Hello students, welcome to this course Heat and thermodynamics and properties of matter and acoustics. This is Section 1 Heat and Thermodynamics. The name of this unit is second law of thermodynamics and the name of the module is reversibility of Carnot cycle and Carnot's theorem, coefficient of performance of a refrigerator.

I am Yatin Desai, assistant professor in Physics, Chowgule College Margao.

Outline of this module is reversibility of Carnot cycle, Carnot theorem, coefficient of performance of a refrigerator. At the end of this module, you will be able to discuss reversibility of Carnot cycle, Prove Carnot theorem, Compare engine and a refrigerator and derive an expression for coefficient of performance of a refrigerator.

Reversibility of Carnot cycle: the four stages through which the working substance is taken are perfectly reversible because it is assumed in describing the cycle that the processes are carried out extremely slowly, the source and the sink have infinite thermal capacity so that their temperatures do not change due to exchange of heat with the working substance, there is no friction between the piston and the wall of the cylinder, the piston and the side of the cylinder are impermeable to heat, the base of the cylinder is a thin sheet of a good conducting material. However, all these conditions are ideal conditions which cannot be completely realized in a practical heat engine.

Next is Carnot theorem. The statement is, no engine can be more efficient than reversible engine working between same two temperatures.

To prove this, we consider a reversible engine R and an irreversible engine I coupled in such a way that I works in the forward direction and drives capital R in the reverse direction. That is, engine R works as an refrigerator as shown in the figure below.

If possible, we assume that I is more efficient than R. And let I absorb heat Q1 from the hot reservoir at T_1 degrees Kelvin, convert part of heat into work W and reject heat Q2 to the cold reservoir at a temperature T_2 degrees Kelvin. Thus, we can write an expression for the work as W equal to Q1 – Q2. This is equation one or Q2 equals Q1 minus W, equation #2.

Similarly, let engine R absorb heat Q2' from the cold reservoir at T2 degrees Kelvin and W' be the work done on it as it is working as a refrigerator. For the sake of simplicity, we shall assume that the heat rejected by R to the hot reservoir at T1 degree K is equal to Q1, the same as that taken by it by I. Therefore, W' equals Q1 minus Q2' which is equation #3. Or, Q2' is Q 1 – W' which is equation #4.

We have assumed that I is more efficient than R. That is the efficiency eta of irreversible engine, eta I is greater than efficiency of the reversible engine that is eta R. Therefore, it follows that W by Q1 is greater than W' by Q1, and since knowing the work equations, we can write the next step as Q 1 -- Q2 divided by Q1 is greater than Q1 minus Q2' divided by Q1. Therefore, we can write Q1 – Q2 to be greater than Q1 minus Q2' or Q2' is greater than Q2. This is say, equation #5. This equation 5 shows that the heat lost by the cold reservoir Q2' to R is more than the heat Q2 gained by it from I. Thus. the cold reservoir continuously loses an amount of heat Q2' minus Q2 and the work is being done without producing any change in the hot reservoir. That is, the heat is continuously extracted from a single body and converted into work, which is contrary to the experience and violates the second law of thermodynamics. Hence our initial assumption that I is more efficient than R is wrong. Therefore, I cannot be more efficient than R or R is more efficient than I. So, out of the two engines working between same two temperatures, reversible engine is always more efficient than the irreversible engine. This proves the Carnot's theorem.

Next, we compare engine and a refrigerator. The working of an ideal heat engine and that of an ideal refrigerator are just reverse of each other. In a heat engine, the working substance extracts heat from the hot reservoir, some of which is utilized in doing external work and rest of it is rejected into cold reservoir. In the refrigerator, an external agency, for example, an electric motor, does mechanical work on the working substance which extracts heat from a cold reservoir and whole amount of energy is rejected to the hot reservoir. This is the working principle of an ideal refrigerator.

Stages in refrigeration plant and PV diagram: To understand the thermodynamic aspect of a refrigeration plant, we follow Carnot cycle in the reverse direction as shown in the figure below. The closed figure ABCD represents the cycle, which consists of four parts. AD, DC, CB & BA. Each part corresponds to a stage. Stage one: during expansion AD. Work is done by the gas and its temperature falls from T1 to T2. Stage two: during isothermal expansion DC at temperature T2 an amount of heat Q2 is absorbed from the cold reservoir of lower temperature T2 and the work is done by the gas. There is no change in temperature. Stage three: during the adiabatic compression CB, work is done on the gas with an external agency so that its temperature rises from T2 to T1. No heat is either absorbed or rejected. Stage four: during adiabatic compression BA, an amount of heat Q1 is transferred by the gas to the outer system at a higher temperature T1. Some work is done on the gas. The original state is restored and one cycle of refrigeration is complete.

Principle of refrigeration: The schematic representation of a refrigerator is as follows: Heat Q2 is absorbed from a cold reservoir at temperature T2. Work W is done on the system with an external agency like Electric motor. Heat Q1 which equals Q2 plus W; is transferred by the working substance to the hot reservoir at temperature T1. Thus, work is always necessary to transfer heat from cold reservoir to a hot reservoir. A refrigerator cannot work without supply of electrical energy.

Next coefficient of performance COP: let W be the total amount of work done by the gas during the refrigeration cycle. There is no change in the internal energy as the original state is restored. The net amount of energy absorbed is Q2 minus Q1. Applying first law of thermodynamics,

Q2 - Q1 = 0 - W

Therefore, W = Q1 - Q2.

Thus, the heat Q2 is transferred from the cold reservoir at temperature T2 to the hot reservoir at temperature T1. Such a device is a refrigerator and the working substance is known as the refrigerant. A good refrigerator is the one which removes more heat Q2 from the cold reservoir with less expenditure of work W. The capacity to do this task is measured in terms of coefficient of performance, that is COP and is defined as the ratio of heat removed Q2 from the cold reservoir at temperature T2 to the corresponding work done W, on the working substance. That is in the equation form we write C equals Q2 by W. For Carnot refrigerator, we have, C equals Q2 divided by Q1 – Q2. This is because we have W as written as Q1 – Q2. Since we have Q2 by Q1 equals T2 by T1, we can write that C in terms of temperatures, that is C = T2 divided by T1 – T2. Or after rearranging or dividing by T2 both in numerator as well as denominator, we get it as 1 divided by T1 – [(T1 by T 2) – 1].

The efficiency of Carnot engine is given by eta equals T1 minus T2 by T1 or 1 – T2 by T1. Therefore, 1 – eta is T2 by T1 or we can relate C, the coefficient of performance to the efficiency by an equation C = (1 – eta) by eta. These are the references for this module.

Thank you.