STEAM

Steam is the gaseous phase of water. It is considered as an excellent working agent as it can carry large quantity of heat. It is produced from water, which is cheap and readily available. There are three types of steams :

a. Dry and Saturated Steam

The steam, which is available at saturation temperature and contains no moisture, is known as dry and saturated steam.

b. Wet Steam

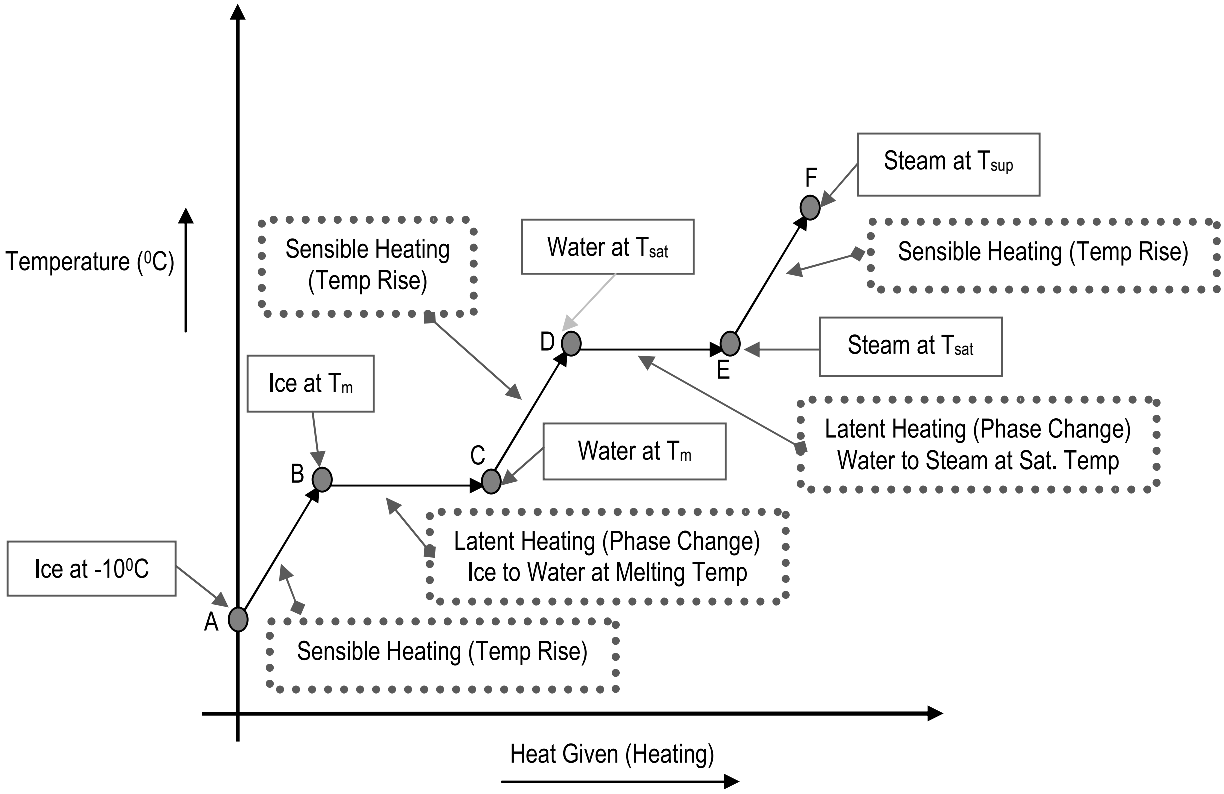
The steam, which is available at saturation temperature and contains moisture, is known as wet steam. It is characterized by dryness fraction (x) and value of x varies from 0 to 1. For '0' means, there is water at saturation temperature and phase change (from water to steam) is to be started. While, x=1 indicates that entire water is converted into steam at saturation temperature and this steam is known as Dry and Saturated Steam. Thus, steam of x>0 but x<1 is known as Wet Steam that contains steam and moisture (water).

c. Super-heated Steam

The steam, which is available at a temperature which is more than saturation temperature, is known as super heated steam.

GENERATION OF STEAM

Let, one kg of ice is available at -10^0C. Heat is given. In case of sensible heating, temperature gets increased, while, in case of latent heating phase change occurred. Consider the pressure as atmospheric pressure and saturation temperature of water at atmospheric pressure is 100^0C. The processes involved in generation of steam are as follows :



Description of Figure

Points	Processes
Point – A : Ice of -10^0C Point – B : Ice at T_m (Melting Point) Point – C : Water at T_m Point – D : Water at $T_{saturation}$ (T_{sat}) Point – E : Steam at $T_{saturation}$ (T_{sat}) Point – F : Steam at T_{super} (T_{sup})	Process A ➔ B : Sensible Heating (Temperature rise, from current temperature to Melting Point of Ice)
	Process B ➔ C : Latent Heating (Phase change from Ice to Water at T_m (at Melting Point temperature; No change in Temp)
	Process C ➔ D : Sensible Heating (Temperature rise, from current temperature of water i.e. melting point to Saturation Temp of Water)
	Process D ➔ E : Latent Heating (Phase change from Water to Steam at T_{Sat} (at Saturation temperature; No change in Temp)
	Process E ➔ F : Sensible Heating (Temperature rise, from current temperature of dry & Sat. Steam (T_{sat}) to T_{Sup} (Superheated Temp)

Note that Phase change occurs at constant temperature and heat given is known as Latent Heat, while, Temperature get increased by sensible heating. Heat is absorbed till saturation temperature during current phase and on subsequent heating, phase change occurs (i.e. latent heating).

The Steam available at various locations is as follows :

At Point – D : Saturated Liquid (Water) is available at Saturation Temperature (T_{sat}). At this point, value of x is 0.

At Point – E : Saturated Steam (Dry and Saturated) is available at Saturation Temperature (T_{sat}). It means, entire water is converted into steam. At this point, value of x is 1.

Between Point – D and Point – E : The mixture of Water and Steam is available, which is known as Wet Steam and value of x varies from 0 to 1 (x > 0 but < 1). The temperature is T_{sat}.

Beyond Point – E : Further addition of heat increases the temperature of dry and saturated steam and thus, is known as Superheated steam. It is characterized by Degree of Superheat where,

$$\text{Degree of Superheat} = T_{\text{Super-heated}} - T_{\text{Saturation}}$$

Specific Enthalpy for various types of Steam :

Type of Steam	Specific Enthalpy	Remarks
Dry & Sat. Steam	$h = h_g = h_f + h_{fg}$	*In Steam Table, values are given with reference to the Water at 0^0C.* *In these table, suffix 'f' stand for fluid (i.e. water) and 'g' stands for gas (i.e. Steam)*
Wet Steam	$h_{wet} = h_f + x.h_{fg}$	
Superheated Steam	$h_{sup} = h_g + C_{ps} (T_{sup} - T_{sat})$	

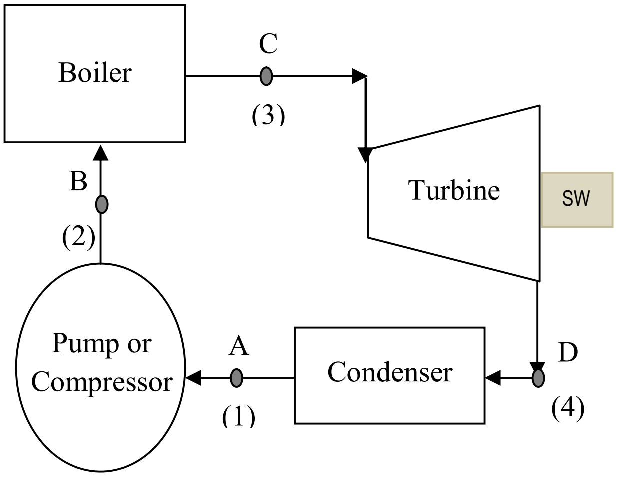
Specific Enthalpy, Sp. Volume, Sp. Entropy, Work-done and Sp. Internal Energy of various Steams

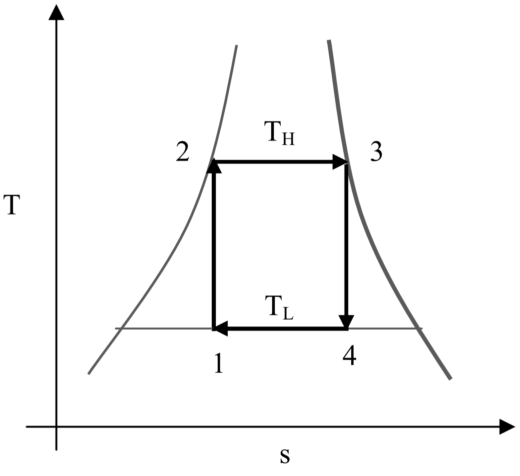
Property	Dry & Sat. Steam	Wet Steam	Superheated Steam
Sp. Enthalpy (h; kJ/kg)	$h_{dry} = h_g = h_f + h_{fg}$	$h_{wet} = h_f + x.h_{fg}$	$h_{sup} = h_g + C_{ps} (T_{sup} - T_{sat})$
Sp. Volume (v; m^3/kg)	$v_{dry} = v_g$	$v_{wet} = x.v_g$	$v_{super} = v_g . (T_{super} / T_{sat})$
Sp. Entropy (s ; kJ/kg K)	$s_{dry} = s_f + s_{fg} = s_g$	$s_{wet} = s_f + x. s_{fg}$	$s_{super} = s_g + C_{ps}. \ln (T_{super} / T_{sat})$
Work-done (pv ; kJ/kg-sec)	$p. v_{dry}$	$p. v_{wet}$	$p. v_{super}$
Sp. Internal Energy (u=h-pv) kJ/kg	$h_{dry} - p. v_{dry}$	$h_{wet} - p. v_{wet}$	$h_{sup} - p. v_{super}$
Mass = m = V (in m^3) / Sp. Vol.		$s_{fg} = (h_{fg} / T_{sat})$	

CARNOT VAPOUR CYCLE

A French military engineer Nicolas Sadi Carnot was among the first to study the principles of the II law of thermodynamics. In 1824, he introduced a classical ideal cycle, on the basis of which Clausius and Kelvin were able to define the II law of thermodynamics. The carnot cycle consists of an alternative series of two reversible isothermal processes and two reversible adiabatic processes, carnot cycle is a reversible cycle.

This cycle devised by Sadi Carnot has highest possible efficiency and consists of two isothermal and two adiabatic processes.





Processes :

- **Process 1-2** : Reversible adiabatic compression process from P_1 to P_2.
- **Process 2-3** : Reversible isothermal heat addition process at constant temperature T_H.
- **Process 3-4** : Reversible adiabatic expansion process from P_3 to P_4.
- **Process 4-1** : Reversible isothermal heat rejection process at constant temperature T_L.

Saturated vapor leaves the boiler at state 3, enters the turbine and expands to state 4. The fluid then enters the condenser, where it is cooled to state 1 and then it is compressed to state 2 in the pump.

Starting with saturated water at state *B*, isothermal process *BC* can easily be carried out in an ordinary boiler. The saturated steam at *C* then expands isentropically in an engine or turbine and the process is represented by *CD*. From *D* to *A*, heat rejection occurs isothermally in an ordinary condenser. The condensation is stopped at the point *A* which lies on the isentropic line drawn from the point *B*. At state *A*, the vapour enters into the compressor (or pump), undergoes isentropic compression, and is discharges as a saturated liquid.

The net work done during the cycle is equal to the difference between the work done by the engine (or turbine) and the work required to run compressor (or pump). The efficiency of the cycle is as follows:

Net Work Done = Heat Supplied – Heat Rejected

Thermal Efficiency = Work Done / Heat Supplied

$$\eta_{Carnot} = \frac{T_H - T_L}{T_H} \quad \text{OR} \quad \eta_{Carnot} = 1 - \frac{T_L}{T_H} \quad \text{OR} \quad \eta_{Carnot} = 1 - \frac{T_2}{T_1}$$

Work Ratio

It is defined as the ratio of net output to gross output.

Gross Output = Work done in the engine cylinder

= Work done during adiabatic expansion (isentropic expansion from *C* to *D*)

= $h_c - h_d = h_3 - h_4$

Out of this gross output, some work is spent in the process of compression (pump or compressor) from *A* to *B* (or 1 to 2). This work is equal to ($h_b - h_a$ OR $h_1 - h_2$). Thus,

Net output = $(h_c - h_d) - (h_b - h_a)$ kJ/kg

Hence, work ratio will be :

$$\text{Work Ratio} = \frac{(h_c - h_d) - (h_b - h_a)}{(h_c - h_d)}$$

Specific Steam Consumption

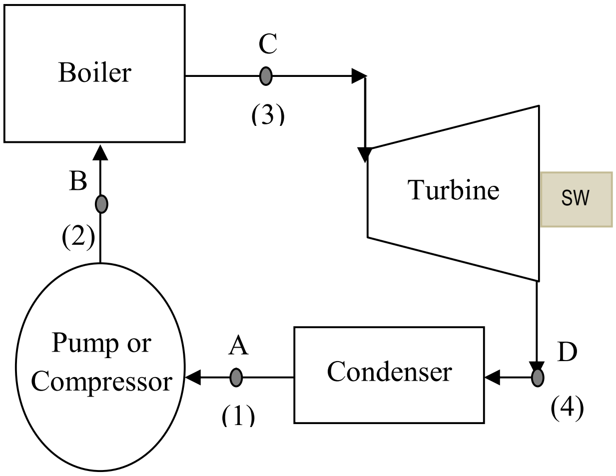
It is the mass of steam in kg that must be supplied to an engine (or turbine) to develop a certain amount of work. It may be expressed as 'kg per kWh'.

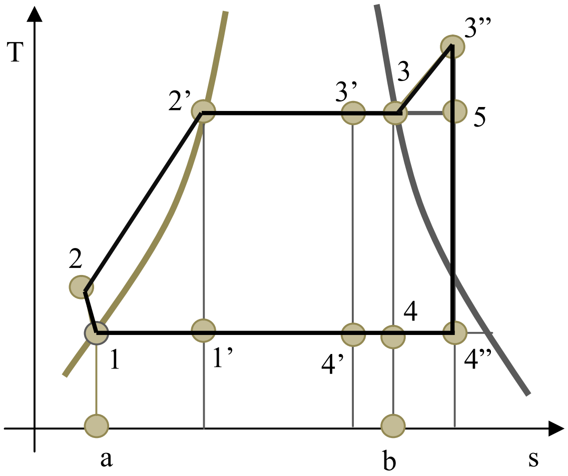
Practically, it is very difficult to add or reject heat to or from the working fluid at constant temperature. But, it is comparatively easy to add or reject heat to or from the working fluid at constant pressure. Therefore, Carnot cycle is not used as an idealized cycle for steam power plants. However, ideal cycle for steam power plant is Rankine cycle in which heat addition and rejection takes place at constant pressure process.

RANKINE CYCLE

Rankine Cycle is the ideal cycle on which steam engine works. It may be seen that the Rankine Cycle is not reversible on account of the operation (da), during which, in practice, the heat is supplied at a higher temperature than the water; hence, the operation (da) cannot be reversed. For this reason, Rankine cycle is not as efficient as the Carnot cycle (which is reversible) working between the same temperature limits.

This cycle devised by Rankine consists of two constant pressure and two adiabatic processes.





Processes

Process 1-2 : Water from the condenser at low pressure is pumped into the boiler at high pressure. This process is reversible adiabatic.

Process 2-3 : Water is converted into steam at constant pressure by the addition of heat in the boiler.

Process 3-4 : Reversible adiabatic expansion of steam in the steam turbine.

Process 4-1 : Constant pressure heat rejection in the condenser to convert condensate into water.

The steam leaving the boiler may be dry and saturated, wet or superheated. The corresponding T-s diagrams are as follows :

For Dry and Saturated Steam : The T-s diagram is 1-2-3-4-1.

For Wet Steam : The T-s diagram is 1-2-3'-4'-1.

For Superheated Steam : The T-s diagram is 1-2-3"-4"-1.

T-s diagram for Carnot Cycle : 1' – 2' – 3 – 4 – 1'.

T-s diagram for Rankine Cycle : 1 – 2 – 3 – 4 – 1.

Thermal Efficiency

The net work done during the cycle is equal to the difference between the work done by the engine (or turbine) and the work required to run compressor (or pump). The efficiency of the cycle is as follows:

Net Work Done = Heat Supplied – Heat Rejected

Thermal Efficiency = Work Done / Heat Supplied

Thermal Efficiency ➔ $$\eta_{\text{Rankine}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} = \frac{\text{Area } 122'341}{\text{Area } a22'3ba}$$

The pump (or compressor) work is negligible, because specific volume of water is very small (WD = p.dv). Therefore,

$$\eta_{\text{Rankine}} = \frac{(h_3 - h_4)}{(h_3 - h_2)} = \frac{\text{Area } 12'341}{\text{Area } a12'3ba} \quad \text{(neglecting pump work)}$$

Note that the Rankine cycle has a lower efficiency compared to corresponding Carnot cycle 2’-3-4-1’ with the same maximum and minimum temperatures. The reason is that the average temperature at which heat is added in the Rankine cycle lies between T_2 and T^1_2 and is thus less than the constant temperature T^1_2 at which heat is added to the Carnot cycle.

Reasons for Considering Rankine Cycle as an Ideal Cycle for Steam Power Plants

1. It is very difficult to build a pump that will handle a mixture of liquid and vapor at state 1’ (refer T-s diagram) and deliver saturated liquid at state 2’. It is much easier to completely condense the vapor and handle only liquid in the pump.
2. In the Rankine cycle, the vapor may be superheated at constant pressure from 3 to 3” without difficulty. In a Carnot cycle using superheated steam, the superheating will have to be done at constant temperature along path 3-5. During this process, the pressure has to be dropped. This means that heat is transferred to the vapor as it undergoes expansion doing work. This is difficult to achieve in practice.

THERMODYNAMIC PROCESSES FOR AN IDEAL GAS

PV^n = Constant

Process	Isobaric	Isochoric	Isothermal	Adiabatic
Variable =>	Pressure	Volume	Tempemature.	No Heat Flow
Quantity Constant =>	$\Delta P = 0$	$\Delta V = 0$	$\Delta T = 0$	$Q = 0$
n	0	∞	1	$\gamma = C_p/C_v$
First Law	$\Delta U = Q - W$	$\Delta U = Q$ $W = 0$	$\Delta U = 0$ $Q = W$	$\Delta U = -W$ $Q = 0$
Work $W = \int P dV$	$P(V_2 - V_1)$	0	$P_1 V_1 \ln\left(\frac{V_2}{V_1}\right)$	$\frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$
Heat Flow Q	$m C_p (T_2 - T_1)$	$m C_v (T_2 - T_1)$	$P_1 V_1 \ln\left(\frac{V_2}{V_1}\right)$	0
Heat Capacity	C_p	C_v	∞	0
Internal Energy $\Delta U = U_2 - U_1$	$m C_v (T_2 - T_1)$	$m C_v (T_2 - T_1)$	0	$m C_v (T_2 - T_1)$
Enthalpy $\Delta H = H_2 - H_1$ $H = U + PV$	$m C_p (T_2 - T_1)$	$m C_p (T_2 - T_1)$	0	$m C_p (T_2 - T_1)$
Entropy $\Delta S = S_2 - S_1$ $= \int dQ/T$	$m C_p \ln \frac{T_2}{T_1}$	$m C_v \ln \frac{T_2}{T_1}$	$nR \ln \frac{V_2}{V_1}$	0*
Ideal Gas Relations $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$ $PV = NkT$	$\frac{}{T_2} = \frac{}{V_2}$	$\frac{}{T_2} = \frac{}{P_2}$	$\frac{}{P_2} = \frac{}{V_1}$	$\frac{}{T_2} = \left(\frac{}{V_1}\right)$

* For Adiabatic Reversible Processes

$n c_p = m C_p$ **$n c_v = m C_v$** **$c_p - c_v = R$** **$n R = N k$**

$\gamma = C_p/C_v = c_p/c_v$ = Ratio of Specific Heats

C_p = Constant Pressure Specific Heat Capacity (J/kg/ °C)

C_v = Constant Volume Specific Heat Capacity (J/kg/ °C)

c_p = Molar Constant Pressure Heat Capacity (J/mole/oC)

c_v = Molar Constant Volume Heat Capacity (J/mole/oC)