

ESO 201A: Thermodynamics

2016-2017-I semester

Properties: part 4

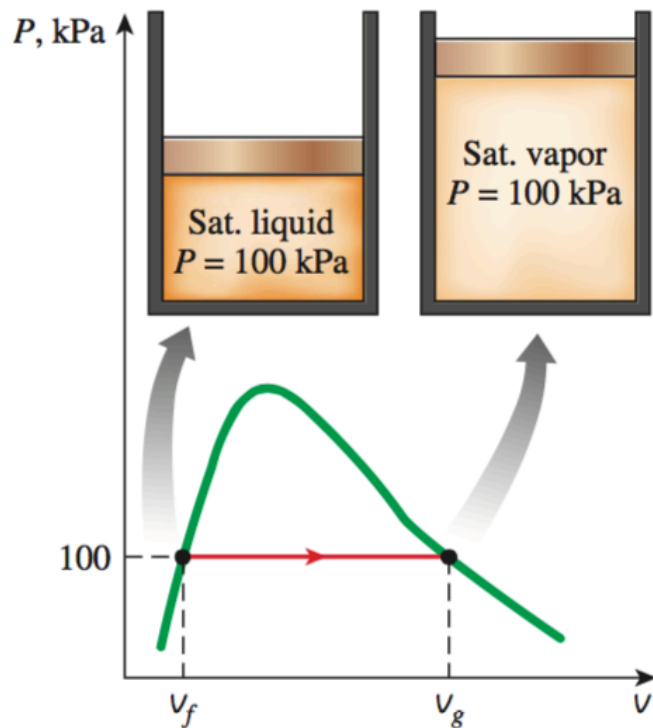
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Learning objective

1. Introduce the concept of a pure substance.
2. Discuss the physics of phase change processes.
3. Illustrate the P-v, T-v and P-T property diagram, and P-v-T surfaces of pure substances.
4. Obtaining thermodynamic properties of a pure substance from a property table.
5. Define Ideal gas equation of state and demonstrate its use.
6. Introduce to compressibility.
7. Present the commonly used equation of states.

Example

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy transferred to the water.



Volume change is v_{fg}

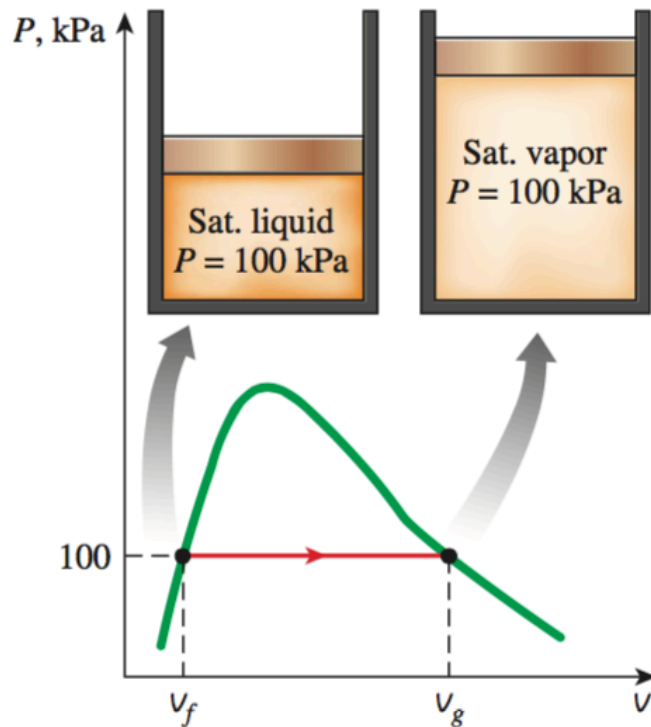
TABLE A-5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg		
		Sat. liquid, ν_f	Sat. vapor, ν_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6

Example

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy transferred to the water.



$$v_{fg} = 1.6941 - 0.001043 = 1.6931 \text{ m}^3/\text{kg}$$

$$\text{Volume change} = \\ m v_{fg} = (0.2 \text{ kg}) (1.6931 \text{ m}^3/\text{kg})$$

Amount of energy transferred is enthalpy of vaporisation: $m h_{fg}$

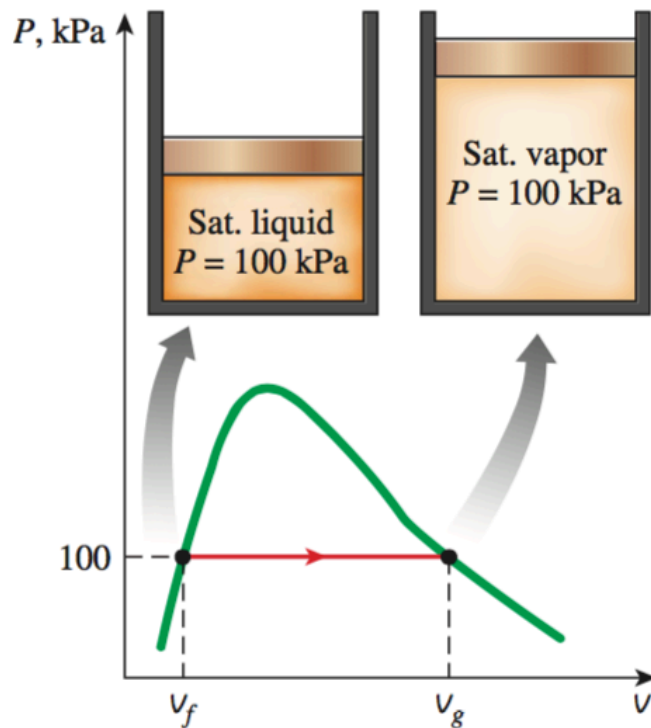
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Example

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy transferred to the water.



$$v_{fg} = 1.6941 - 0.001043 = 1.6931 \text{ m}^3/\text{kg}$$

Volume change =

$$mv_{fg} = (0.2 \text{ kg}) (1.6931 \text{ m}^3/\text{kg})$$

Amount of energy transferred is enthalpy of vaporisation: mh_{fg}

$$mh_{fg} = (0.2 \text{ kg}) (2257.5 \text{ kJ/kg}) = 451.5 \text{ kJ}$$

TABLE A-11

Saturated refrigerant-134a—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, $\text{kJ/kg}\cdot\text{K}$		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
−40	51.25	0.0007053	0.36064	−0.036	207.42	207.38	0.00	225.86	225.86	0.00000	0.96869	0.96869
−38	56.86	0.0007082	0.32718	2.472	206.06	208.53	2.512	224.62	227.13	0.01071	0.95516	0.96588
−36	62.95	0.0007111	0.29740	4.987	204.69	209.68	5.032	223.37	228.40	0.02137	0.94182	0.96319
−34	69.56	0.0007141	0.27082	7.509	203.32	210.83	7.559	222.10	229.66	0.03196	0.92867	0.96063

TABLE A-12

Saturated refrigerant-134a—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, $\text{kJ/kg}\cdot\text{K}$		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.01633	0.94812	0.96445
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.03264	0.92783	0.96047
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.04707	0.91009	0.95716
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.06003	0.89431	0.95434
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.07182	0.88008	0.95191

Superheated vapor

In the region to the right of the saturated vapor line and at temperatures above the saturation temperature, a substance exists as superheated vapor.

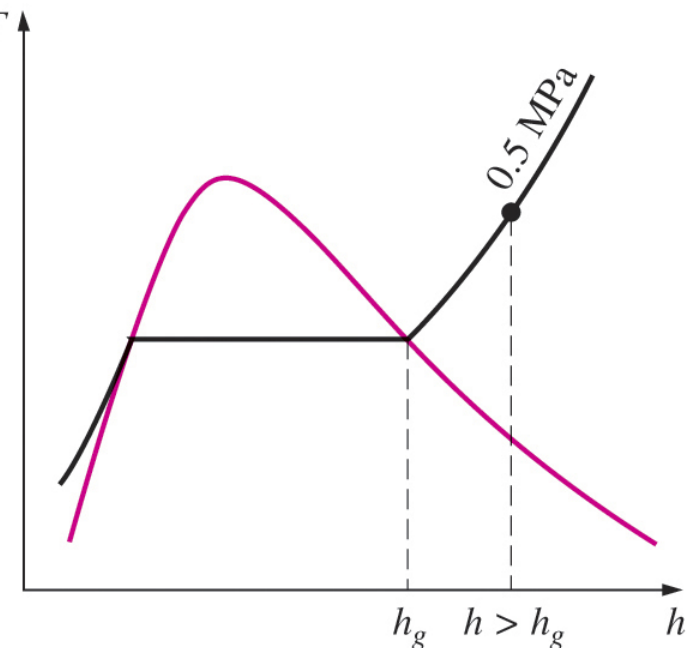
In this region, temperature and pressure are independent properties.

$T, ^\circ\text{C}$	v m^3/kg	u kJ/kg	h kJ/kg
$P = 0.1 \text{ MPa (99.61}^\circ\text{C)}$			
Sat.	1.6941	2505.6	2675.0
100	1.6959	2506.2	2675.8
150	1.9367	2582.9	2776.6
\vdots	\vdots	\vdots	\vdots
1300	7.2605	4687.2	5413.3
$P = 0.5 \text{ MPa (151.83}^\circ\text{C)}$			
Sat.	0.37483	2560.7	2748.1
200	0.42503	2643.3	2855.8
250	0.47443	2723.8	2961.0

Compared to saturated vapor, superheated vapor is characterized by

At a specified P , superheated vapor exists at a higher h than the saturated vapor.

A partial listing of Table A-6.



Example

Determine the temperature of water at a state of $P = 0.5 \text{ MPa}$ and $h = 2890 \text{ kJ/kg}$.

Press., $P \text{ kPa}$	Sat. temp., $T_{\text{sat}} \text{ } ^\circ\text{C}$
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450	147.90	0.001088
500	151.83	0.001093

Enthalpy, kJ/kg		
Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g

623.14	2120.3	2743.4
640.09	2108.0	2748.1

$$h > h_g$$

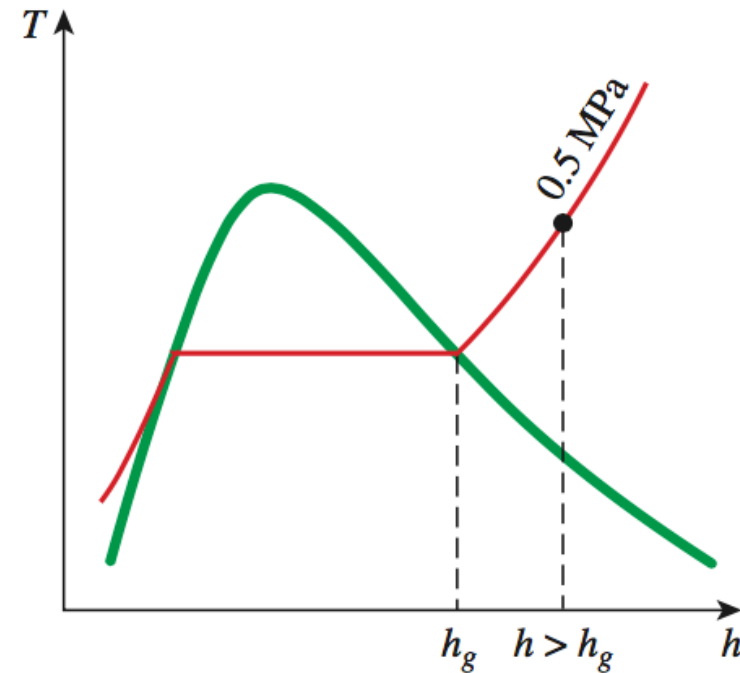


TABLE A-6

Superheated water

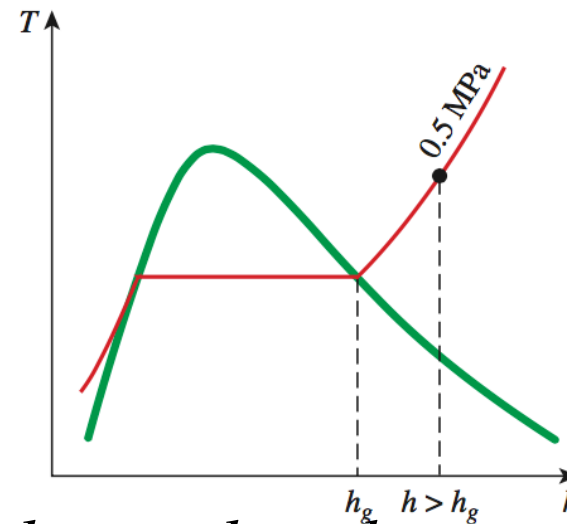
T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K
$P = 0.01 \text{ MPa (45.81°C)*}$					$P = 0.05 \text{ MPa (81.32°C)}$				$P = 0.10 \text{ MPa (99.61°C)}$			
Sat. [†]	14.670	2437.2	2583.9	8.1488	3.2403	2483.2	2645.2	7.5931	1.6941	2505.6	2675.0	7.3589
50	14.867	2443.3	2592.0	8.1741								
100	17.196	2515.5	2687.5	8.4489	3.4187	2511.5	2682.4	7.6953	1.6959	2506.2	2675.8	7.3611
150	19.513	2587.9	2783.0	8.6893	3.8897	2585.7	2780.2	7.9413	1.9367	2582.9	2776.6	7.6148
200	21.826	2661.4	2879.6	8.9049	4.3562	2660.0	2877.8	8.1592	2.1724	2658.2	2875.5	7.8356
250	24.136	2736.1	2977.5	9.1015	4.8206	2735.1	2976.2	8.3568	2.4062	2733.9	2974.5	8.0346
300	26.446	2812.3	3076.7	9.2827	5.2841	2811.6	3075.8	8.5387	2.6389	2810.7	3074.5	8.2172
400	31.063	2969.3	3280.0	9.6094	6.2094	2968.9	3279.3	8.8659	3.1027	2968.3	3278.6	8.5452
500	35.680	3132.9	3489.7	9.8998	7.1338	3132.6	3489.3	9.1566	3.5655	3132.2	3488.7	8.8362
600	40.296	3303.3	3706.3	10.1631	8.0577	3303.1	3706.0	9.4201	4.0279	3302.8	3705.6	9.0999
700	44.911	3480.8	3929.9	10.4056	8.9813	3480.6	3929.7	9.6626	4.4900	3480.4	3929.4	9.3424
800	49.527	3665.4	4160.6	10.6312	9.9047	3665.2	4160.4	9.8883	4.9519	3665.0	4160.2	9.5682
900	54.143	3856.9	4398.3	10.8429	10.8280	3856.8	4398.2	10.1000	5.4137	3856.7	4398.0	9.7800
1000	58.758	4055.3	4642.8	11.0429	11.7513	4055.2	4642.7	10.3000	5.8755	4055.0	4642.6	9.9800
1100	63.373	4260.0	4893.8	11.2326	12.6745	4259.9	4893.7	10.4897	6.3372	4259.8	4893.6	10.1698
1200	67.989	4470.9	5150.8	11.4132	13.5977	4470.8	5150.7	10.6704	6.7988	4470.7	5150.6	10.3504
1300	72.604	4687.4	5413.4	11.5857	14.5209	4687.3	5413.3	10.8429	7.2605	4687.2	5413.3	10.5229
$P = 0.20 \text{ MPa (120.21°C)}$					$P = 0.30 \text{ MPa (133.52°C)}$				$P = 0.40 \text{ MPa (143.61°C)}$			
Sat.	0.88578	2529.1	2706.3	7.1270	0.60582	2543.2	2724.9	6.9917	0.46242	2553.1	2738.1	6.8955
150	0.95986	2577.1	2769.1	7.2810	0.63402	2571.0	2761.2	7.0792	0.47088	2564.4	2752.8	6.9306
200	1.08049	2654.6	2870.7	7.5081	0.71643	2651.0	2865.9	7.3132	0.53434	2647.2	2860.9	7.1723
250	1.19890	2731.4	2971.2	7.7100	0.79645	2728.9	2967.9	7.5180	0.59520	2726.4	2964.5	7.3804
300	1.31623	2808.8	3072.1	7.8941	0.87535	2807.0	3069.6	7.7037	0.65489	2805.1	3067.1	7.5677
400	1.54934	2967.2	3277.0	8.2236	1.03155	2966.0	3275.5	8.0347	0.77265	2964.9	3273.9	7.9003

Example

Determine the temperature of water at a state of $P = 0.5 \text{ MPa}$ and $h = 2890 \text{ kJ/kg}$.

$$h > h_g$$

$P = 0.50 \text{ MPa (151.83}^\circ\text{C)}$				
Sat.	0.37483	2560.7	2748.1	6.8207
200	0.42503	2643.3	2855.8	7.0610
250	0.47443	2723.8	2961.0	7.2725
300	0.52261	2803.3	3064.6	7.4614
350	0.57015	2883.0	3168.1	7.6346
400	0.61731	2963.7	3272.4	7.7956
500	0.71095	3129.0	3484.5	8.0893



$$\frac{h_{250} - h_{200}}{250 - 200} = \frac{h_T - h_{200}}{T - 200}$$

$$200 < T < 250$$

$$T = 200 + \frac{h_T - h_{200}}{h_{250} - h_{200}} (250 - 200)$$

Linear interpolation: $T = 216.3^\circ\text{C}$

The compressed liquid properties depend on temperature much more strongly than they do on pressure.

$$y \cong y_f @ T \quad y = v, u, \text{ or } h$$

A more accurate relation for h

$$h \cong h_f @ T + v_{f@T} (P - P_{\text{sat}@T})$$

Given: P and T

$$v \cong v_f @ T$$

$$u \cong u_f @ T$$

$$h \cong h_f @ T$$

A compressed liquid may be approximated as a saturated liquid at the given temperature.

At a given P and T , a pure substance will exist as a compressed liquid if

$$T < T_{\text{sat}@P}$$

Compressed Liquid

Compressed liquid is characterized by

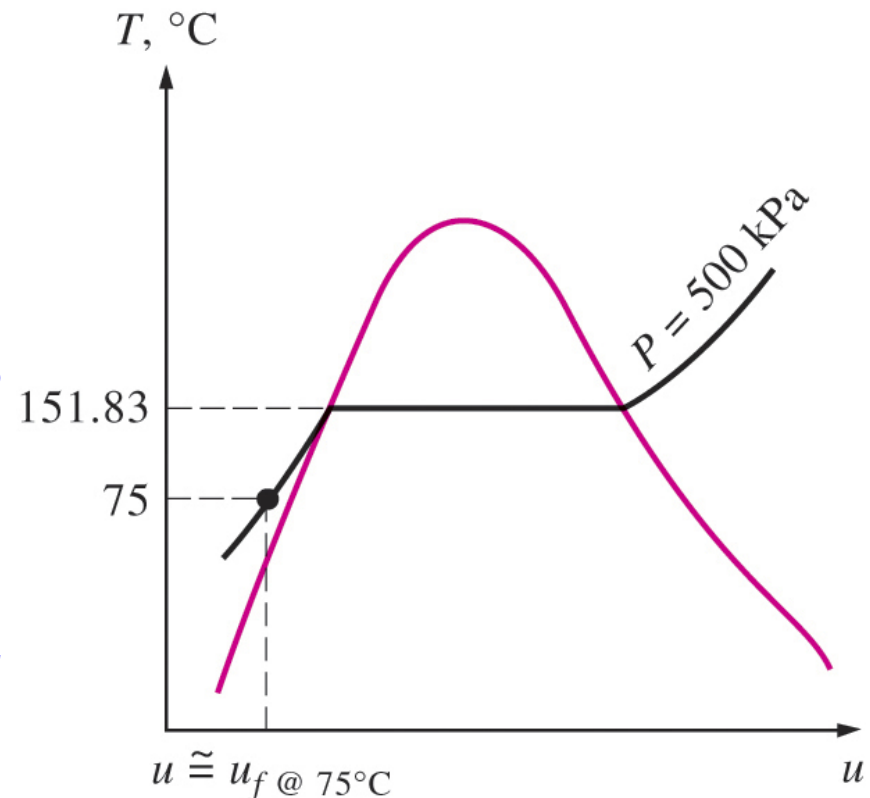
Higher pressures ($P > P_{\text{sat}}$ at a given T)

Lower temperatures ($T < T_{\text{sat}}$ at a given P)

Lower specific volumes ($v < v_f$ at a given P or T)

Lower internal energies ($u < u_f$ at a given P or T)

Lower enthalpies ($h < h_f$ at a given P or T)



Reference State and Reference Values

- The values of u , h , and s cannot be measured directly, and they are calculated from measurable properties using the relations between properties.
- However, those relations give the *changes* in properties, not the values of properties at specified states.
- Therefore, we need to choose a convenient *reference state* and assign a value of *zero* for a convenient property or properties at that state.
- The reference state for water is 0.01°C and for R-134a is -40°C in tables.
- Some properties may have negative values as a result of the reference state chosen.
- Sometimes different tables list different values for some properties at the same state as a result of using a different reference state.
- However, In thermodynamics we are concerned with the *changes* in properties, and the reference state chosen is of no consequence in calculations.

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0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

Saturated refrigerant-134a—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, $\text{kJ/kg} \cdot \text{K}$		
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-40	51.25	0.0007054	0.36081	-0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866

Next lecture

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