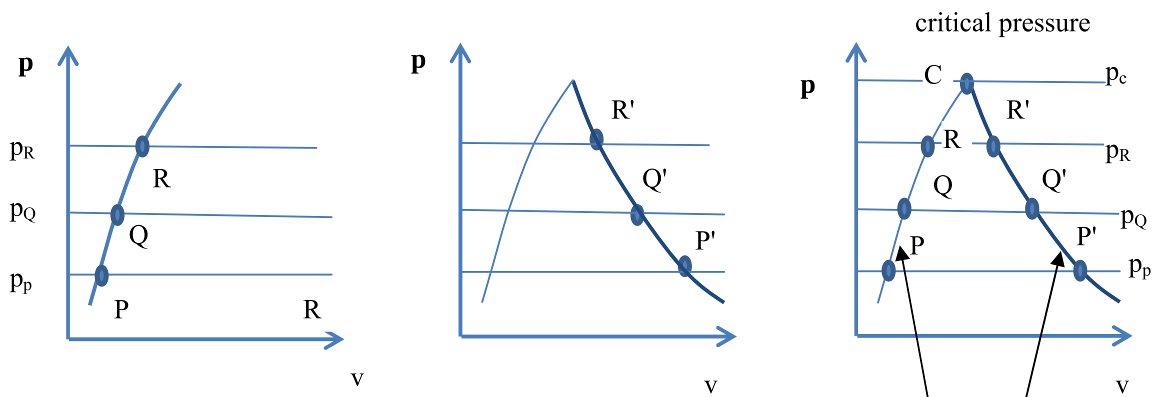
Working Fluid

Liquid, vapor, gas; use of vapor tables; perfect gas



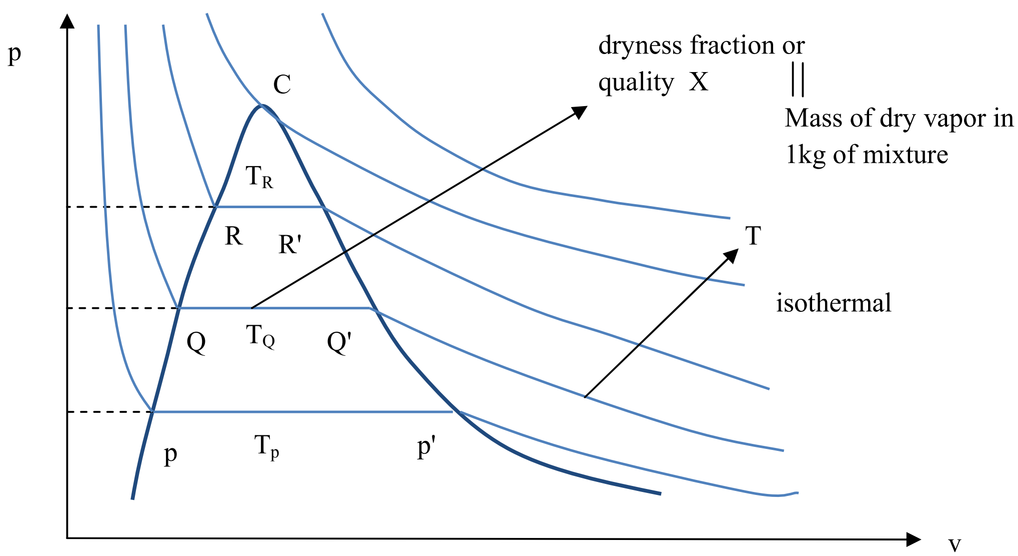
Curve pQRC: saturated liquid

Curve CR'Q'p': saturated vapor

RR', QQ', pp': latent heat of vaporization

C: critical point

V of 1kg of a boiling liquid at high pressure is larger than V of the same at low pressure



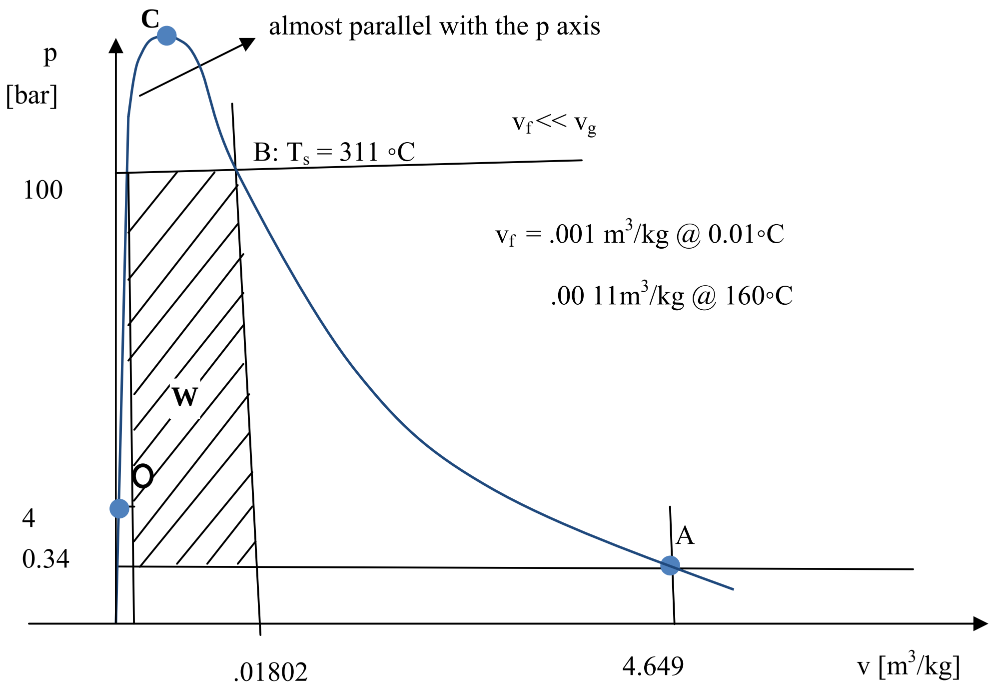
$h_{gf} = h_g - h_f$

$S_{fg} = S_g - S_f$

Vapor (steam) Table

Sat. liq → h_f; Sat. vap → h_g

p	T_s	v_g	U_f	U_g	h_f	h_{fg}	h_g	S_f	S_{fg}	S_g
bar	°C	m^3/kg	kJ/kg		kJ/kg			kJ/kgK		
.34	72	4.649	302	2472	302	2328	2630	.980	6.745	7.725



O: 4 bar, T_s = 143.6◦C, u_f = 605kJ/kg, h_f = 605 kJ/kg

C: critical point, T_c = 374.15◦C, V_c= 0.00317 m^3/kg, P_c =221.2 bar

Saturated water is changed to dry saturated vapor

$Q_{fg} = Q_{1\text{-}2} = (u_2 - u_1) + W_{1\text{-}2} = (u_g - u_f) + W_{fg}$

$W_{fg} = (v_g - v_f)p$

$Q_{fg} = (u_g - u_f) + (v_g - v_f)p$

$= (u_g + v_g p) - (u_f + v_f p) = h_g - h_f = h_{fg}$ ⟶ latent heat of vaporization

Wet vapor

$$v = \frac{\text{volume of liquid + volume of dry vapor}}{\text{total mass of wet vapor}}$$

1kg of wet vapor has x kg of dry vapor + (1-x)kg of liq.

$v = xv_g + (1\text{-}x)v_f \qquad v_f \ll v_g$

$= xv_g$

$h = xh_g + (1\text{-}x)\, h_f$

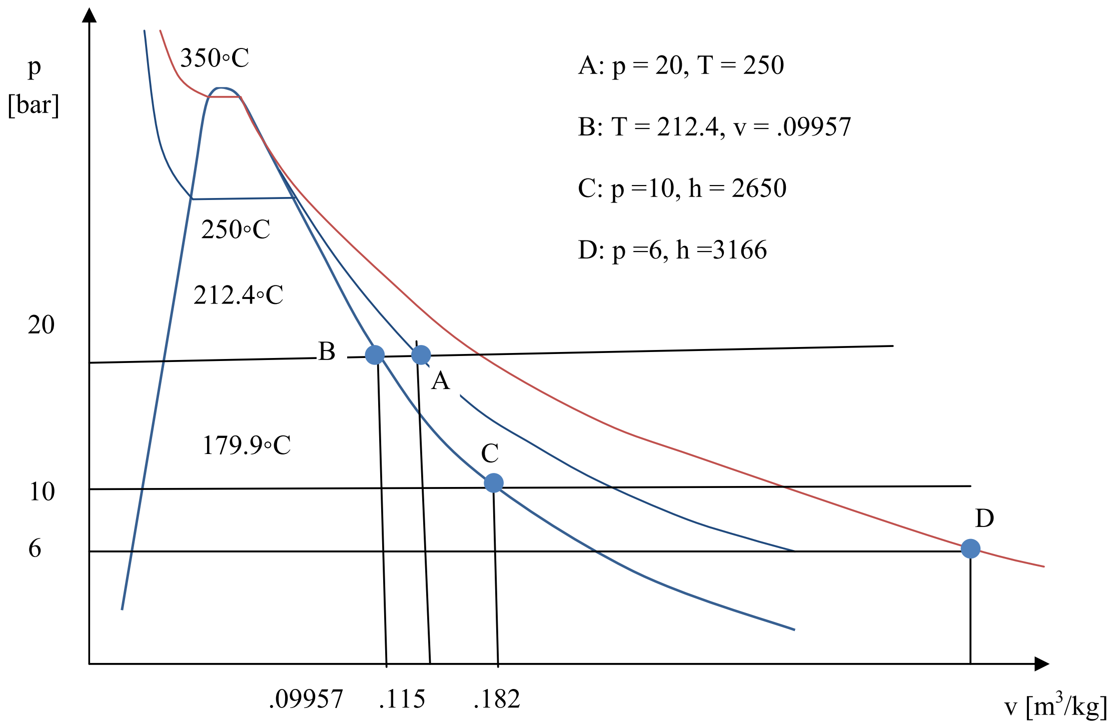
$= h_f + x\,(h_g - h_f) = h_f + xh_{fg}$

$u = xu_g + (1\text{-}x)\, u_f = u_f + xu_{fg}$

Superheated vapor:

Steam @ 2 bar, 200◦C is superheated while its saturation temperature is T_s = 120.2◦C

=> degree of superheat = 200 – 120.2 = 79.8K



Perfect (Ideal) Gas: $\frac{pv}{T}$ = constant = R

(characteristics equation of state)

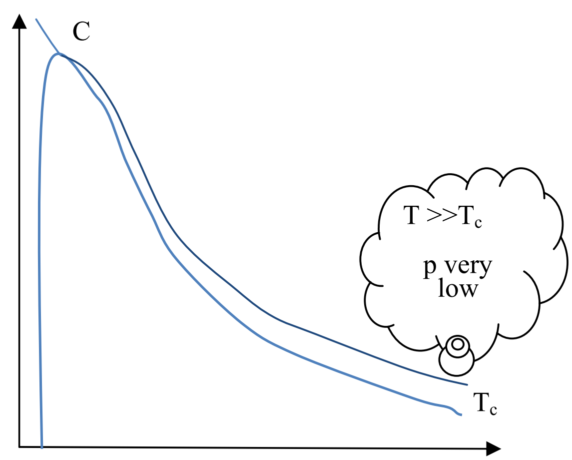
No gases in practice obey this law rigidly, but many gases tend towards it at T >> T_c and p very low.

R: specific gas constant $\frac{Nm}{kgK}$

pv = RT => pV = mRT for mass m occupying V

mole: the amount of substance of a system which contains as many as of elementary entities as there are

Atoms in .012 kg carbon (General Conf. Weight & Measure CGPM Conférence Général de Poids et de Mesures, 1971)
=> mol, kmol



$m = nM$; m[kg]; n: number of kmol; M: molar mass [kg/kmol]

$pV = nMRT$ or $MR = pV/nT = R_o$;

Ro: molar gas constant or universal gas constant = $8314.4 \ \frac{Nm}{kmolK}$

$pV = nRoT$

O_2 of molar mass = 32kg/kmol;

$$R = 8314.4/32 = 259.3 \ \frac{Nm}{kgK}$$

A vessel of $0.2m^3$ contains N_2 @ 1.013 bar and 15◦C .2 kg of N_2 is pumped into the vessel. New pressure when the vessel has returned to it's initial temperature M of N_2 = 28kg/kmol.

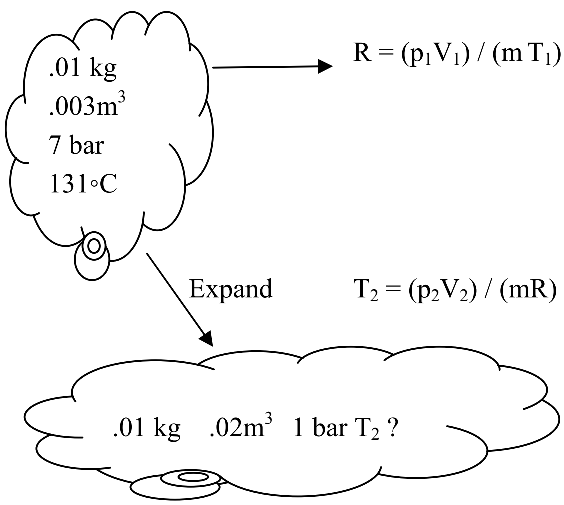
$$R = \frac{Ro}{M} = \frac{8314.4}{28} = 296.9 \frac{Nm}{kgK}$$

$p_1V_1 = m_1 RT_1 \Rightarrow m_1 = (p_1V_1)/(RT_1) = (1.013 * 10^5 * .2) / (2969 * 288) = .237$ kg

$m_2 = .237 + .2 = .437$ kg

$p_2V_2 = m_2 RT_2 \Rightarrow p_2 = (m_2 RT_2)/ V_2 = (.437 * 296.9 * 288) / (.2 * 10^5) = 1.87$ bar

$M = R_0 / R = 8314/ 520 = 16$ kg/ kmol



$R = (p_1V_1) / (m T_1) = (7 * 10^5 * .003) / (.01 * 404) = 520 \ \frac{Nm}{kgK}$

$T_2 = (p_2V_2) / (mR) = (1 * 10^5 * .02) / (16 * 520) = 384.5 K = 111.5$◦C

Specific Heat: Required to raise unit mass by 1◦C

C_p: specific heat @ cont pressure
C_V: specific heat @ cont volume
} reversible non flow

$dQ = m C_p dT$ $\quad$ $dQ = m C_V dT$

$Q_{1-2} = m C_p (T_2 - T_1)$ $\quad$ $Q_{1-2} = m C_V (T_2 - T_1)$

C_p and C_V vary for real gases with T => suitable average

Joule's Law u = u (T only) for a perfect gas

1kg of PG heated @ const volume: $dQ = du + dw = du$ (dw = 0)

$u = C_V T + C_1$ (constant)

$C_1 = 0$, as $u = 0 = C_V\, 0$ at T = 0K

For mass m, $U = m\, C_V\, T$ $\Rightarrow U_2 - U_1 = m\, C_v\, (T_2 - T_1)$

PG is heated @ constant p for T_1 to T_2

$Q_{1\text{-}2} = (U_2 - U_1) + W_{1\text{-}2} = m\, C_V\, (T_2 - T_1) + W$

$W_{1\text{-}2} = p\, (V_2 - V_1) = mR\, (T_2 - T_1)$

$Q_{1\text{-}2} = m\, (C_V + R)\, (T_2 - T_1) = m\, C_p\, (T_2 - T_1)$

⇨ $C_p = C_v + R$ or $C_p - C_v = R$

Enthalpy: $h = u + pv = C_v T + RT = (C_v + R)\, T = C_p T$

$H = m\, C_p\, T$

$$\gamma = \frac{C_p}{C_v} > 1, \text{ as } C_p > C_v \text{ and } C_p - C_v = R > 0$$

≈ 1.4 for diatomic gases (CO, N_2, H_2, O_2….)

≈ 1.6 for monatomic gases (A, He, ….)

≈ 1.3 for triatomic gases (CO_2, SO_2, …..)

$$\frac{C_p}{C_v} - 1 = \frac{R}{C_v} = \gamma - 1, \quad \Rightarrow C_v = \frac{R}{\gamma - 1}$$

$$C_p = \gamma C_v = \frac{\gamma R}{\gamma - 1}$$

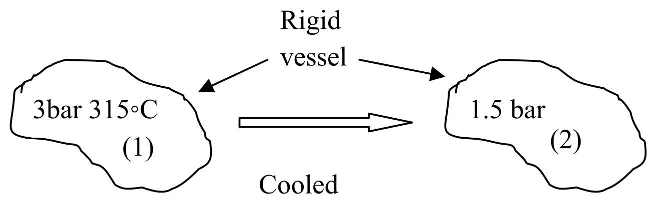
$C_p = .846\ \frac{kJ}{kgK}$, $C_v = .657\ \frac{kJ}{kgK}$; R, M ?

$$R = C_p - C_v = .846 - .657 = .189\ \frac{kJ}{kgK} = 189\ \frac{Nm}{kgK}$$

$$R = \frac{Ro}{M}, \Rightarrow M = \frac{Ro}{R} = \frac{8314}{189} = 44\ \frac{kg}{Kmol}$$

$M = 26 \frac{kg}{Kmol}$; $\gamma = 1.26$; Q rejected / kg?

(a)



$v_2 = v_1$

$$R = \frac{Ro}{M} = \frac{8314}{26} = 319.8 \ \frac{Nm}{kgK}$$

$$C_v = \frac{R}{\gamma\text{-}1} = 319.8/\ \{10^3\ (1.26 - 1)\} = 1.229 \ \frac{kJ}{kgK}$$

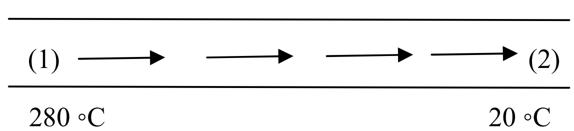
$$C_p = \gamma\ C_v = 1.26 * 1.229 = 1.548 \ \frac{kJ}{kgK}$$

$p_1v_1 = RT_1$, $\quad p_2v_2 = RT_2 \quad v_2 = v_1$

$T_2 = (p_2v_1)/R = (p_2RT_1)/Rp_1 = (p_2\ /p_1)/T_1 = (1.5 * 588)/\ 3 = 294$ K $\quad T_1 = 315 + 273 = 588$K

$$Q_{1\text{-}2} = C_V\ (T_2 - T_1) = 1.229\ (294 - 588) = -\ 361 \ \frac{kJ}{kg}$$

(b) Enters a pipeline



$$h_1 + \cancelto{0}{\frac{V_1^2}{2}} + Q = h_2 + \cancelto{0}{\frac{V_2^2}{2}} + \cancelto{0}{W}$$

$$h_1 + Q = h_2$$

$$Q = h_2 - h_1 = C_p\ (T_2 - T_1) = 1.548\ (20 - 280) = -\ 403 \ \frac{kJ}{kg}$$