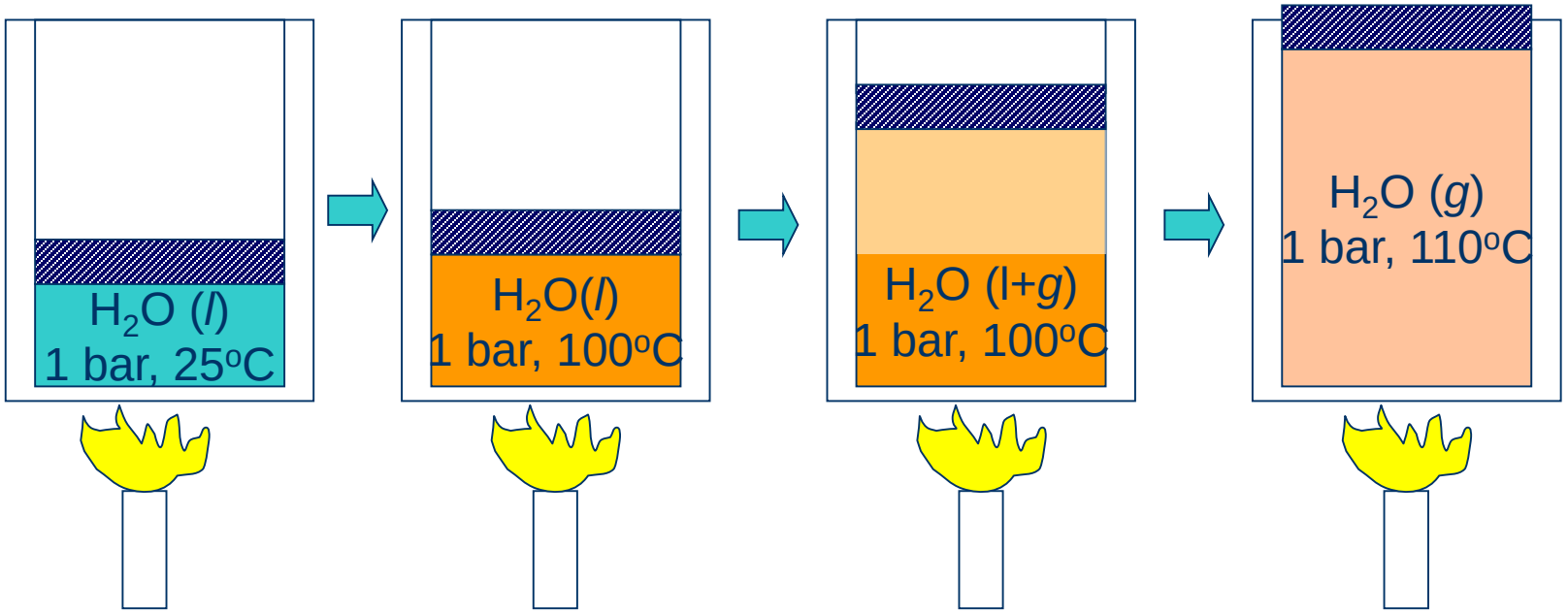
# Properties of Steam

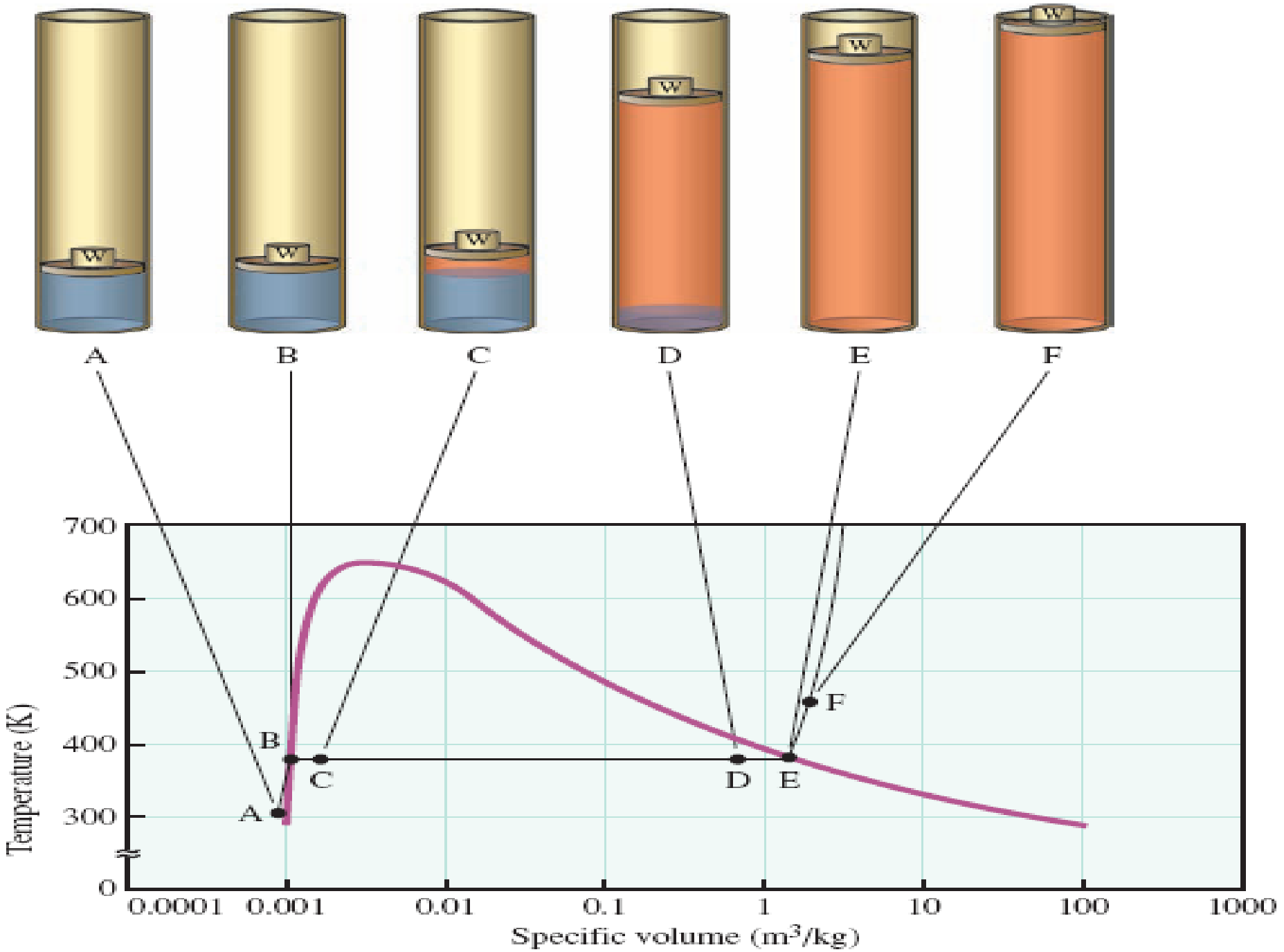
# Heating of water at constant pressure

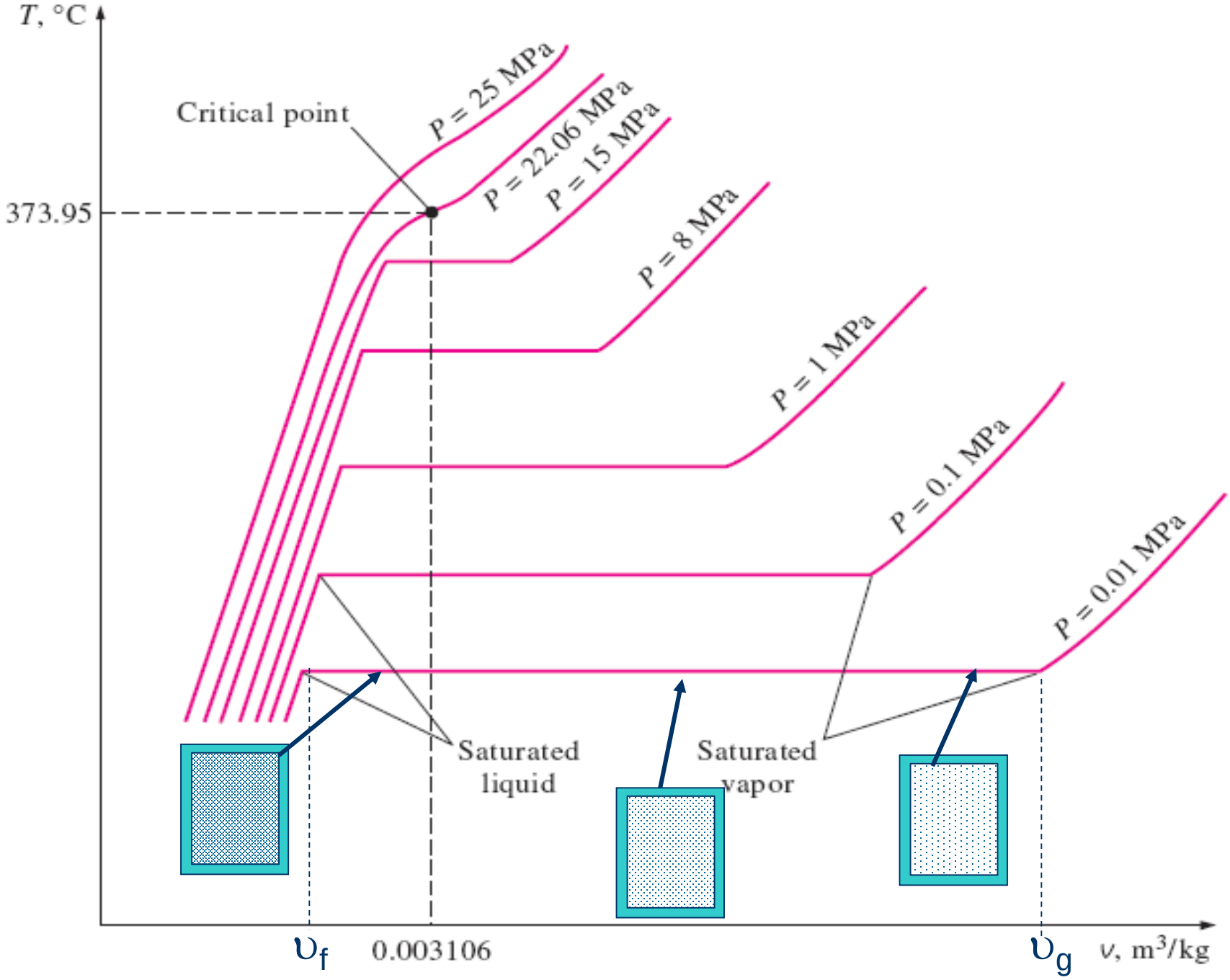



T increases,
Phase doesn't change
*V* increases slightly

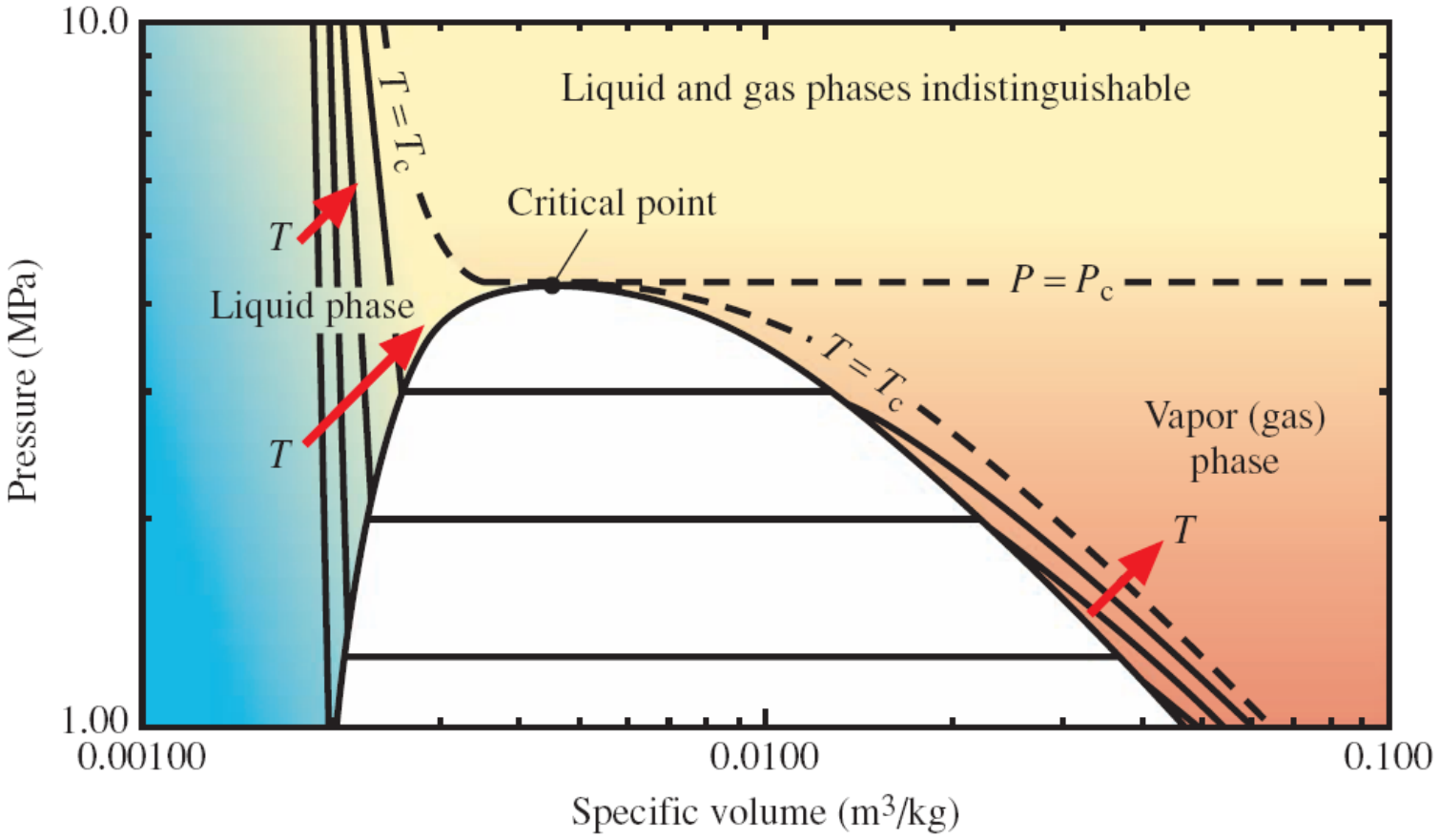
T remains the same,
Phase changes
*V* increases
significantly

T increases,
Phase doesn't change
*V* increases
significantly


W
A
B
C
D
E
F
700
600
500
400
300
0
Temperature (K)
0.0001
0.001
0.01
0.1
1
10
100
1000
Specific volume (m³/kg)

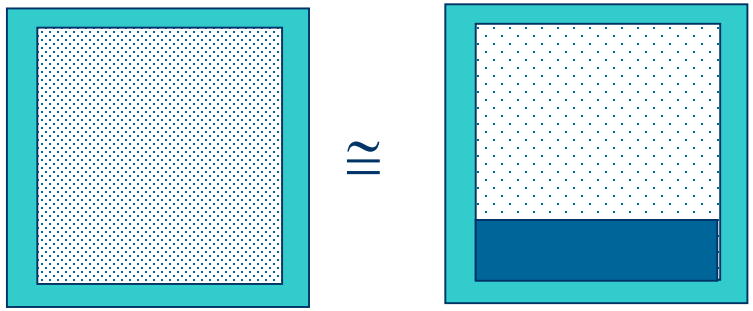

T, °C
Critical point
373.95
P = 25 MPa
P = 22.06 MPa
P = 15 MPa
P = 8 MPa
P = 1 MPa
P = 0.1 MPa
P = 0.01 MPa
Saturated liquid
Saturated vapor
υf
0.003106
υg
v, m³/kg

# The p-v diagram



# The Dryness Factor

$$x = \frac{m_{\text{vapor}}}{m_{\text{liquid}} + m_{\text{vapor}}}$$



- Sp. Volume change:

$$v = (1 - x)v_f + xv_g = v_f + x(v_g - v_f)$$

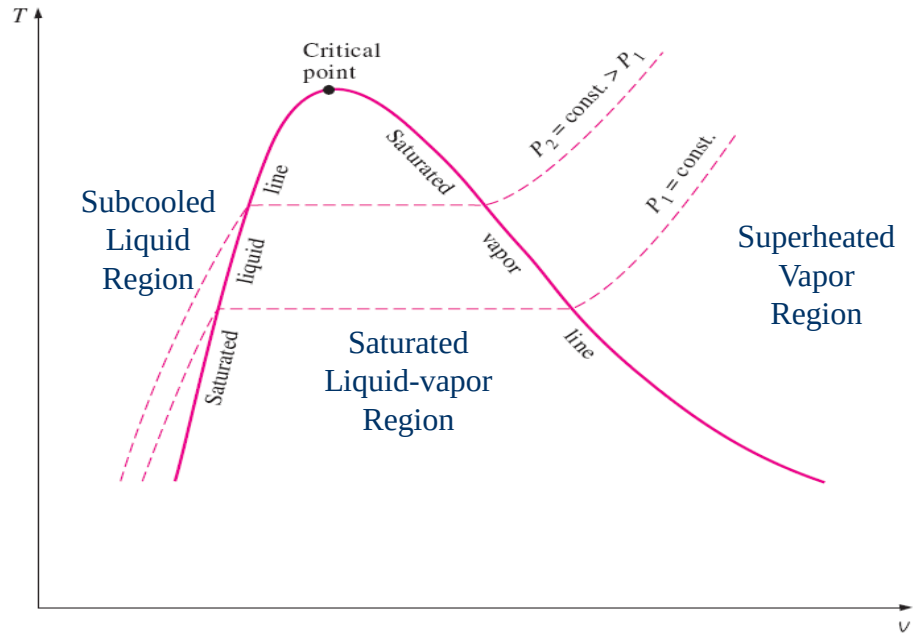
- Sp. Internal Energy and Enthalpy changes

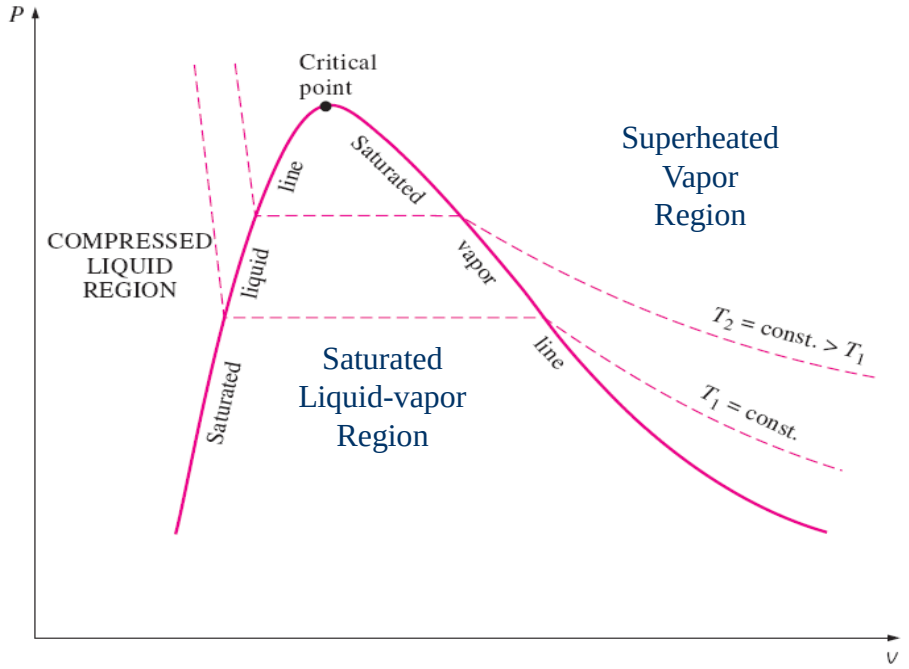
$$u = (1 - x)u_f + xu_g = u_f + x(u_g - u_f)$$

$$h = (1 - x)h_f + xh_g = h_f + x(h_g - h_f)$$

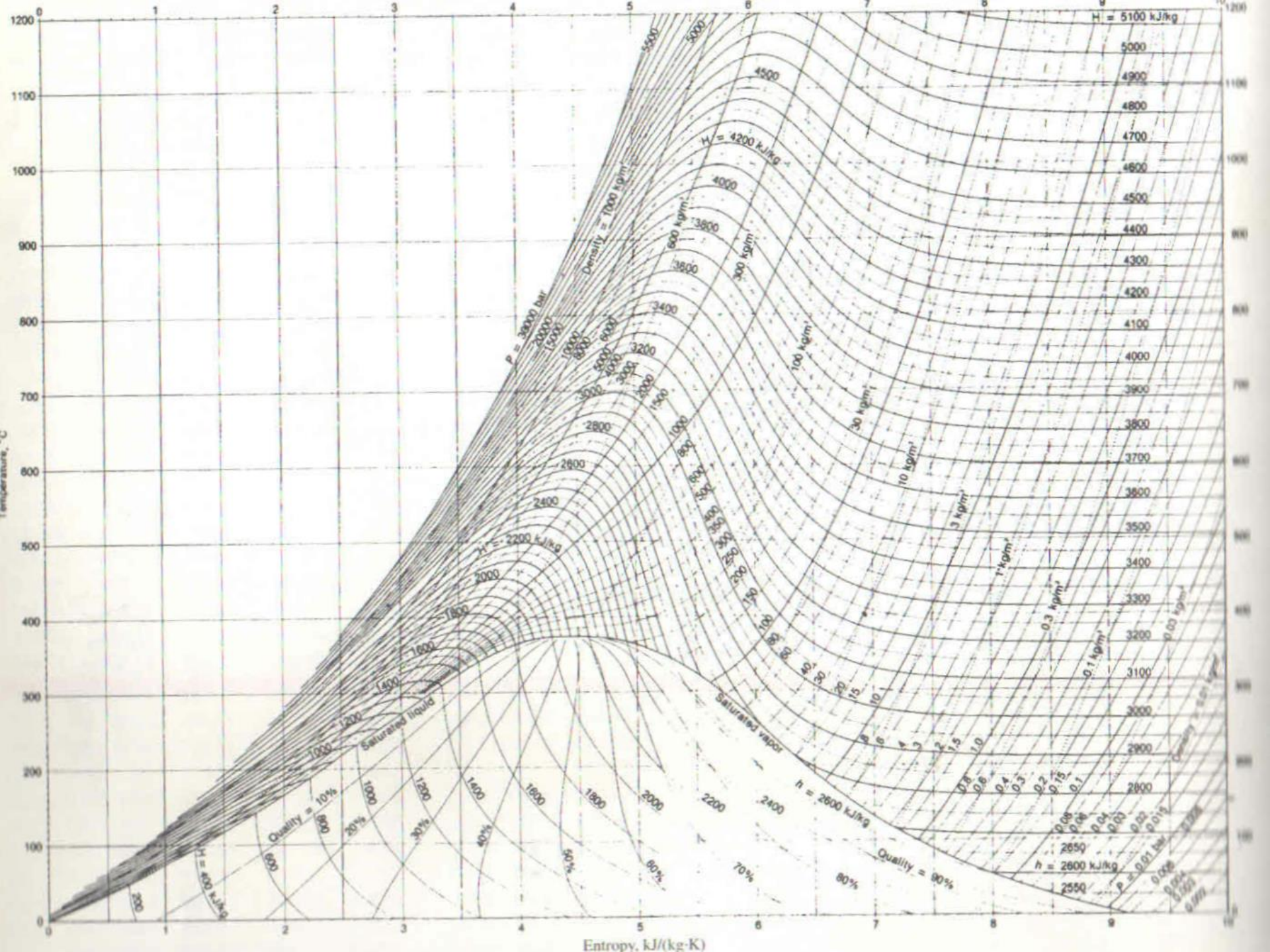
Any specific property: $y = y_f + xy_{fg}$

# The *T-v and p-v diagrams*




*Subcooled liquid is also called the "Compressed Liquid"*


Temperature, °C
Entropy, kJ/(kg·K)
Saturated liquid
Saturated vapor
Quality = 10%
Quality = 90%
H = 400 kJ/kg
H = 2200 kJ/kg
H = 4200 kJ/kg
H = 5100 kJ/kg
h = 2600 kJ/kg
P = 30000 bar
Density = 1000 kg/m³
600 kg/m³
300 kg/m³
100 kg/m³
30 kg/m³
10 kg/m³
3 kg/m³
1 kg/m³
0.3 kg/m³
0.1 kg/m³
0.03 kg/m³
P = 0.01 bar

# Steam Table

f = saturated liquid (x=0)
g = saturated vapor (x =1)

- Saturation Table: Temperature Table

**TABLE A-2** Properties of Saturated Water (Liquid–Vapor): Temperature Table

| Temp. °C | Press. bar | Specific Volume $m^3/kg$ | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | | Entropy kJ/kg · K | | Temp. °C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sat. Liquid $v_f \times 10^3$ | Sat. Vapor $v_g$ | Sat. Liquid $u_f$ | Sat. Vapor $u_g$ | Sat. Liquid $h_f$ | Evap. $h_{fg}$ | Sat. Vapor $h_g$ | Sat. Liquid $s_f$ | Sat. Vapor $s_g$ | |
| .01 | 0.00611 | 1.0002 | 206.136 | 0.00 | 2375.3 | 0.01 | 2501.3 | 2501.4 | 0.0000 | 9.1562 | .01 |
| 4 | 0.00813 | 1.0001 | 157.232 | 16.77 | 2380.9 | 16.78 | 2491.9 | 2508.7 | 0.0610 | 9.0514 | 4 |
| 5 | 0.00872 | 1.0001 | 147.120 | 20.97 | 2382.3 | 20.98 | 2489.6 | 2510.6 | 0.0761 | 9.0257 | 5 |
| 6 | 0.00935 | 1.0001 | 137.734 | 25.19 | 2383.6 | 25.20 | 2487.2 | 2512.4 | 0.0912 | 9.0003 | 6 |
| 8 | 0.01072 | 1.0002 | 120.917 | 33.59 | 2386.4 | 33.60 | 2482.5 | 2516.1 | 0.1212 | 8.9501 | 8 |
| 90 | .7014 | 1.0360 | 2.361 | 376.85 | 2494.5 | 376.92 | 2283.2 | 2660.1 | 1.1925 | 7.4791 | 90 |
| 95 | .8455 | 1.0397 | 1.982 | 397.88 | 2500.6 | 397.96 | 2270.2 | 2668.1 | 1.2500 | 7.4159 | 95 |
| 100 | 1.014 | 1.0435 | 1.673 | 418.94 | 2506.5 | 419.04 | 2257.0 | 2676.1 | 1.3069 | 7.3549 | 100 |
| 110 | 1.433 | 1.0516 | 1.210 | 461.14 | 2518.1 | 461.30 | 2230.2 | 2691.5 | 1.4185 | 7.2387 | 110 |
| 360 | 186.5 | 1.8925 | 0.006945 | 1725.2 | 2351.5 | 1760.5 | 720.5 | 2481.0 | 3.9147 | 5.0526 | 360 |
| 374.14 | 220.9 | 3.155 | 0.003155 | 2029.6 | 2029.6 | 2099.3 | 0 | 2099.3 | 4.4298 | 4.4298 | 374.14 |

Properties of saturated liquid at 0.01°C are taken as reference

# Steam Table

f = saturated liquid (x=0)
g = saturated vapor (x =1)

- Saturation Table: Pressure Table

**TABLE A-3** Properties of Saturated Water (Liquid–Vapor): Pressure Table

| Press. bar | Temp. °C | Specific Volume $m^3/kg$ | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | | Entropy kJ/kg · K | | Press. bar |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sat. Liquid $v_f \times 10^3$ | Sat. Vapor $v_g$ | Sat. Liquid $u_f$ | Sat. Vapor $u_g$ | Sat. Liquid $h_f$ | Evap. $h_{fg}$ | Sat. Vapor $h_g$ | Sat. Liquid $s_f$ | Sat. Vapor $s_g$ | |
| 0.04 | 28.96 | 1.0040 | 34.800 | 121.45 | 2415.2 | 121.46 | 2432.9 | 2554.4 | 0.4226 | 8.4746 | 0.04 |
| 0.06 | 36.16 | 1.0064 | 23.739 | 151.53 | 2425.0 | 151.53 | 2415.9 | 2567.4 | 0.5210 | 8.3304 | 0.06 |
| 0.08 | 41.51 | 1.0084 | 18.103 | 173.87 | 2432.2 | 173.88 | 2403.1 | 2577.0 | 0.5926 | 8.2287 | 0.08 |
| 0.10 | 45.81 | 1.0102 | 14.674 | 191.82 | 2437.9 | 191.83 | 2392.8 | 2584.7 | 0.6493 | 8.1502 | 0.10 |
| 0.20 | 60.06 | 1.0172 | 7.649 | 251.38 | 2456.7 | 251.40 | 2358.3 | 2609.7 | 0.8320 | 7.9085 | 0.20 |
| 0.90 | 96.71 | 1.0410 | 1.869 | 405.06 | 2502.6 | 405.15 | 2265.7 | 2670.9 | 1.2695 | 7.3949 | 0.90 |
| 1.00 | 99.63 | 1.0432 | 1.694 | 417.36 | 2506.1 | 417.46 | 2258.0 | 2675.5 | 1.3026 | 7.3594 | 1.00 |
| 1.50 | 111.4 | 1.0528 | 1.159 | 466.94 | 2519.7 | 467.11 | 2226.5 | 2693.6 | 1.4336 | 7.2233 | 1.50 |
| 200. | 365.8 | 2.036 | 0.005834 | 1785.6 | 2293.0 | 1826.3 | 583.4 | 2409.7 | 4.0139 | 4.9269 | 200. |
| 220.9 | 374.1 | 3.155 | 0.003155 | 2029.6 | 2029.6 | 2099.3 | 0 | 2099.3 | 4.4298 | 4.4298 | 220.9 |

# Superheated Steam

**Table C-3 (*Continued*)**

| $P$, MPa ($T_{sat}$, °C) | | Temperature °C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 700 | 800 |
| 1 | $v$, m³/kg | | 0.2060 | 0.2327 | 0.2579 | 0.2825 | 0.3066 | 0.3304 | 0.3541 | 0.3776 | 0.4011 | 0.4478 | 0.4943 |
| (179.9) | $u$, kJ/kg | | 2621.9 | 2709.9 | 2793.2 | 2875.2 | 2957.3 | 3040.2 | 3124.3 | 3209.8 | 3296.8 | 3475.4 | 3660.5 |
| | $h$, kJ/kg | | 2827.9 | 2942.6 | 3051.2 | 3157.7 | 3263.9 | 3370.7 | 3478.4 | 3587.5 | 3697.9 | 3923.1 | 4154.8 |
| | $s$, kJ/kg · K | | 6.6948 | 6.9255 | 7.1237 | 7.3019 | 7.4658 | 7.6188 | 7.7630 | 7.8996 | 8.0298 | 8.2740 | 8.5005 |
| 1.5 | $v$, m³/kg | | 0.1325 | 0.1520 | 0.1697 | 0.1866 | 0.2030 | 0.2192 | 0.2352 | 0.2510 | 0.2668 | 0.2981 | 0.3292 |
| (198.3) | $u$ kJ/kg | | 2598.1 | 2695.3 | 2783.1 | 2867.6 | 2951.3 | 3035.3 | 3120.3 | 3206.4 | 3293.9 | 3473.2 | 3658.7 |
| | $h$, kJ/kg | | 2796.8 | 2923.2 | 3037.6 | 3147.4 | 3255.8 | 3364.1 | 3473.0 | 3582.9 | 3694.0 | 3920.3 | 4152.6 |
| | $s$, kJ/kg · K | | 6.4554 | 6.7098 | 6.9187 | 7.1025 | 7.2697 | 7.4249 | 7.5706 | 7.7083 | 7.8393 | 8.0846 | 8.3118 |

h(p=1MPa, T=350°C)=3157.7 kJ/kg

h(p=1.5MPa, T=350°C)=3147.4 kJ/kg

h(p=1.4MPa, T=350°C)=3157.7+(3147.7-3157.7)*(0.4/0.5)
=3149.7 (kJ/kg)

# Compressed Liquid

**Table C-4 Compressed Liquid**

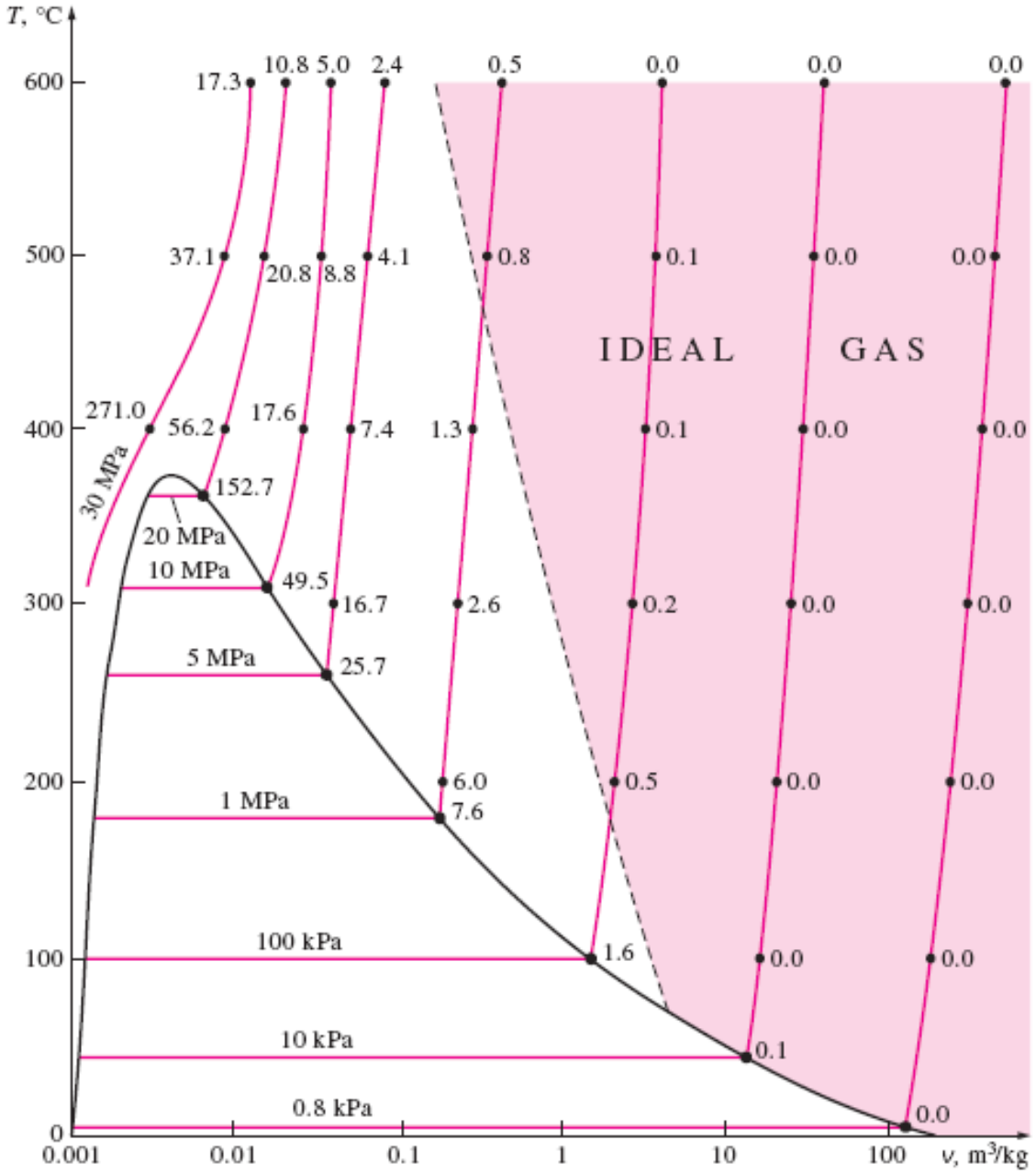
| | $P = 5$ MPa (263.99) | | | | $P = 10$ MPa (311.06) | | | |
|---|---|---|---|---|---|---|---|---|
| $T$ | $v$ | $u$ | $h$ | $s$ | $v$ | $u$ | $h$ | $s$ |
| 0 | 0.000 997 7 | 0.04 | 5.04 | 0.0001 | 0.000 995 2 | 0.09 | 10.04 | 0.0002 |
| 20 | 0.000 999 5 | 83.65 | 88.65 | 0.2956 | 0.000 997 2 | 83.36 | 93.33 | 0.2945 |
| 40 | 0.001 005 6 | 166.95 | 171.97 | 0.5705 | 0.001 003 4 | 166.35 | 176.38 | 0.5686 |
| 60 | 0.001 014 9 | 250.23 | 255.30 | 0.8285 | 0.001 012 7 | 249.36 | 259.49 | 0.8258 |
| 80 | 0.001 026 8 | 333.72 | 338.85 | 1.0720 | 0.001 024 5 | 332.59 | 342.83 | 1.0688 |
| 100 | 0.001 041 0 | 417.52 | 422.72 | 1.3030 | 0.001 038 5 | 416.12 | 426.50 | 1.2992 |
| 120 | 0.001 057 6 | 501.80 | 507.09 | 1.5233 | 0.001 054 9 | 500.08 | 510.64 | 1.5189 |

- Similar to the format of the superheated vapor table
- In general, properties are not sensitive to pressure, therefore, can treat the compressed liquid as saturated liquid at the given TEMPERATURE.
- Given: P and T: $v \cong v_{f@T}, u \cong u_{f@T}, s \cong s_{f@T}$

- But not h, since h=u+pv, and it depends more strongly on p. It can be approximated as $h \cong h_{f@T} + v_f(p - p_{sat})$

# Is Steam an Ideal Gas?

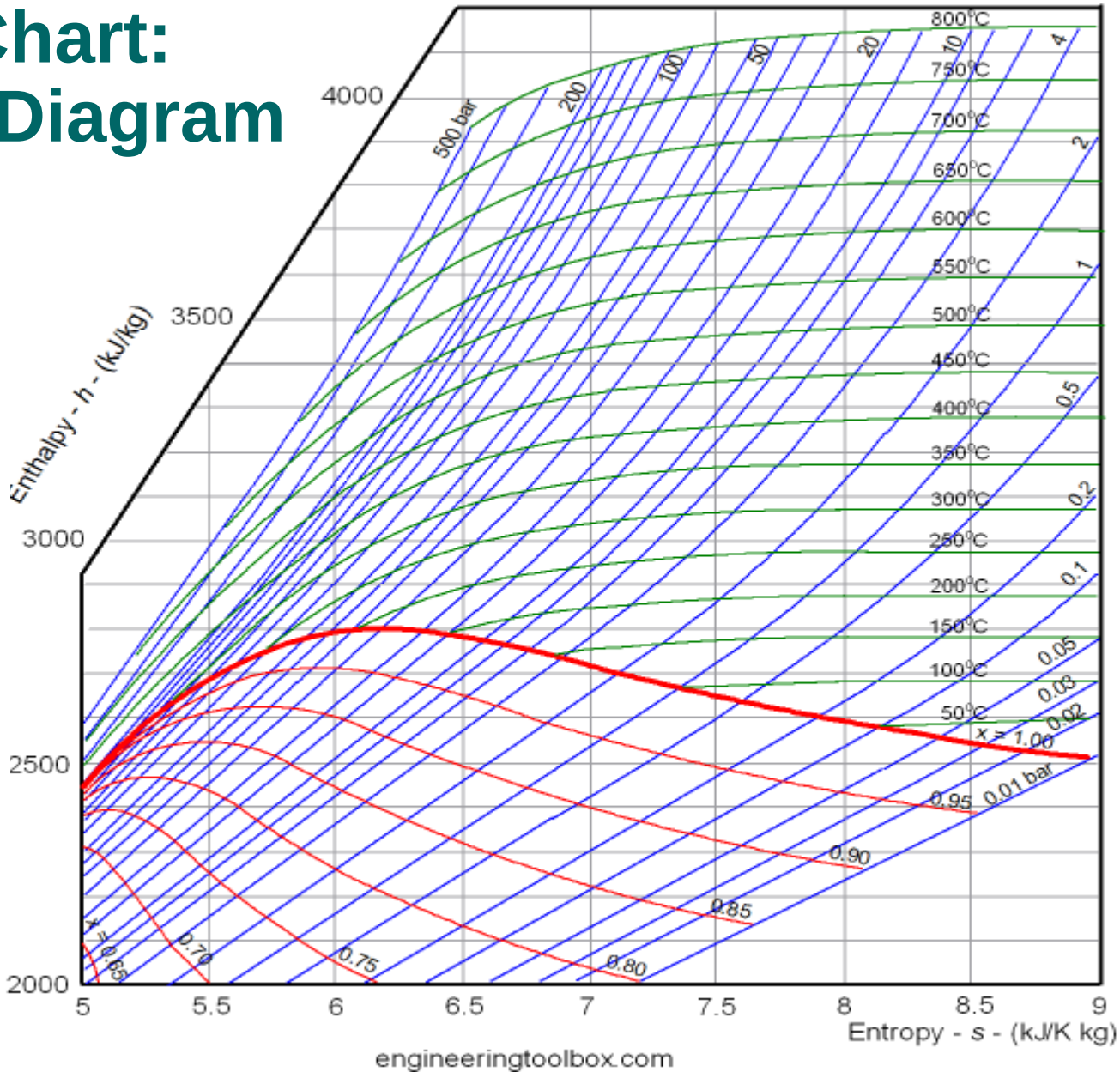
Only if the degree of superheat exceeds a certain value, or when the pressure is very low

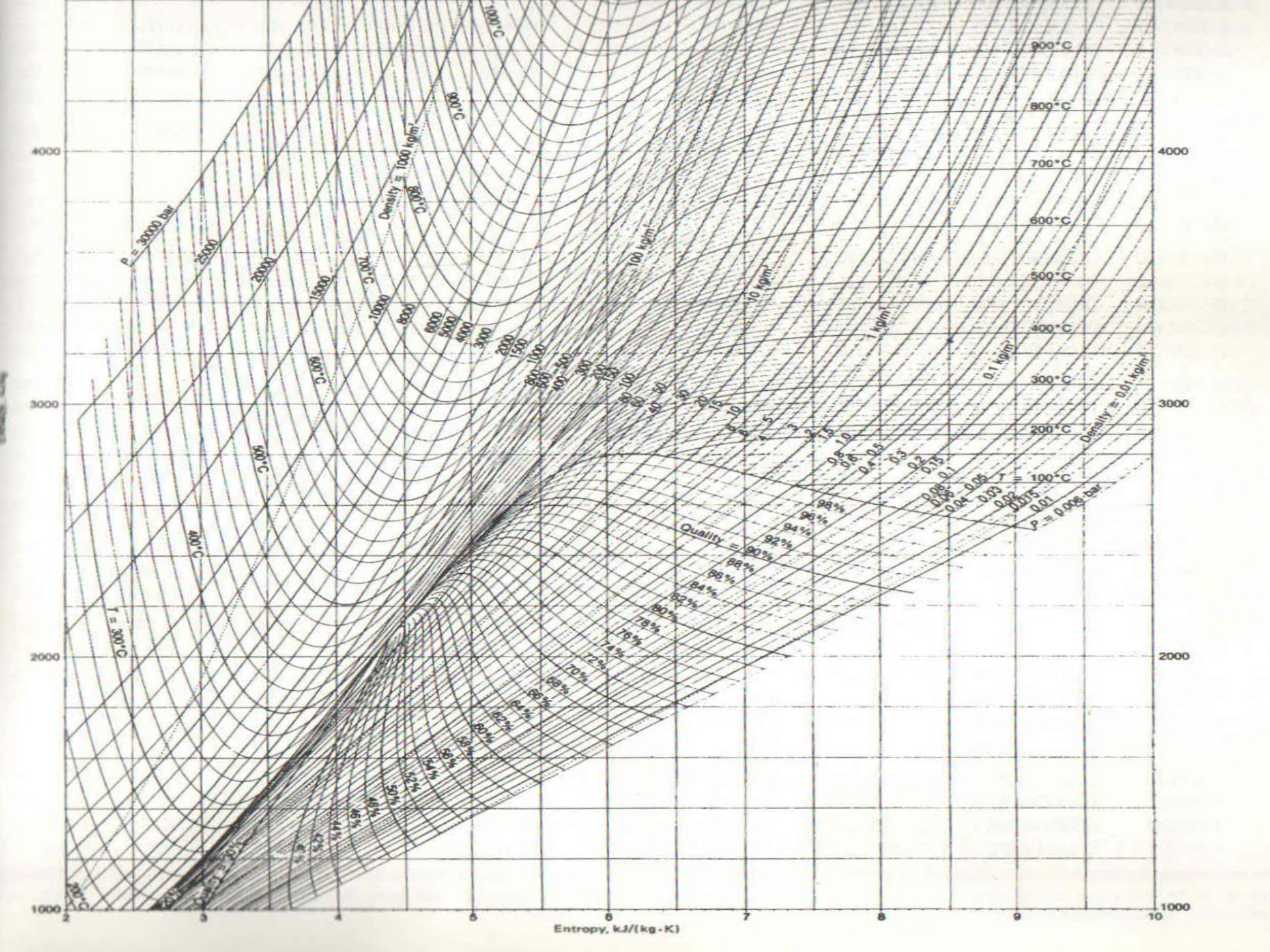



Percentage of error ($[|v_{table} - v_{ideal}|/v_{table}] \times 100$) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

# Steam Chart: Mollier Diagram

- Plots h (kJ/kg) along the y axis and s (kJ/kgK) along the x axis
- Difference of y in a process directly provides the work done in a turbine or work consumed in a compressor/ pump




Entropy, kJ/(kg·K)
2
3
4
5
6
7
8
9
10
1000
2000
3000
4000
P = 30000 bar
25000
20000
15000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1500
1000
900
800
700
600
500
400
300
200
150
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1.0
0.8
0.6
0.5
0.4
0.3
0.2
0.15
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.015
0.01
P = 0.006 bar
Density = 1000 kg/m³
100 kg/m³
10 kg/m³
1 kg/m³
0.1 kg/m³
Density = 0.01 kg/m³
1000°C
900°C
800°C
700°C
600°C
500°C
400°C
300°C
200°C
T = 100°C
T = 300°C
Quality =
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
78%
76%
74%
72%
70%
68%
66%
64%
62%
60%
58%
56%
54%
52%
50%
48%
46%
44%
42%

# Sample problems

4. 4 kg of steam at $x = 0.5$ and $p = 6$ bar is heated so that it becomes a (a) 0.95 dry at constant pressure; (b) dry saturated at constant pressure; (c) superheated to 300 $^{o}$C at 6 bar, (d) Superheated to 250 degree of superheat at 6 bar. Find the heat added in each case.