**Thermodynamics** is a branch of physics concerned with heat and temperature and their relation to energy and work.

#### <u>Heat</u>

Heat is a form of energy whose absorption makes a body hot and rejection makes a body cold. Heat is a form of energy which produces the sensation of hotness or coldness of a body.

Heat is a form of energy which flows from higher temperature to lower temperature by conduction, convection and radiation processes.

# **Temperature**

When we touch a piece of ice, we feel cold but if we touch a boiling kettle we feel hot. The amount of hotness or coldness of a body is measured by a quantity called temperature. Apparently, the degree of hotness is expressed by temperature. Alternatively, the temperature of a body is the property that determines whether or not the body is in thermal equilibrium with another body.

#### Distinction between heat and temperature

Though closely related, heat and temperature do not bear same meaning' There is a great difference between them. The differences are stated below:

1. Heat is a form of energy but temperature represents a thermal condition of the body.

2. Heat is the cause and temperature is the effect.

3. The instrument for measuring heat is called calorimeter and the instrument for measuring temperature is called thermometer.

4. The unit of heat is Joule and the unit of temperature is oC or K or oF.

5. Heat is energy and temperature is the demonstration of energy.

6. Heat flows from a body of higher temperature to a body of lower temperature.

7. Heat is proportional to the total energy of the molecules in the body; but temperature is proportional to the average kinetic energy of a molecule of the body.

8. The branch of physics which measures heat is called calorimetry and the branch which measures temperature is called thermometry.

9. Temperature does not have dimension but dimension of heat is the dimension of energy  $[ML^2T^{-2}]$ .

# **Thermometer**

The name of the thermometers depends on which property or thermal properties used to measure temperature. Like



Name	<b>Thermal Property</b>	Example
Liquid Thermometer	Liquid	Mercury thermometer
Constant volume gas thermometer	Pressure of gases	Constant volume H2 gas thermometer
Resistance	Resistance of the	Platinum resistance
Thermometer	material	thermometer
Thermo – electric	EMF/Current	Platinum-Rhodium
Thermometer		thermometer
Radiation	Radiated heat	Pyrometer
thermometer		

#### **Temperature Scale**

There are four types of temperature scales. The temperature scales are Celsius, Kelvin, Fahrenheit and Romer / Rankine scale.



The relation of the temperature scales is based on the relation in temperature scale-ice point/ steam point-ice point.

Temperature scale - ice point / steam point - ice point

$$\frac{C-0}{100-0} = \frac{F-32}{212-32} = \frac{K-273}{373-273} = \frac{R-492}{672-492}$$
$$\frac{C}{100} = \frac{F-32}{180} = \frac{R-492}{180} = \frac{T-273}{100}$$
$$Or, \ \frac{C}{5} = \frac{F-32}{9} = \frac{R-492}{9} = \frac{T-273}{5}$$

#### **Platinum Resistance Thermometer**

The platinum resistance thermometer is based on the principle that the electrical resistance of metallic wire is found to increase uniformly with temperature. The device in which temperature can be found out by measuring the resistance is called a resistance thermometer. Platinum is extensively used as resistance thermometer. Platinum is very rigid metal and dependable. Its characteristics are not changed by repeated use.



#### Advantages of platinum resistance thermometer:-

a) it use is easier than that of a gas thermometer .

b) it gives a precise measurement of a temperature because the resistance of the wire can be measured with high accuracy.

c) it has a wide range from - 200 to 1200 degrees Celsius

d) it is quite sensitive . Its sensitivity is .01 degree up to 600 degree.

e) it is free from change of zero as pure and annealed platinum wire has always the same resistance at the same temperature.

The relation between temperature and resistance is given below

 $R_{\theta} = R_0 (1 + \alpha \theta) \dots (1)$ 

Where  $R_{\theta}$  represents the resistance of the platinum wire at  $R_0$  is the resistance of platinum wire at temperature  $0^0$ , and  $\alpha$  is a constant.

Let  $R_0$  and  $R_{100}$  be the resistance of platinum resistance thermometer at 0°C and 100°C respectively.

Now from Eq. (1) we get,  

$$R_{100} = R_0(1 + \alpha. 100)$$
  
=>  $\alpha = \frac{R_{100} - R_0}{100R_0}$ .....(3)  
By using Eqs. (2) and (3) we can write,  
 $\frac{R_{100} - R_0}{100\alpha} = \frac{R_{\theta} - R_0}{\theta\alpha}$   
 $\Rightarrow \theta = \frac{R_{\theta} - R_0}{R_{100} - R_0} \times 100$ .....(4)

 $R_{100} - R_0$ 

Eq. (4) represents the temperature measuring equation for platinum resistance thermometer.

#### Seebeck effect

When two dissimilar metals make two junctions and one of them being heated while the other junction is kept cold, without using any cell or battery in the circuit, current flow is the Seebeck effect.





# Peltier effect

When two dissimilar metals make two junctions and by using cell or battery current flows into the circuit, then one of the junction will be heated while other will be cold is called Peltier effect.

#### **Isothermal Change**

When a gas undergoes a change in pressure and volume at constant temperature, the gas is said to undergo an isothermal change, and the process in which the change takes place is called isothermal process.

In isothermal process, the relation between pressure and volume of a gas follows the Boyle's law, i.e.

A practical example of this is some heat engines which work on the basis of the Carnot cycle. The Carnot cycle works on the basis of isothermal.



# ISOTHERMAL PROCESS

#### **Conditions for isothermal change**

The following conditions are to be satisfied for isothermal process

- (i) Container of the gas must be good conductor of heat.
- (ii) Thermal capacity of the surroundings should be high.

- (iii) Change of pressure should be made very slowly.
- (iv) By absorption or rejection of necessary heat the temperature is to be kept constant.

#### Adiabatic Change

The process in which a system neither receives heat nor rejects heat is called adiabatic process. In this process, a gas undergoes changes in pressure, volume and temperature under thermal isolation.

Alternatively, when no heat is allowed to enter or leave the gas, it is called an adiabatic process and change under this process is called adiabatic change. In case of adiabatic process, Boyle, s law does not apply.

The relation between pressure and volume in adiabatic process is  $PV^{\gamma} = constant$ . Pressure versus volume curve is called adiabatic curve [Fig. 2]. The adiabatic curve is steeper than isothermal curve.

The compression and expansion strokes in an internal- combustion engine are both approximately adiabatic processes. What little heat transfers outside of the system is negligible and virtually all of the energy change goes into moving the piston.

Air is made up of a mixture of gases that is subject to adiabatic heating when it is compressed and adiabatic cooling when it is expanded.



#### **Conditions for adiabatic change**

The following conditions are to be satisfied for adiabatic change

- (i) The container of the gas should be non-conducting.
- (ii) Thermal capacity of the surrounding should be low.
- (iii) Change of pressure of the gas must be very rapid so that heat exchange with the surrounding does not take place.

#### Difference between isothermal and adiabatic change

SI. No.	Isothermal change	Adiabatic change
1	The change of pressure and volume of a gas at constant temperature is called isothermal change.	The change of pressure and volume of a gas by keeping the total heat content of the gas fixed is called adiabatic change.
2	In this change necessary heat is taken or rejected to keep the temperature constant.	Change of temperature takes place in this process.
3	It is very slow process.	It is very fast process.
4	The container of the gas should be good conductor of heat.	The container of the gas should be non-conducting.
5	It follows Boyle's law.	It does not follow Boyle's law.



#### **Reversible Process**

A reversible process is one which can be retraced in the opposite direction so that the working substance passes through exactly the same state in all respects as in the direct process.

#### **Example**

A given mass of ice changes to water when a certain amount of heat is absorbed by it and the same mass of water changes to ice when the same quantity of heat is removed from it.

# **Reversible Processes**



#### **Irreversible Process**

An irreversible process is one which cannot be retraced in the opposite direction by reversing the controlling factor. All changes which occur suddenly like the explosion etc may be considered as irreversible. Some examples of irreversible process are

- 1. Sudden unbalanced explosion of a gas either isothermal or adiabatic.
- 2. Heat produced by friction.
- 3. Heat generated when current flows through an electrical resistance.



- Irreversible processes cannot be undone by exactly reversing the change to the system.
- All Spontaneous processes are irreversible.
- · All Real processes are irreversible.

# Laws of thermodynamics

The four laws of thermodynamics define fundamental physical quantities (temperature, energy, and entropy) that characterize thermodynamic systems. The laws describe how these quantities behave under various circumstances, and forbid certain phenomena (such as perpetual motion).

The four laws of thermodynamics are-

- 1. Zeroth law of thermodynamics
- 2. First law of thermodynamics
- 3. Second law of thermodynamics
- 4. Third law of thermodynamics

# (1) Zeroth law of thermodynamics

If two bodies are separately in thermal equilibrium with a third body then the first two bodies must be in thermal equilibrium with each other".

# (2) First law of thermodynamics

Famous scientist Joule first established the relation between heat and work and expressed the relation in terms of law. The law is stated below:

"When work is transformed into heat or heat is transformed into work, then work and heat is directly proportional to each other".

# **Explanation**

If Q be the amount of heat produced due to transformation of W amount of work, then according to first law of thermodynamics.

Here J is proportionality constant. It is called mechanical equivalent of heat or Joule's equivalent. This law is a special form of the principle of conservation of energy.

#### **General form of first law of thermodynamics**

Clausius expressed the first law of thermodynamics in a general form. He expressed the law in the following way.

"If some heat is supplied to a system which can do work, then the quantity of heat absorbed by the system is equal to the sum of the increase in internal energy of the system and the external work done by the system".

If dQ be the amount of heat absorbed by a system and dU be the change in the internal energy and dW be the work done by

the system due to absorption of heat, according to the first law of thermodynamics, dQ = dU + dW. This is the special form of the principle of conservation of energy. It is valid for any system.

In above equation, dQ,dU and dW may be positive or negative.

1. dQ is positive when the system absorbs heat and is negative when it loses heat,

2. dU is positive when the internal energy of the system increases and is negative when it decreases,

3. dW is positive when the system does work on the environment and is negative when the surrounding does work on the system.

#### Significance of the 1st law of thermodynamics:

- 1. It establishes the relation between heat and work,
- 2. Heat and work are equivalent to each other,
- 3. It is nothing but the principle of conservation of energy,
- 4. Work or heat cannot be obtained from nothing,
- 5. It is impossible to design a machine of perpetual motion without spending energy.

#### Relation between pressure and volume of a gas in adiabatic change:

Let dQ amount of heat be supplied in 1 mole of an ideal gas. Due to this temperature of the gas will increase and the gas will do some work i.e., the supplied heat will be used in two ways.

Let the change in volume and temperature be dV and dT respectively

So, from the first law of thermodynamics we get,

dQ = du + dW

dQ = Cv dT + P dV....(1)

Here

Cv = Specific heat of the gas at constant volume

PdV =Work done due to the expansion of gas at constant pressure.

We know, in adiabatic process no heat exchange takes place with the surroundings, so

dQ = 0.....(2)

So from equation (1),

 $C_v dT + P dV = 0$ (3)

Again, for an ideal gas, PV = RT-----(4)

Where, R is the molar gas constant.

By differentiation equation (4) we get,

PdV + VdP = RdT

$$\therefore dT = \frac{PdV + VdP}{R}$$
(5)

Now from equation (3) we get

 $C_{v}\left(\frac{PdV+VdP}{R}\right) + PdV = 0$  $or_{1}C_{2}PdV + C_{2}VdP + RPdV = 0$ or,  $C_v P dV + C_v V dP + (C_p - C_v) P dV = 0$  [since,  $R = C_p - C_v$ ]  $or_{v}C_{v}PdV + C_{v}VdP + C_{v}PdV - C_{v}PdV = 0$  $or, C_v V dP + C_p P dV = 0$  $or, VdP + \frac{c_p}{c_v}PdV = 0$  [dividing by  $C_v$ ]  $or, VdP + \gamma PdV = 0$  $or, \frac{dP}{P} + \frac{\gamma dV}{V} = 0$  [dividing by PV]  $\therefore \frac{dP}{P} + \frac{\gamma dV}{V} = 0 \quad -----(6)$ By integrating equation (6), we get,  $\ln(P) + \gamma \ln(V) = constant = \ln K$  where, K=constant  $or, \ln(P) + \ln(V^{\gamma}) = \ln K$  $or, \ln(PV^{\gamma}) = \ln K$ or,  $PV^{\gamma} = K$  $\therefore PV^{\gamma} = constant -----(7)$ 

This is the relation between pressure and volume for adiabatic process.

#### Relation between temperature and volume of a gas in adiabatic change

We know, for an ideal gas PV = RT

 $\therefore P = \frac{RT}{V}$  (1)

Where, P is the pressure, V is the volume, T is the temperature and R is the molar gas constant.

Again, we know,

 $PV^{\gamma} = constant -----(2)$ 

Where,  $\gamma = \frac{C_P}{C_P}$ 

Now putting the value of P in the above equation, we get-

$$\frac{RT}{V}V^{\gamma} = constant$$

$$or, TV^{\gamma-1} = \frac{constant}{R}$$

As *R* is the molar gas constant so  $\frac{constant}{R} = constant$ 

 $\therefore TV^{\gamma-1} = constant -----(3)$ 

This is the relation between volume and temperature in adiabatic process.

#### Difference between Cp and Cv for an ideal gas

In order to find the difference between Cp and  $C_{p}$ , let us take a cylinder C with a frictionless movable piston D. Both the cylinder and the piston are bad conductors of heat. Consider that an amount of n moles of an ideal gas is kept in the cylinder at volume V and

Pressure P. keeping the volume fixed, the temperature of the gas is raised by dT, by supplying heat.

So heat required.

 $dQ = nC_v dT$ 

Where,  $C_v$  is the molar specific heat at constant volume.



According to the first law of thermodynamics

dQ = du + dW

Since volume is constant, so dV = 0

dQ = du

Now keeping the pressure constant, the temperature of the gas is raised by the same amount dT by supplying heat. The gas will expand in volume doing some external work. If dV be the increase in volume due to expansion against the pressure P, the work done. dW = PdV.

The amount of heat supplied to the gas.

 $dQ = n C_P dT$ 

Inserting the values of dW and dQ in equation (1) we get,

 $n C_p dT = du + P dV \qquad ....(3)$ 

Here also the change in internal energy is du because temperature change is dT in both cases.

From equation (2) and (3) we get,

 $n C_P dT = n C_v dT + P dV \dots (4)$ 

But for n mole of ideal gas.

PV = nRT .....(5)

Differentiating equation (5) we get,

PdV = nRdT [ P, n and R constant]

 $n C_P dT = n C_v dT + n R dT$ 

or, n  $C_p = n C_v + n R$ 

or,  $n(C_p - C_v) = n R$ 

or,  $C_p - C_v = R$ 

The difference between the two specific heats of a gas in equal to the molar gas constant (R).

#### (3) Second law of thermodynamics

#### Clausius's statement

It is impossible to make heat flow from a body at a lower temperature to a body at a higher temperature without doing external work on the substance.

#### Kelvin's statement

Continuous flow of energy cannot be obtained from an object cooling it from its surrounding.

#### Plank's statement

It is impossible to construct an engine which can extract heat continuously from a heat source and completely transforms into work.

#### Carnot's statement

No engine can be built which can extract a fixed amount of heat and will convert totally into work.

# Carnot's engine

The device which transforms heat energy into mechanical energy is called heat engine. In order to explain this phenomenon theoretically Carnot proposed an ideal engine. This engine is called Carnot's engine. All practical engines have many defects and limitations, but Carnot's engine is free from all defects and limitations. It should be remembered that Carnot's engine is an imaginary one. it is impossible to construct such an engine. But it is very easy to explain theoretically its working principle or operation.



Fig.1: P-V diagram of Carnot's engine

# Operations of Carnot's cycle and work done

The Carnot's cycle and the work done can be expressed by a diagram. It is called index diagram. The Carnot's cycle and work done are explained by the index diagram (fig.1)

**First step:** In this step, the cylinder is placed on the source of heat. Very quickly the temperature of the working substance (gas) becomes equal to the temperature  $T_1$  of the source. In the index diagram, it is represented by the point A. let the pressure and volume in this state are  $P_1$  and  $V_1$  respectively. Then the gas is allowed to expand isothermally. During the expansion, it takes Q amount of heat from the source. After isothermal expansion, the pressure and volume of the gas become  $P_2$  and  $V_2$  respectively. In the figure, it is represented by point B.

In the index diagram, work done for the isothermal expansion W<sub>1</sub>=area ABba.

**Second step:** In this step, the cylinder is placed on the insulated platform and the confined gas is allowed to expand adiabatically. In the adiabatic expansion, the temperature of the gas becomes  $T_2$ . After adiabatic process, the pressure and volume of the gas are respectively  $P_3$  and  $V_3$  which is represented by the point C in the figure.

In the index diagram, work done by the adiabatic expansion,  $W_2$ =area BCcb

**Third step:** Now, the cylinder is placed on the heat sink and the gas is compressed isothermally by the piston. As a result, the pressure of the gas increases. In this step work is done by the piston on the gas. During compression, it rejects Q amount of heat to the sink at temperature  $T_2$ . The pressure and volume of the gas in this step are P<sub>4</sub> and V<sub>4</sub> respectively. This is represented by point D in the diagram.

The CD protion of the index diagram represents compression of the gas at temperature  $T_2$  and the work done,  $W_3$ =area CcdD

**Fourth step:** In this step, the cylinder is placed on the insulated platform and the confined gas is allowed to compress adiabatically. Due to the work done on the confined gas the temperature of the gas increases and becomes equal to the temperature of the source. In this process, the pressure and volume of the gas are  $P_1$  and  $V_1$  respectively i.e., the cycle returns to its initial state.

In the diagram, point A represents this state. Graph DA in the index diagram indicates the adiabatic compression and the work done in this step,  $W_4$ = area DdaA.

Now according to the convention, work done by the confined gas is positive and work done on this gas is negative. So, total work done by the confined gas is

 $W = W_1 + W_2 - W_3 - W_4 = area of ABba + area of BCcb - area of CcdD - area of DdaA = area of ABCD.$ 

From the above discussion, it is evident that in the Carnot's cycle the work done by this working formula substance i.e., gas is represented by two isothermal graphs and two adiabatic graphs in the index diagram and is equal to the areas under the graphs. This cycle is called the Carnot's cycle.

# Efficiency of Carnot's engine:

In one cycle, the ratio of the heat converted into work and the amount of heat taken from the source by the engine is called efficiency of the engine. It is represented by  $\eta$ 

Let Q<sub>1</sub>=heat taken by the working substance (gas)

Q<sub>2</sub>= heat rejected by the gas

 $\therefore$  amount of heat converted into work = Q<sub>1</sub>-Q<sub>2</sub>

: efficiency of the engine,  $\eta = (Q_1 - Q_2)/Q_1 = 1 - Q_2/Q_1$  -----(1)

In case of Carnot's engine, the amount of heat taken and rejected are respectively proportional to the temperature of the source and the sink i.e., Q/T=constant

So,  $Q_1/T_1 = Q_2/T_2$ 

Or,  $Q_1/Q_2 = T_1/T_2$ 

: from the equation (1) we get,  $\eta = (T_1 - T_2)/T_1 = 1 - T_2/T_1$  -----(2)

In terms of percentage,  $\eta = (1 - T_2/T_1) \times 100\%$  -----(3)

From equation (3), it is seen that efficiency of the Carnot's engine depends on the temperatures of the heat and sink and not on the working substance.

# <u>Entropy</u>

Entropy is the physical property of an object which remains constant in adiabatic process. It is represented by S.

Entropy has tremendous importance and significance in thermodynamics. It tells us about the direction of heat flow and helps in determining the thermodynamic condition. Entropy is measured by the rate of change of heat absorbed or rejected with respect to temperature of the system.

The change in entropy (dS) of a system was originally defined for a thermodynamically reversible process as

#### dS=dQ/T

Where T is the absolute temperature of the system, dividing an incremental reversible transfer of heat into that system (dQ). (If heat is transferred out the sign would be reversed giving a decrease in entropy of the system.)

#### Significance of entropy

Entropy is very significant in thermodynamics. The significances are mention below

- 1. Entropy is a physical quantity. It is equal to the ratio of heat absorbed or rejected to the temperature.
- 2. It indicates the direction of heat flow.
- 3. It helps in determining the thermodynamic state of an object.
- 4. like temperature, pressure, volume, internal energy, magnetic behavior it expresses the state of a body.
- 5. The orderliness of an object decreases with the increase of entropy.
- 6. Like temperature or pressure it cannot be felt.

#### (4) Third law of thermodynamics

The entropy of a system approaches a constant value as the temperature approaches zero. The entropy of a system at absolute zero is typically zero, and in all cases, is determined only by the number of different ground states it has. Specifically, the entropy of a pure crystalline substance at absolute zero temperature is zero.

#### Change of entropy in a reversible process

Let abcd be a complete reversible Carnot's cycle. It is shown in the figure below, in that cycle ab and cd are two isothermal graphs and bc and da are two adiabatic graphs. Let the working substance absorb and amount of heat  $Q_1$  from the heat source a temperature  $T_1$  while moving from a to b along the isothermal graph ab. Let the working substance reject  $Q_2$  amount of heat to be heat sink at temperature  $T_2$  while going c to d along the isothermal graph cd. But graphs bc and da the adiabatic, hence no heat will be absorbed or rejected along this graphs.

Consequently, there will be no changes of entropy.



So, increase of entropy in isothermal process  $ab = \frac{Q1}{T1}$ And decrease of entropy in isothermal process  $cd = \frac{Q2}{T2}$ Total change of entropy in the complete cycle  $= \frac{Q1}{T1} - \frac{Q2}{T2}$ But, as the cycle is reversible, so,  $\frac{Q1}{T1} = \frac{Q2}{T2}$ Change of entropy,

$$\Delta S = \frac{Q1}{T1} - \frac{Q2}{T2} = 0$$
$$\Delta S = \sum \frac{Q}{T} = 0$$

Conclusion: In reversible process, the change of entropy is zero.

#### Change the entropy in an irreversible process

Let an irreversible engine take up  $Q_1$  amount of heat from a source at temperature  $T_1$  and  $Q_2$  amount of heat to the sink at temperature  $T_2$ .

So, the efficiency  $\boldsymbol{\eta}$ 

$$\eta = \frac{Q1-Q2}{Q1}$$

But the efficiency of a reversible cycle (Carnot's cycle) working within the above temperature limit is

$$\eta' = \frac{T1 - T2}{T1}$$

Now, according to Carnot's theorem,  $\eta > \acute{\eta}$ 

 $\frac{T_1 - T_2}{T_1} > \frac{Q_1 - Q_2}{Q_1}$ or,  $1 - \frac{T_2}{T_1} > 1 - \frac{Q_2}{Q_1}$ or,  $\frac{Q_2}{Q_1} > \frac{T_2}{T_1}$ or,  $\frac{Q_2}{T_2} > \frac{Q_1}{T_1}$ or,  $\frac{Q_2}{T_2} - \frac{Q_1}{T_1} > 0$ 

So, if the working system is considered as a whole. We find that the heat source entropy  $\frac{Q1}{T1}$  and the heat sink gains entropy  $\frac{Q2}{T2}$ .

Hence, the net gain of entropy =  $\frac{Q^2}{T^2} - \frac{Q^1}{T^1}$ . The value of which is positive.

# # Draw the T-S diagram of an ideal Carnot engine and show that the area enclosed by the T-S diagram is equal to the amount of work done by the engine.

Thermodynamic changes in the state of a substance can be represented by plotting entropy (S) along horizontal axis and temperature (T) along perpendicular axis. Such a diagram is called temperature entropy diagram (i.e., T-S diagram) for the substance.

A Carnot's reversible cycle is shown on P-V diagram (fig.1). It is composed of two isothermals AB and CD at constant temperatures  $T_1$  and  $T_2$  respectively.

On the *T*-*S* diagram (fig.1), the isothermal curves are shown by two straight lines *AB* and *CD* parallel to *S*-axis and the adiabatic curves are shown by the straight lines *BC* and *DA* parallel to *T*-axis. The resulting *T*-*S* diagram is a rectangle *ABCD*.



Fig.1. P-V and T-S diagrams of Carnot Cycle

Consider a Carnot's reversible cycle on *T-S* diagram (fig.1). Suppose  $S_1$  be the entropy of working substance in state *A*,  $S_2$  the entropy in state *B*,  $Q_1$  be the heat absorbed along *AB* i.e., during isothermal expansion at constant temperature  $T_1$  and  $Q_2$  is the heat rejected in the isothermal compression at constant temperature  $T_2$  along *CD*.

In going from A to B, along isothermal expansion AB, the gain in the entropy of the working substance is given by

 $S_2 - S_1 = \frac{Q_1}{T_1}$ -----(1)

In going from B to C, along adiabatic expansion BC, there is no change in the entropy.

In going from C to D, along isothermal compression CD, the loss in the entropy of the working substance is given by

 $S_2 - S_1 = \frac{Q_2}{T_2}$ -----(2)

Along adiabatic compression DA, there is no change in the entropy. Therefore, from equations (1) and (2), we get-

 $Q_1 = (S_2 - S_1)T_1 - \dots - (3)$ 

and  $Q_2 = (S_2 - S_1)T_2$  -----(4)

subtracting equation (4) from equation (3), we get

$$Q_1 - Q_2 = (S_2 - S_1)T_1 - (S_2 - S_1)T_2$$
  

$$\therefore Q_1 - Q_2 = (S_2 - S_1)(T_1 - T_2)$$
(5)

The quantity  $(Q_1 - Q_2)$  represents the external work done in the cycle and  $(S_2 - S_1)(T_1 - T_2)$  is the area of the rectangle on the *T*-*S* diagram.

Thus, the area of the rectangle on the T-S diagram represents the external work done in the reversible Carnot's cycle.