heat into work varies for different heat engines. Basically, there are two ways:

- **The system (say a gas or a mixture of gases) is heated by an external furnace, as in a steam engine;**

or

- **It is heated internally by an exothermic chemical reaction as in an internal combustion engine.**

The various steps involved in a cycle also differ from one engine to another

A refrigerator is the reverse of a heat engine

5. REFRIGERATOR:

Everyone enjoys drinking a glass of cold water taken out of refrigerator especially in the month of summer, when the sun is scorching the earth outdoors.

http://res.freestockphotos.biz/pictures/15/15330-a-glass-of-cold-water-with-ice-cubes-pv.jpg

Refrigerators are an important part of our lives. They cool our drinks; keep our vegetables fresh; preserve milk and give us ice for our use. So it is important that we understand how they work.

The purpose of a refrigerator is to keep the things kept inside it cool.

In other words, it should be able to extract heat from the things which are kept inside it. So this is the output expected from a refrigerator. But to keep things cool inside a refrigerator we use electricity, for which we have to pay the electricity bills.

The performance of a refrigerator is rated on two criteria:

i) **Ability to keep things cool inside it**
ii) **Amount of electricity bill we have to pay to keep the refrigerator running.**

A good refrigerator is one which uses optimal amount electricity bill and cool things kept inside it efficiently.

An ideal situation would be when we don't have to pay any bill to keep the refrigerator running.

But we all know that this can never happen.

We may buy the best refrigerator available in the market, but we cannot escape from paying electricity bill.

In fact, if this happened it would violate the second law of thermodynamics.

COMPONENTS OF A REFRIGERATOR:

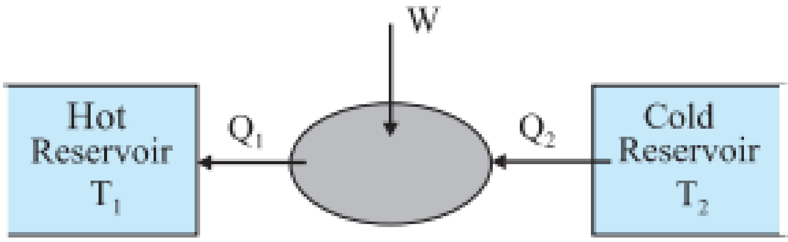
Components of a refrigerator can be broadly categorized as

a) **Cold reservoir (Sink): It is the inside of the refrigerator which is at a lower temperature**
b) **Hot reservoir (Source): It is the outside environment which is at a higher temperature**
c) **Working substance: It is the basic machinery of the refrigerator which works to extract heat from substances kept inside the refrigerator (cold reservoir) and transfers it to the outside environment (hot reservoir).**

Schematic diagram of the working of a refrigerator:

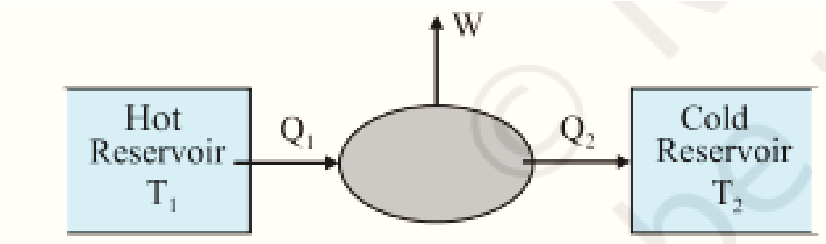
The working of a refrigerator mainly involves the flow of heat from a cold region to a hot region. But this cannot happen spontaneously. Work has to be done to transfer heat from a cold region to a hot region.

The diagram shows that the heat Q_2 is extracted from the cold reservoir and a heat Q_1 is transferred to the hot reservoir while some external work W is done on the working substance.

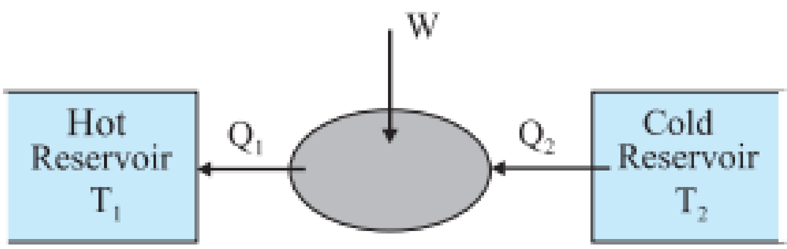


Schematic representation of a refrigerator or a heat pump, the reverse of a heat engine.

Compare the schematic diagram with that for a heat engine, notice the direction of arrows. Make a note of the direction of arrows showing heat transfer



Schematic representation of a heat engine



Schematic representation of a refrigerator

The **coefficient of performance(COP)** of the refrigerator is given by the ratio of the output Q_2 which is heat extracted from the sink or the cold reservoir(T_2) and the input W which is the work done on the system.

Heat Pump

A heat pump is the same as a refrigerator.

What term we use depends on the purpose of the device.

- **If the purpose is to cool a portion of space, like the inside of a chamber, and higher temperature reservoir is surrounding, we call the device a refrigerator;**
- **If the idea is to pump heat into a portion of space (the room in a building when the outside environment is cold), the device is called a heat pump**.

Working of a domestic refrigerator:

In the actual refrigerator work is done by the compressor of the refrigerator which uses the electrical energy from the household electricity supply. **The purpose is to extract heat from things kept inside the cold compartment of a refrigerator.**

The working substance in a refrigerator is a fluid called the refrigerant.

This refrigerant **(can be fluorocarbons, Ammonia, Sulphur Dioxide etc.)** is made to circulate in a loop.

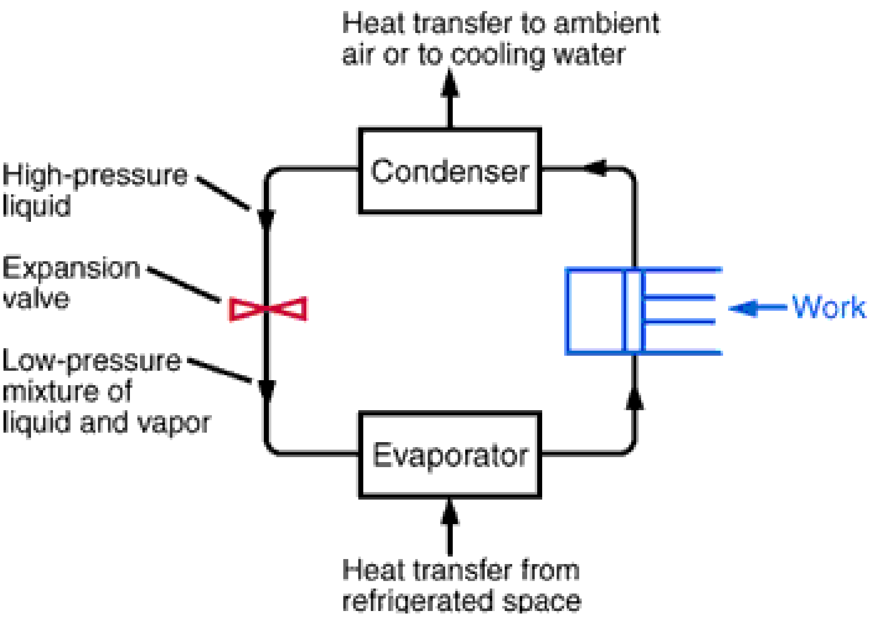
The process involves the raising and lowering of internal energy of the refrigerant in a cyclic process.

The actual stages are briefly described below,

- **The refrigerant is made to go through an expansion valve. Work is done by the refrigerant when it passes through the expansion valve. This causes a decrease in the internal energy of the refrigerant and the temperature of the refrigerant becomes lower than that inside the compartment of the refrigerator.**

- **The refrigerant is then made to go through the coils (called the evaporator coils) inside the refrigerator. So the heat gets transferred from the contents (food) kept inside the refrigerator to the refrigerant. This transfer of heat takes place through all the processes of convection, radiation and conduction which raises the internal energy of the refrigerant.**

- **The refrigerant is then made to go through a compressor where work is done on it to further increase its internal energy and temperature. The temperature of the refrigerant now becomes higher than the temperature of the outside environment of the refrigerator.**
- **This high temperature refrigerant travels to the condenser coils outside the refrigerator and transfers heat to the surroundings. In the process its temperature and internal energy lowers. Then it is again made to go through the expansion valve which further lowers its energy and temperature.**
- **Now the refrigerant is again ready to take heat from the inside of the refrigerator and deliver to the outside environment. This cyclic process continues.**



EXAMPLE

The door of a refrigerator kept in the kitchen is open. What will happen to the temperature of the kitchen?

SOLUTION:

The temperature of the kitchen will rise. Here both hot and cold reservoir is the kitchen so the heat given to it is more than the heat taken away, hence the temperature rises.

So do not try and treat it like an air conditioner.

Coefficient of performance

$$\text{Coefficient of performance (COP)} = \frac{\textit{Heat extracted from the cold reservoir}}{\textit{Work done on the system}}$$

$$= Q_2 / W$$

$$= Q_2 / (Q_1 - Q_2)$$

Or

$$COP = \frac{T_2}{(T_1 - T_2)}$$

Points to be noted:

- **The coefficient of performance of a refrigerator will be higher if the heat extracted from the cold reservoir is higher which means that refrigerator is capable of greater cooling of the contents inside it.**
- **The coefficient of performance of a refrigerator will also be higher if the work done on the system is smaller. Less work means that we have to pay lower electricity bill for the running of the refrigerator.**
- **An ideal situation would be when we do not have to pay any electricity bill for the refrigerator which in turn means that the heat is being transferred on its own from the cold compartment of the refrigerator to the hot outer surroundings. The coefficient of performance would then be equal to infinity as work done on the system would be zero. But this is a violation of the fundamental second law of thermodynamics. So it is impossible.**
- **A reversible refrigerator could also work as a heat engine.**

EXAMPLE

A refrigerator absorbs 5 kJ of energy from a cold reservoir and rejects 6 kJ to a hot reservoir.

(a) Find the coefficient of performance of the refrigerator.

(b) The refrigerator is reversible and is run backward as a heat engine between the same two reservoirs. What is its efficiency?

SOLUTION:

Work done on the system = Heat rejected – Heat extracted = (6 – 5) kJ = **1 kJ**

Coefficient of performance = $\frac{\text{Heat extracted from the cold reservoir}}{\text{Work done on the system}}$

= 5kJ/1kJ = 5

Efficiency of heat engine = $\frac{\text{Work done by the system}}{\text{Heat extracted from the hot reservoir}}$

= 1kJ/ 6kJ = 0.166 or **16.6%**

6. SECOND LAW OF THERMODYNAMICS FOR REFRIGERATOR:

The **Clausius Statement**: **It is impossible to construct a device which operates on a cycle and produces no effect other than the transfer of heat from a cooler body to a hotter body.**

This means that

- Heat can never flow from a cold body to a hot body spontaneously.
- Work has to be done by the compressor of a refrigerator to make it work
- The electrical bill of a working refrigerator cannot be zero.
- The coefficient of performance of a refrigerator cannot be infinity.

These are the constraints imposed by the Second law of thermodynamics

7. CARNOT REFRIGERATOR AND ITS FEATURES

A reversible heat engine was conceptualized by Carnot. Its efficiency depends only on the temperature of the hot and the cold reservoir. On similar lines a reversible refrigerator was conceptualized. In the Carnot refrigerator

- the dissipative forces are zero
- the temperature of the hot and cold reservoir never change in any process

- the coefficient of performance depends only on the temperature of hot and cold reservoir

Coefficient of performance = $\frac{\textbf{Temperature of the cold reservoir}}{\textbf{Difference in temperature of the hot and cold reservoir}}$.

A Carnot refrigerator needs minimum amount of work to extract a given amount of heat from the colder object.

EXAMPLE

A refrigerator is rated at 350 W. What is the maximum amount of heat it can remove in 1 min if the inside temperature of the refrigerator is 2°C and it exhausts into a room at 27°C?

SOLUTION:

Work done by the refrigerator per second = 350J

Temperature of cold reservoir = 2^oC = (2 + 273) K = 275K

Temperature of hot reservoir = 27^oC = (27 + 273) K = 300K

Difference in temperature = 330 – 275 = 25K

Coefficient of performance = $\frac{275}{25}$ = 15

Heat extracted from inside the refrigerator = COP x work done = 15 x 350 = 5250J/s

Heat extracted per minute = 5250 x 60 = 315000 J = 315 kJ

8. COMPARISON OF SECOND LAW OF THERMODYNAMICS FOR HEAT ENGINE AND REFRIGERATOR

The statements for the heat engine and refrigerator (Kelvin and Clausius statements) are

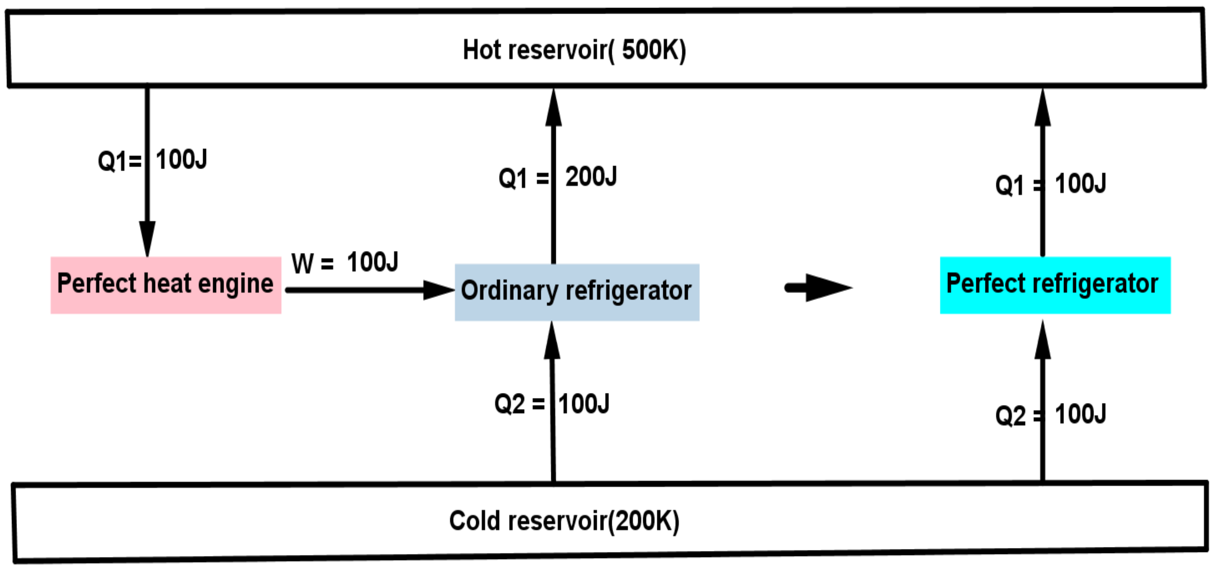
a. Heat engine cannot have 100% efficiency
b. Coefficient of performance of refrigerator cannot be infinite

The question which arises is **"Are these statements really different or does one lead to the other?"**

We will show that actually both these statements are equivalent. Violation of the refrigerator statement (Clausius statement) will directly lead to the violation of heat engine statement (Kelvin statement) and vice versa. We will do this with the help of an example.

In our example the hot reservoir is at 500K and the cold reservoir is at 200K. Let us suppose we have a perfect engine which converts all the 100J of heat taken by it from the hot reservoir into 100 J work in a cyclic process. Hence it does not reject any heat to the cold reservoir and its efficiency is 100%. This work is used by a normal refrigerator working between the same two reservoirs. This refrigerator extracts 100J of heat from the cold reservoir and rejects 200J of heat to the hot reservoir. An ideal segment would extract 100J from the cold reservoir and reject 100 J to the hot reservoir. It will have COP = ∞

So we see that the violation of Kelvin statement for heat engine, that it does external work will directly lead to the violation of Clausius statement for refrigerator. Hence we can conclude that both the statements are equivalent.



Violation of Kelvin statement **leading to Violation of Clausius statement**

9. HEAT PUMP

Heat pump works on the principle of a refrigerator. But the objective of a heat pump is not to extract heat from a certain region. A heat pump is used to deliver heat to a certain region. The heat pump will extract heat from the cold outside surroundings and transfer it to a warmer room. For this work has to be done on the heat pump. So the output from a heat pump is measured in terms of the heat transferred to the warmer regions

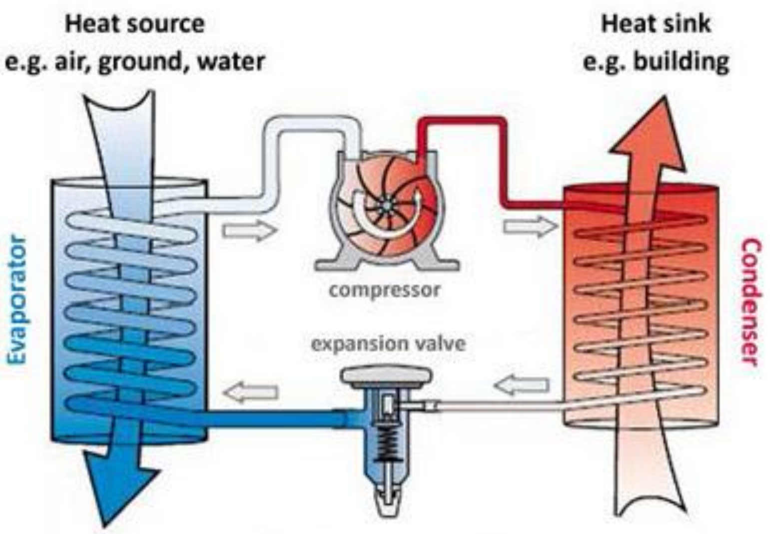
The coefficient of performance of a heat pump is the ratio of heat transferred to the warmer region and the work done on the heat pump.

Coefficient of performance (COP) = $\frac{\textbf{Heat transferred to the hot reservoir}}{\textbf{Work done on the heat pump}}$

For an ideal heat pump or the Carnot heat pump, the coefficient of performance is given by

Coefficient of performance = $\frac{\textbf{Temperature of the hot reservoir}}{\textbf{Difference in temperature of the hot and cold reservoir}}$.

This is the maximum possible coefficient of performance of a heat pump working between two given hot and cold reservoirs.



Heat pump cycle

EXAMPLE

A heat pump delivers 10 kW to heat a house. The outside temperature is -10^{o}C and the inside temperature of the house is to be maintained at 25^{o}C (a) What is the coefficient

of performance of a Carnot heat pump operating between these temperatures? (b) What must be the minimum power of the engine needed to run the heat pump? (c) If the COP of the heat pump is 50% of the efficiency of an ideal pump, what must be the minimum power of the engine?

SOLUTION

For the Carnot pump

Coefficient of performance = $\frac{\text{Temperature of the hot reservoir}}{\text{Difference in temperature of the hot and cold reservoir.}}$

$$= \frac{273+25}{25-(-10).} = 8.5$$

Power needed to run the heat pump = Work/ sec

Hence Power needed = Heat delivered **/** COP = 10 / 8.5 = 1.17W

If COP = 50% of the ideal heat pump

Power needed = Heat delivered/ COP = 10/ 4.25 = **2.35W**

Conclusion

If a heat pump is ideal, it will require minimum power to operate. Hence the electricity bill for it will be minimum. But ordinary heat pumps as compared to the ideal reversible heat pumps always have lesser COP, so greater power is required by them to operate and we pay greater electricity bills.

Greater the COP, lesser will be the bills.

10. OTHER DOMESTIC HEATING DEVICES:

Electric toaster: Heating effect of current is used in the toaster to raise temperatures inside the toaster. When current is passed through the conducting coils of the toaster, the coils become red hot and the temperature rises. The bread which is put inside the toaster gets heated. The energy transfer from the red hot coil is mainly in the form of radiation. The internal energy of the bread molecules increases. After a while the bread gets cooked.

Electric geyser: The water heater used at home consists of heating element which become hot when electricity is passed through them. These heating elements are dipped inside the water to be heated. So heat is transferred, from the heating element, to the water through the process of conduction. The internal energy of the water molecules rises causing an increase in the temperature of water. When the temperature of water reaches a set value, the thermostat switches off the current through the heating elements. So the water is maintained at a certain temperature. This hot water can then be used for domestic purposes.

Stove: In a stove a flame is produced using fossil fuels or with the help of electricity. The pan with liquid food is put over the flame. The pan gets heated by conduction from the hot flame and the food which is contact with the pan gets heated by conduction of heat from the pan. This heat is transferred in the entire food kept in the pan through convection currents set inside the liquid food. This increases the internal energy of the food which results in a rise in its temperature.

Microwave oven: Microwaves are a part of the electromagnetic spectrum. These waves can be produced using a magnetron. The microwaves travel with the speed of light and have frequencies ranging from 300MHz to 300GHz. In a microwave the frequency of microwaves is 2450MHz. The water molecules in the food absorb the microwaves and vibrate rapidly. This increases the internal energy of the food and the temp of the food rises.

Point to be noted:

- In all methods of heating some energy is consumed. This may be electrical energy or fossil fuel energy
- The heat is transferred to the required material through conduction, convection or radiation.
- This in turn increases the internal energy of the material thereby increasing its temperature.

11. SUMMARY:

Refrigerator: It is a device which transfers heat from a cold reservoir to a hot reservoir when work is done on it.

Coefficient of performance of refrigerator: It is the ratio of heat extracted from the cold reservoir to the work done on it

$$\text{Coefficient of performance (COP)} = \frac{\text{Heat extracted from the cold reservoir}}{\text{Work done on the system}}$$

Second law of thermodynamics for refrigerator:

The coefficient of performance of a refrigerator can never be infinite.

Carnot refrigerator:

- Carnot refrigerator operates on reversible process.
- There are no dissipative forces acting on the refrigerator.
- The system is always in its equilibrium state at every step of the process

Coefficient of performance of the Carnot refrigerator:

It depends only on the temperature of the hot reservoir $\mathbf{T_1}$ and the cold reservoir $\mathbf{T_2}$ and it is equal to

$$\text{COP} = \mathbf{T_2 / (T_1 - T_2)}$$

The COP of a Carnot refrigerator is greater than any other refrigerator working between the same two temperatures.

The statements of second law of thermodynamics for refrigerator and the heat engine are equivalent.

Commonly used heating devices increase the internal energy of the substance to heat up the substance.