Chapter 6
Properties and Property Relations

6.1 State Properties and Their Relations

The thermodynamic laws contain many state properties, e.g. [SI units in brackets]

T	temperature $[\mathrm{K}]$
p	pressure $[\mathrm{kPa}]$
m	mass $[\mathrm{kg}]$
V	volume $[\mathrm{m}^3]$
$v = V/m$	specific volume $[\frac{\mathrm{m}^3}{\mathrm{kg}}]$
$\rho = \frac{1}{v}$	mass density $[\frac{\mathrm{kg}}{\mathrm{m}^3}]$
$\mathcal{V}$	velocity $[\frac{\mathrm{m}}{\mathrm{s}}]$
u	specific internal energy $[\frac{\mathrm{kJ}}{\mathrm{kg}}]$
$h = u + pv$	specific enthalpy $[\frac{\mathrm{kJ}}{\mathrm{kg}}]$
s	specific entropy $[\frac{\mathrm{kJ}}{\mathrm{kg\,K}}]$

However, only few properties $(T, p, m, V, \mathcal{V})$ can be measured directly, while many of the quantities that appear in the thermodynamic laws $(u, h, s, \ldots)$ cannot be measured directly.

Experience shows that state properties are not independent, but are related through property relations, which depend on the substance. By means of property relations, thermodynamic quantities $(u, h, s, \ldots)$ can be determined indirectly, through measurement of $(T, p, m, V, \mathcal{V})$.

Measurements show that for simple substances it is sufficient to know two properties to find all others. This implies property relations of the form

$p = p(T, v)$	thermal equation of state
$v = v(T, p)$	thermal equation of state
$u = u(T, v)$	caloric equation of state
$h = h(T, p)$	caloric equation of state
$s = s(T, p)$	entropy

H. Struchtrup, *Thermodynamics and Energy Conversion*,
DOI: 10.1007/978-3-662-43715-5_6,

and so on. The thermal and caloric equations of state, $p(T,v)$ and $u(T,v)$, must be determined in careful measurements, where the measurement of the latter relies on the first law. In most cases, the equations of state are not given as explicit equations, but in form of tables. The best known exception is the ideal gas law, $p = RT/v$.

Entropy must be determined from the thermal and caloric equations of state through integration of the Gibbs equation, which gives a differential relation between properties, and holds for *all* simple substances in the form

$$Tds = du + pdv \ , \tag{6.1}$$

or, with $h = u + pv$ and thus $dh = du + pdv + vdp$, in the alternative form

$$Tds = dh - vdp \ . \tag{6.2}$$

Property relations can be formulated between any set of three properties. For instance: Considering the entropy as function of temperature and pressure, $s(T,p)$, together with the thermal equation of state, $p(T,v)$, both can be combined to $s(T,p(T,v)) = s(T,v)$, that is entropy as function of temperature and volume. Inversion of the caloric equation of state $u(T,v)$ for temperature yields temperature as a function of energy and volume, $T(u,v)$. Considering the latter in the entropy expression $s(T,v)$ yields entropy as function of energy and volume, $s(u,v)$. Solving this relation for energy, yields energy as a function of entropy and volume, $u(s,v)$. And so on. These are just some examples of variable changes in property relations. A detailed analysis of property relations, where variable changes are used to identify deeper relations between properties can be found in Chapter 16, where it will be seen that the Gibbs equation substantially reduces the measurements necessary to produce thermodynamic tables.

6.2 Phases

Depending on the conditions, e.g., the values of pressure and temperature, a substance assumes different phases—solid, liquid, vapor—which can also coexist. We shall need property relations for all individual phases as well as for the coexisting states.

Atoms and molecules interact through interatomic potentials $\phi(r)$ of the form depicted in Fig. 6.1. For intermediate particle distances around d, the particles attract each other, while they repel each other when they are pushed very close together ($r < d$). For large distances ($r \gg d$), the particles do not notice each others presence ($\phi(r) \to 0$ for $r \to \infty$).

In a solid, the particles sit at fixed locations in the atomic compound, e.g., a crystal lattice, and oscillate around the minimum of the potential. The interatomic forces are strong, and keep the solid together.

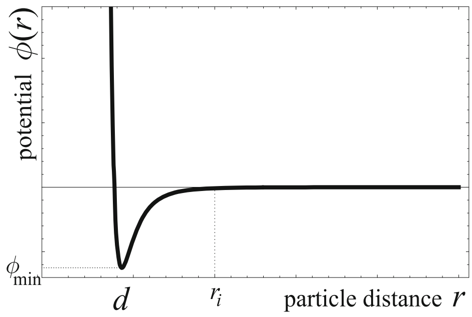

Fig. 6.1 Interparticle potential ϕ as function of interparticle distance r

When the temperature is increased, the oscillations become stronger, and the particles have enough energy to split the molecular bonds with their neighbors, while the attractive forces are still significant. The particles can move freely, but are densely packed with distances close to d. This is the liquid state.

At even higher temperatures the particle energies exceed the attractive potentials which cannot hold the particles together anymore. The particles move fast at greater average distances. This is the gaseous, or vapor, state.

In solid and liquid states, the particles are in permanent contact and interaction. While gas particles have a large average distance, they nevertheless interact through frequent collisions. The interaction between particles leads to microscopic exchange of energy and momentum which facilitates the macroscopic transfer of energy and momentum. The constant redistribution of momentum and energy between particles drives the system towards the equilibrium state.

6.3 Phase Changes

It is a daily experience that matter changes between phases: ice will melt, water will boil and evaporate, dew will condense out of moist air, and so on.

We study the evaporation of liquid water at constant pressure $p = 1\text{atm}$, as depicted in Fig. 6.2. Water is confined in a piston-cylinder system with a moving piston, the mass of the piston fixes the pressure in the system.

We go through the figure from left to right: At temperatures below 100 °C (and above 0 °C) only the liquid phase is found, we speak of *compressed liquid*. Isobaric heat supply increases the temperature of the compressed liquid. When the temperature reaches 100 °C, the water starts to evaporate. Further heat supply does not increase the temperature, which still is 100 °C, but leads to more evaporation. As evaporation occurs, liquid and vapor are in an equilibrium state where both phases coexist, the *saturated state*. The corresponding liquid and vapor states are denoted as *saturated liquid* and

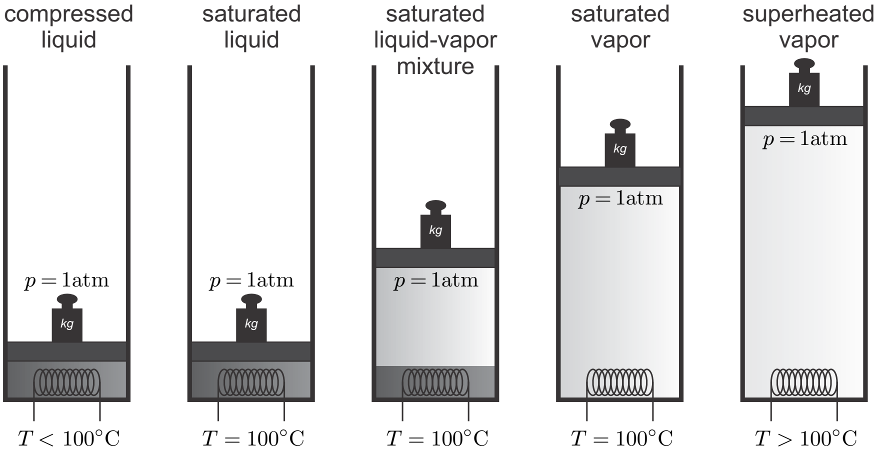

Fig. 6.2 Constant pressure evaporation of water at $p = 1$ atm

saturated vapor, respectively. Finally, when all liquid is evaporated, further heat supply increases the temperature of the vapor above 100 °C, we speak of *superheated vapor*.

When heat is withdrawn, the opposite process happens: the superheated vapor will cool down until it reaches 100 °C, then vapor will start to condense. After all vapor is condensed, the compressed liquid cools to lower temperatures.

The *saturation temperature* depends on pressure, we write $T_{\text{sat}}(p)$. The inversion gives the *saturation pressure*, denoted as $p_{\text{sat}}(T)$. In the example we have $T_{\text{sat}}(1\,\text{atm}) = 100\,°\text{C}$ and $p_{\text{sat}}(100\,°\text{C}) = 1\,\text{atm}$. Figure 6.3 shows a sketch of the saturation curve of water in the p-T-diagram. The curve begins in the *triple point* $(611\,\text{Pa}, 0.01\,°\text{C})$ and ends in the *critical point* (22.09 MPa, 374.14 °C).

For temperatures above the critical temperature, and for pressures above the critical pressure, a saturated liquid-vapor equilibrium is not possible. In the critical point all properties agree between vapor and liquid, and above the critical point only one phase exists, one speaks of *supercritical fluid*.

The triple point gives the lowest temperature/pressure at which a saturated liquid-vapor equilibrium is possible; only at this point all three phases, solid, liquid and vapor, can coexist.

Apart from the liquid-vapor phase change, i.e., evaporation and condensation, one observes the phase changes between solid and liquid, i.e., melting and freezing (solidification), and between solid and vapor, i.e., sublimation and deposition. For each, phase equilibrium is only possible for values of pressure and temperature T and pressure p on the corresponding *saturation curve*, $p_{\text{sat}}(T)$.

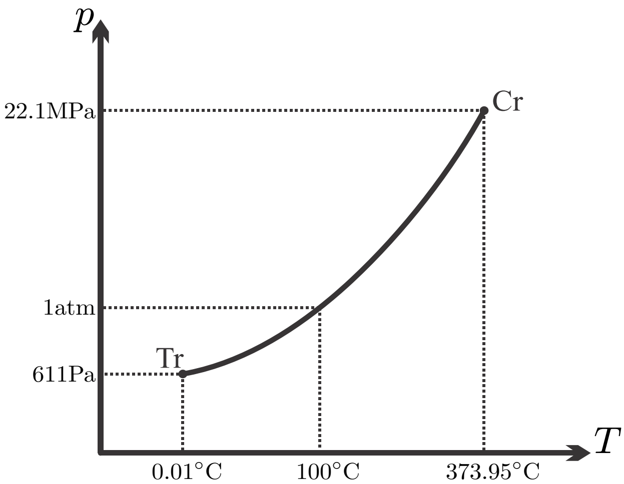

Fig. 6.3 Liquid-vapor saturation curve for water in the p-T-diagram with data for triple point (Tr), critical point (Cr), and the boiling point of water at standard pressure

Figure 6.4 shows the saturation curves for water as ice, liquid, and vapor in a p-T-diagram. Note the large number of different ice phases, which reflect different lattice configurations.[1] Phase equilibria (coexistence of two phases) are only possible on those curves which are given by the saturation pressure $p_{\text{sat}}(T)$ for the respective phase equilibrium, or, alternatively, by the saturation temperature $T_{\text{sat}}(p)$ which is the inverse function. All three phases can coexist in only one point, the triple point. Away from the saturation lines the substance will be in just one of the phases as indicated in the figure. An interesting information that can be drawn from the diagram is that no liquid water exists at temperatures below $-23\,°\text{C}$.

A particular feature of water is the negative slope of its melting curve which implies that ice will melt under pressure. This behavior is related to the volume change: A given amount of ice has a larger volume than the same amount of liquid water, as can be seen by ice swimming on water. Melting reduces the volume and thus counteracts the pressure increase. Melting under pressure might play a role in the flow of glaciers, but does not explain the slipperiness of ice, see Sec. 17.12.

Sublimation can be observed in winter, where snow evaporates, in particular on dry sunny days, without melting. An industrial application of

[1] Read about Kurt Vonnegut's fictitious *ice-nine* in his book *Cat's Cradle*. Fortunately, the real ice IX (not included in the diagram) has properties that differ from those fabled by Vonnegut. Everything you want to know about water (including full phase diagrams up to ice XV) can be found on Martin Chaplin's water site at http://www1.lsbu.ac.uk/water.

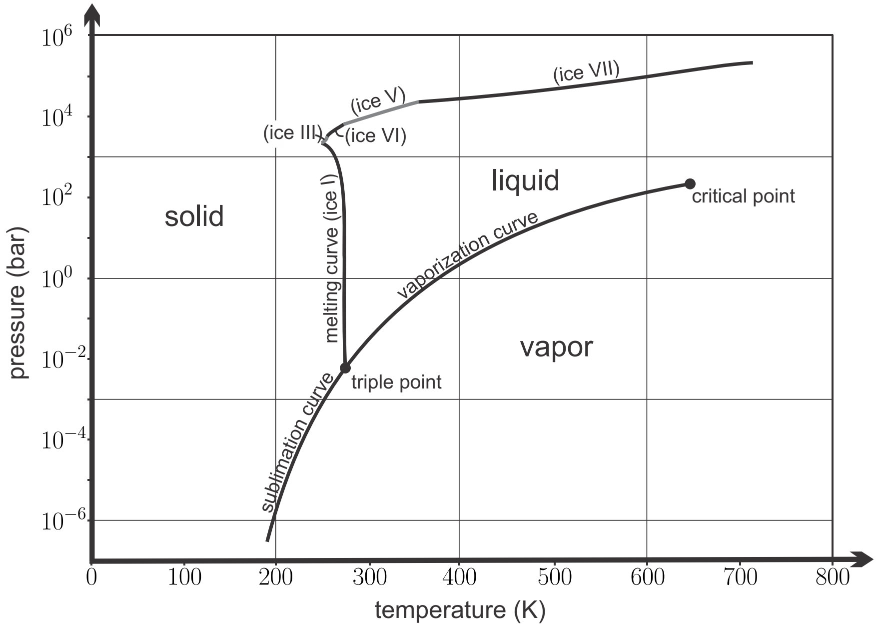

Fig. 6.4 Phase diagram of water (after chart from http://www.chemicalogic.com). Note that the pressure axis is logarithmic.

sublimation is the process of freeze-drying which is used to produce instant coffee: coffee is frozen at a temperature T_C, and then subjected to a pressure p_C below the sublimation pressure, $p_C < p_{\rm sub}(T_C)$; this forces direct evaporation of ice.

Saturation curves for other substances show the same principal characteristics as those for water, in particular the existence of critical and triple points. However, for almost all other substances the solid has a smaller volume than the liquid, and the solid-liquid line has a positive slope. Figure 6.5 shows p-T-diagrams with the saturation lines for sublimation, melting and vaporization, and indication of the solid, liquid, and vapor regions. For supercritical fluid there is no distinction between liquid and vapor.

Phase changes are related to volume changes. For most substances the volume of the liquid is larger than that of the solid (see the left Fig. 6.5), with water being an exception (see the right Fig. 6.5). Other substances that exhibit expansion on freezing are silicon, gallium and bismuth. Vapor volume is always larger than liquid volume at the same pressure. The volume differences do not become apparent in the p-T-diagram, where the saturated states appear as lines, but in the pressure-volume diagram (p-v-diagram). For a substance that contracts on freezing, such a diagram is sketched in Fig. 6.6. Saturated state lines in the diagram are indicated. There are two lines for saturated liquid, one describes phase equilibrium with saturated vapor, the

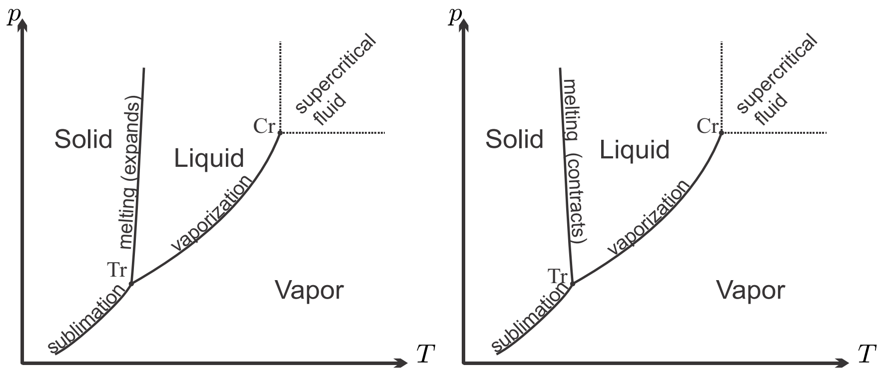

Fig. 6.5 Saturation lines and phases in the p-T-diagram. Left: Ordinary substance, which expands on melting. Right: Water, which contracts on melting.

other phase equilibrium with saturated solid. In the two-phase regions (solid + liquid, liquid + vapor, solid + vapor) one observes mixtures of saturated states, as discussed in the next section. On the triple line, one observes mixtures of all three phases, solid (volume v_s^{tr}), liquid (v_l^{tr}) and vapor (v_v^{tr}) where all three phases are at triple point pressure and temperature, p_{tr}, T_{tr}.

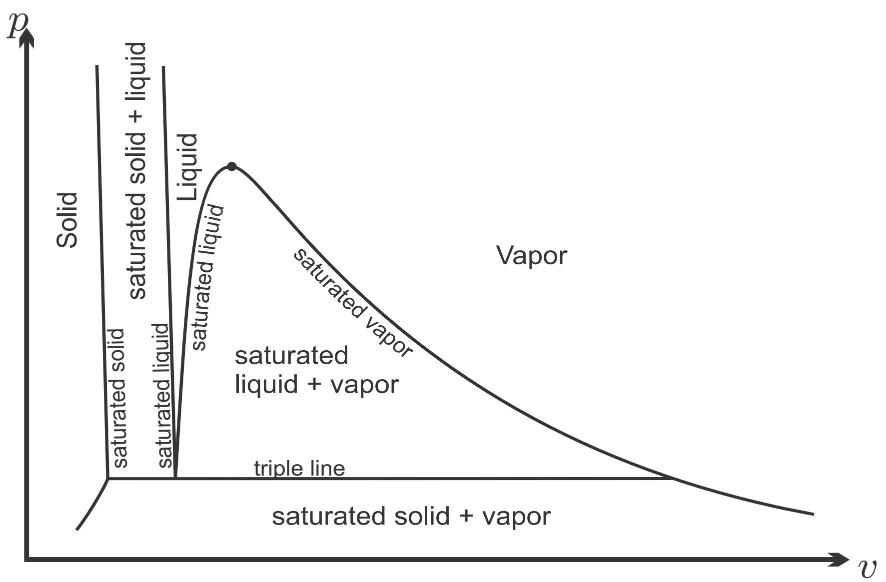

Fig. 6.6 p-v-diagram for an ordinary substance

We could also plot a T-v-diagram, but instead we show, in Fig. 6.7, the p-v-T-surface of an ordinary substance (contracts on freezing). The p-T-, p-v-, and T-v-diagrams are just the appropriate projections of the surface.

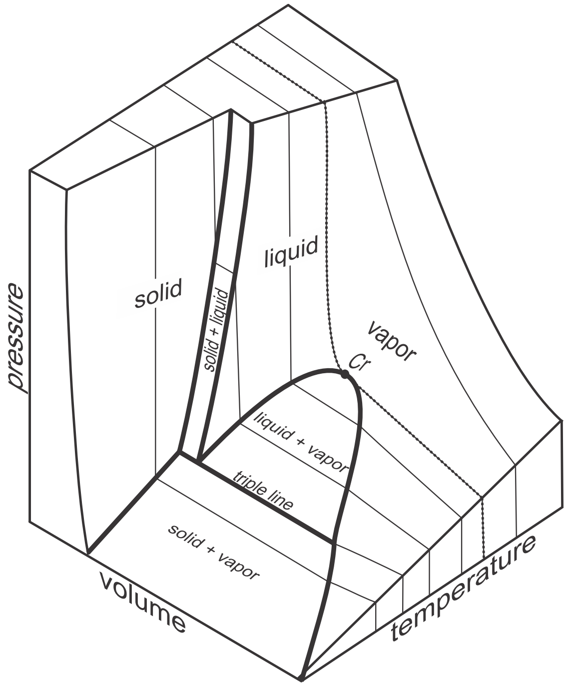

Fig. 6.7 p-v-T-surface of an ordinary substance

6.4 p-v- and T-s-Diagrams

An indispensable tool for thermodynamic analysis are plots of processes in suitable diagrams. The diagrams most often used are the p-v- and the T-s-diagram. For most processes only liquid and vapor or gas phases are encountered, and thus one uses diagrams that only show liquid and vapor states, and the corresponding two-phase region.

Figure 6.8 shows both diagrams including saturation lines and critical point. Isothermal lines (constant temperature) are sketched in the p-v-diagram, and isobaric lines (constant pressure) are sketched in the T-s-diagram. Note that both are horizontal in the two-phase region, where pressure and temperature are related through the saturation equation $p = p_{\mathrm{sat}}(T)$. Obviously, in the p-v-diagram constant pressure lines are horizontal, and constant volume lines are vertical; in the T-s-diagram constant temperature lines are horizontal, and constant entropy lines are vertical.

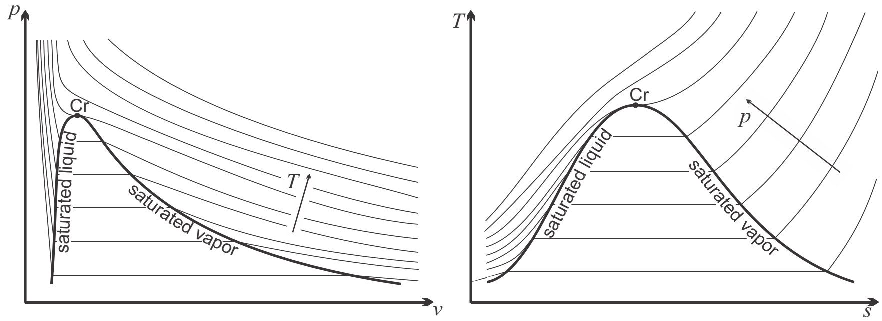

Fig. 6.8 p-v-diagram with two-phase region and isothermal lines (left), and T-s-diagram with two-phase region and isobaric lines (right)

6.5 Saturated Liquid-Vapor Mixtures

For technical applications the most important phase change is that between liquid and vapor; it is, e.g., employed in steam power plants and vapor refrigeration systems. We describe the properties of liquid-vapor mix in detail. Other phase equilibria, e.g., liquid-solid equilibrium, can be treated along the same lines.

We consider a mass m of a substance at temperature T and saturation pressure $p_{\rm sat}(T)$ in liquid-vapor equilibrium. In phase equilibrium, saturated liquid and vapor can either be separated, with the liquid on the bottom of the container, or they can be mixed, with the liquid dispersed as droplets in the vapor, see Fig. 6.9. The mass of substance in the liquid phase is m_f, and the mass of substance in the vapor phase is m_g, where $m_f + m_g = m$. The use of the indices f (for *fluid*) and and g (for *gaseous*) stems from a time when the word *fluid* was synonymous with *liquid*, while the word today includes gaseous states as well.

The specific volumes of the saturated liquid and vapor are $v_f(T)$ and $v_g(T)$, respectively,[2] and thus the total volume of the saturated mixture is

$$V = m_f v_f + m_g v_g \ . \tag{6.3}$$

The specific volume of the mixture is obtained by division with the total mass,

$$v = \frac{V}{m} = \frac{m_f}{m} v_f + \frac{m_g}{m} v_g = (1 - x)\, v_f + x v_g \ . \tag{6.4}$$

Here, we have introduced

[2] Normally, specific volume is a function of temperature and pressure, $v(T, p)$. For saturated states, however, the pressure is the saturation pressure $p_{\rm sat}(T)$ which is a function of temperature. Therefore the specific volume of a saturated state is a function only of temperature. The same holds for other specific quantities (energy, enthalpy, entropy).

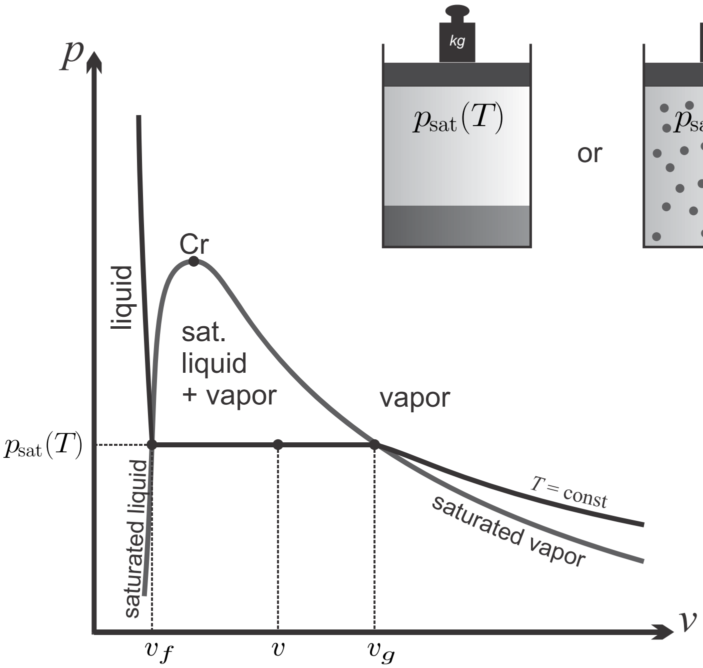

Fig. 6.9 Saturated state in p-v-diagram. The liquid might collect on the container bottom, or might be dispersed as droplets.

$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g} \tag{6.5}$$

as the *quality* of the saturated liquid-vapor mixture, defined as the relative mass of saturated vapor. Note that $\frac{m_f}{m} = \frac{m-m_g}{m} = 1 - x$.

Other extensive quantities, e.g., internal energy U, enthalpy H, or entropy S, are computed from the specific properties of the saturated liquid and vapor states just like volume. The specific energy, enthalpy, entropy of the saturated liquid are denoted as $u_f(T)$, $h_f(T)$, $s_f(T)$, and those of the saturated vapor as $u_g(T)$, $h_g(T)$, $s_g(T)$. Total energy, enthalpy, entropy of the mixture are

$$\begin{aligned} U &= m_f u_f + m_g u_g \ , \\ H &= m_f h_f + m_g h_g \ , \\ S &= m_f s_f + m_g s_g \ . \end{aligned} \tag{6.6}$$

The corresponding specific properties, $u = U/m$ etc., are weighted averages,

$$\begin{aligned} v &= (1-x)\, v_f + x v_g \ , \\ u &= (1-x)\, u_f + x u_g = u_f + x u_{fg} \ , \\ h &= (1-x)\, h_f + x h_g = h_f + x h_{fg} \ , \\ s &= (1-x)\, s_f + x s_g = s_f + x s_{fg} \ . \end{aligned} \tag{6.7}$$

Here,

$$u_{fg} = u_g - u_f, \ \ h_{fg} = h_g - h_f, \ \ s_{fg} = s_g - s_f \tag{6.8}$$

are the energy of vaporization, the enthalpy of vaporization, and the entropy of vaporization. For the quality the above implies the identities

$$x = \frac{m_g}{m_f + m_g} = \frac{v - v_f}{v_g - v_f} = \frac{u - u_f}{u_{fg}} = \frac{h - h_f}{h_{fg}} = \frac{s - s_f}{s_{fg}} \ . \tag{6.9}$$

Property data for saturated states are listed in tables, either ordered by temperature (“temperature table”, with $p = p_{sat}(T)$) or by pressure (“pressure table”, with $T = T_{sat}(p)$). Figure 6.10 shows an excerpt of a temperature table and Fig. 6.11 shows an excerpt of a pressure table, both for water. Saturation tables for other substances are widely available.

Property data for internal energy and enthalpy is determined from experiments by evaluating the first law, which only allows to determine energy or enthalpy *differences*. Therefore, in designing a property table, one has the freedom to choose the value of a reference energy. For the tables shown, the internal energy of the saturated liquid at the triple point was chosen as $u_f(T_{Tr}) = 0$. All other energy and enthalpy values refer to this choice. Entropy is determined from integration of the Gibbs equation, and one has a choice of an integrating constant, which was chosen here such that, $s_f(T_{Tr}) = 0$. Often, the reference value used in tables is determined from the third law (Sec. 23.6).

Care has to be taken when one uses data from different tables, since these might rely on different choices for the energy and entropy references, which will lead to errors, if not properly corrected.

6.6 Identifying States

Quality can only have values between 0 and 1. If one finds values outside this range, one either has compressed liquid, or superheated vapor.

A state of given temperature T for which another property (v or u or h or s) is known, is compressed liquid for

$$v < v_f(T) \ \text{ or } \ u < u_f(T) \ \text{ or } \ h < h_f(T) \ \text{ or } \ s < s_f(T) \ ,$$

and it is superheated vapor if

$$v > v_g(T) \ \text{ or } \ u > u_g(T) \ \text{ or } \ h > h_g(T) \ \text{ or } \ s > s_g(T) \ .$$

Liquid-vapor saturation states of water, temperature table

T deg-C	psat kPa	vf m3/kg	vg m3/kg	uf kJ/kg	ug kJ/kg	hf kJ/kg	hfg kJ/kg	hg kJ/kg	sf kJ/kgK	sfg kJ/kgK	sg kJ/kgK
0.01	0.6113	0.001000	206.14	0.00	2375.3	0.00	2501.4	2501.4	0.0000	9.1562	9.1562
10	1.2276	0.001000	106.38	42.00	2389.2	42.01	2477.8	2519.8	0.1510	8.7498	8.9008
20	2.339	0.001002	57.79	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.3706	8.6672
30	4.246	0.001004	32.89	125.78	2416.6	125.79	2430.5	2556.3	0.4369	8.0164	8.4533
40	7.384	0.001008	19.52	167.56	2430.1	167.57	2406.7	2574.3	0.5725	7.6845	8.2570
50	12.35	0.001012	12.03	209.32	2443.5	209.33	2382.8	2592.1	0.7038	7.3725	8.0763
60	19.94	0.001017	7.671	251.11	2456.6	251.13	2358.5	2609.6	0.8312	7.0784	7.9096
70	31.19	0.001023	5.042	292.95	2469.6	292.98	2333.8	2626.8	0.9549	6.8004	7.7553
80	47.39	0.001029	3.407	334.86	2482.2	334.91	2300.4	2635.3	1.0753	6.5369	7.6122
90	70.14	0.001036	2.361	376.85	2494.5	376.92	2283.2	2660.1	1.1925	6.2866	7.4791
	MPa										
100	0.10135	0.001044	1.6729	418.94	2506.5	419.04	2257.1	2676.1	1.3069	6.0480	7.3549
110	0.14327	0.001052	1.2102	461.14	2518.1	461.30	2230.2	2691.5	1.4185	5.8202	7.2387
120	0.19853	0.001060	0.89190	503.50	2529.3	503.71	2202.6	2706.3	1.5276	5.6020	7.1296
130	0.2701	0.001070	0.66850	546.02	2539.9	546.31	2174.2	2720.5	1.6344	5.3925	7.0269
140	0.3613	0.001080	0.50890	588.74	2550.0	589.13	2144.8	2733.9	1.7391	5.1908	6.9299
150	0.4758	0.001091	0.39280	631.68	2559.5	632.20	2114.3	2746.5	1.8418	4.9961	6.8379
160	0.6178	0.001102	0.30710	674.87	2568.4	675.55	2082.6	2758.1	1.9427	4.8075	6.7502
170	0.7917	0.001114	0.24280	718.33	2576.5	719.21	2049.5	2768.7	2.0419	4.6244	6.6663
180	1.0021	0.001127	0.19405	762.09	2583.7	763.22	2015.0	2778.2	2.1396	4.4461	6.5857
190	1.2544	0.001141	0.15654	806.19	2590.0	807.62	1978.8	2786.4	2.2359	4.2720	6.5079
200	1.5538	0.001157	0.12736	850.65	2595.3	852.45	1940.8	2793.2	2.3309	4.1014	6.4323
210	1.9062	0.001173	0.10441	895.53	2599.5	897.76	1900.7	2798.5	2.4248	3.9337	6.3585
220	2.318	0.001190	0.08619	940.87	2602.4	943.62	1858.5	2802.1	2.5178	3.7683	6.2861
230	2.795	0.001209	0.07158	986.74	2603.9	990.12	1813.9	2804.0	2.6099	3.6047	6.2146
240	3.344	0.001229	0.05976	1033.21	2604.0	1037.32	1766.5	2803.8	2.7015	3.4422	6.1437
250	3.973	0.001251	0.05013	1080.39	2602.4	1085.36	1716.1	2801.5	2.7927	3.2803	6.0730
260	4.688	0.001276	0.04221	1128.39	2599.0	1134.37	1662.5	2796.9	2.8838	3.1181	6.0019
270	5.499	0.001302	0.03564	1177.36	2593.7	1184.51	1605.2	2789.7	2.9751	2.9550	5.9301
280	6.412	0.001332	0.03017	1227.46	2586.1	1235.99	1543.6	2779.6	3.0668	2.7903	5.8571
290	7.436	0.001366	0.02557	1278.92	2576.0	1289.07	1477.1	2766.2	3.1594	2.6227	5.7821
300	8.581	0.001404	0.02167	1332.0	2563.0	1344.0	1405.0	2749.0	3.2534	2.4511	5.7045
310	9.856	0.001447	0.018350	1387.1	2546.4	1401.3	1326.0	2727.3	3.3493	2.2737	5.6230
320	11.27	0.001499	0.015488	1444.6	2525.5	1461.5	1238.6	2700.1	3.4480	2.0882	5.5362
330	12.85	0.001561	0.012996	1505.3	2498.9	1525.3	1140.6	2665.9	3.5507	1.8910	5.4417
340	14.59	0.001638	0.010797	1570.3	2464.6	1594.2	1027.8	2622.0	3.6594	1.6763	5.3357
350	16.51	0.001740	0.008813	1641.9	2418.4	1670.6	893.3	2563.9	3.7777	1.4335	5.2112
360	18.65	0.001893	0.006945	1725.2	2351.5	1760.5	720.5	2481.0	3.9147	1.1379	5.0526
370	21.03	0.002213	0.004925	1844.0	2228.5	1890.5	441.6	2332.1	4.1106	0.6865	4.7971
374.14	22.09	0.003155	0.003155	2029.6	2029.6	2099.3	0.0	2099.3	4.4298	0.0000	4.4298

source: http://www.thermofluids.net/

Fig. 6.10 Saturation table for water (temperature table)

A state of given pressure p for which another property (v or u or h or s) is known, is compressed liquid for

$$v < v_f\,(p) \quad \text{or} \quad u < u_f\,(p) \quad \text{or} \quad h < h_f\,(p) \quad \text{or} \quad s < s_f\,(p) \ ,$$

and it is superheated vapor if

$$v > v_g\,(p) \quad \text{or} \quad u > u_g\,(p) \quad \text{or} \quad h > h_g\,(p) \quad \text{or} \quad s > s_g\,(p) \ .$$

A state of given pressure p and temperature T is compressed liquid for

$$T < T_{\rm sat}\,(p) \quad \text{or} \quad p > p_{\rm sat}\,(T) \ ,$$

Liquid-vapor saturation states of water, pressure table

p	Tsat	vf	vg	uf	ug	hf	hfg	hg	sf	sfg	sg
kPa	deg-C	m3/kg	m3/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kgK	kJ/kgK	kJ/kgK
0.6113	0.01	0.001000	206.14	0.00	2375.3	0.00	2501.4	2501.4	0.0000	9.1562	9.1562
1	6.98	0.001000	129.21	29.30	2385.0	29.30	2484.9	2514.2	0.1059	8.8697	8.9756
2	17.50	0.001001	67.00	73.48	2399.5	73.48	2460.0	2533.5	0.2607	8.4630	8.7237
3	24.08	0.001003	45.67	101.04	2408.5	101.05	2444.5	2545.5	0.3545	8.2231	8.5776
5	32.88	0.001005	28.19	137.81	2420.5	137.82	2423.7	2561.5	0.4764	7.9187	8.3951
7.5	40.29	0.001008	19.24	168.78	2430.5	168.79	2406.0	2574.8	0.5764	7.6751	8.2515
10	45.81	0.001010	14.67	191.82	2437.9	191.83	2392.9	2584.7	0.6493	7.5009	8.1502
20	60.06	0.001017	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.0765	7.9085
30	69.10	0.001022	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	6.8247	7.7686
50	81.33	0.001030	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	6.5029	7.5939
75	91.78	0.001037	2.217	384.31	2496.7	384.39	2278.6	2663.0	1.2130	6.2434	7.4564
MPa											
0.100	99.63	0.001043	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.150	111.37	0.001053	1.1593	466.94	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.200	120.23	0.001061	0.8857	504.49	2529.5	504.70	2202.0	2706.7	1.5301	5.5970	7.1271
0.250	127.44	0.001067	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	5.4455	7.0527
0.300	133.55	0.001073	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	5.3201	6.9919
0.350	138.88	0.001079	0.5243	583.95	2548.9	584.33	2148.1	2732.4	1.7275	5.2130	6.9405
0.400	143.63	0.001084	0.4625	604.31	2553.6	604.74	2133.9	2738.6	1.7766	5.1193	6.8959
0.500	151.86	0.001093	0.3749	639.68	2561.2	640.23	2108.5	2748.7	1.8607	4.9606	6.8213
0.600	158.85	0.001101	0.3157	669.90	2567.4	670.56	2086.2	2756.8	1.9312	4.8288	6.7600
0.700	164.97	0.001108	0.2729	696.44	2572.5	697.22	2066.3	2763.5	1.9922	4.7158	6.7080
0.800	170.43	0.001115	0.2404	720.22	2576.8	721.11	2048.0	2769.1	2.0462	4.6166	6.6628
0.900	175.38	0.001121	0.2150	741.83	2580.5	742.83	2031.1	2773.9	2.0946	4.5280	6.6226
1.0	179.91	0.001127	0.19444	761.68	2583.6	762.81	2015.3	2778.1	2.1387	4.4478	6.5865
1.5	198.32	0.001154	0.13177	843.16	2594.5	844.89	1947.3	2792.2	2.3150	4.1298	6.4448
2.0	212.42	0.001177	0.09963	906.44	2600.3	908.79	1890.7	2799.5	2.4474	3.8935	6.3409
3.0	233.90	0.001217	0.06668	1004.78	2604.1	1008.42	1795.8	2804.2	2.6457	3.5412	6.1869
3.5	242.60	0.001235	0.05707	1045.43	2603.7	1049.75	1753.7	2803.4	2.7253	3.4000	6.1253
4.0	250.40	0.001252	0.04978	1082.31	2602.3	1087.31	1714.1	2801.4	2.7964	3.2737	6.0701
6.0	275.64	0.001319	0.03244	1205.44	2589.7	1213.35	1571.0	2784.3	3.0267	2.8625	5.8892
8.0	295.06	0.001384	0.02352	1305.57	2569.8	1316.64	1441.4	2758.0	3.2068	2.5364	5.7432
10	311.06	0.001452	0.018026	1393.04	2544.4	1407.56	1317.1	2724.7	3.3596	2.2545	5.6141
12	324.75	0.001527	0.014263	1473.0	2513.7	1491.3	1193.6	2684.9	3.4962	1.9962	5.4924
14	336.75	0.001611	0.011485	1548.6	2476.8	1571.1	1066.5	2637.6	3.6232	1.7485	5.3717
16	347.44	0.001711	0.009306	1622.7	2431.7	1650.1	930.5	2580.6	3.7461	1.4994	5.2455
18	357.06	0.001840	0.007489	1698.9	2374.3	1732.0	777.1	2509.1	3.8715	1.2329	5.1044
20	365.81	0.002036	0.005834	1785.6	2293.0	1826.3	583.4	2409.7	4.0139	0.9130	4.9269
22.09	374.14	0.003155	0.003155	2029.6	2029.6	2099.3	0.0	2099.3	4.4298	0.0000	4.4298

source: http://www.thermofluids.net/

Fig. 6.11 Saturation table for water (pressure table)

and it is superheated vapor if

$$T > T_{\text{sat}}(p) \quad \text{or} \quad p < p_{\text{sat}}(T) \ .$$

It is a useful exercise to verify the above conditions by means of p-v-, T-s-, and p-T-diagrams!

6.7 Example: Condensation of Saturated Steam

As an example we consider the isochoric (constant volume) condensation of saturated steam from an initial temperature of $T_1 = 280\,°\text{C}$ to $T_2 = 200\,°\text{C}$. In the initial state, the properties are just at the saturation values, which can be read from Fig. 6.10 as

$$p_1 = p_{\text{sat}}(T_1) = 64.12\,\text{bar}\,,\quad v_1 = v_g(T_1) = 0.03017\frac{\text{m}^3}{\text{kg}}\,,$$
$$u_1 = u_g(T_1) = 2586.1\frac{\text{kJ}}{\text{kg}}\,,\quad h_1 = h_g(T_1) = 2779.6\frac{\text{kJ}}{\text{kg}}\,,$$
$$s_1 = s_g(T_1) = 5.8571\frac{\text{kJ}}{\text{kg}\,\text{K}}\,.$$

The values of two properties—two bits of information—are required to fix a state. In state 1 these are the temperature and the knowledge that the steam is saturated. For state 2, we know its temperature T_2, and its volume, which is unchanged, $v_2 = v_1$. To learn more about the final state, it is best to draw the process into a p-v-diagram. As shown in Fig. 6.12, the isochoric process to lower temperature is a vertical line downwards from the saturated vapor curve, and the final state 2 lies in the two-phase region between the saturation lines. Hence, this state is a mixture of saturated liquid at volume $v_f(T_2)$, and saturated vapor at volume $v_g(T_2)$, which we find from the table as $v_f(T_2) = 0.001157\frac{\text{m}^3}{\text{kg}}$ and $v_g(T_2) = 0.12736\frac{\text{m}^3}{\text{kg}}$.

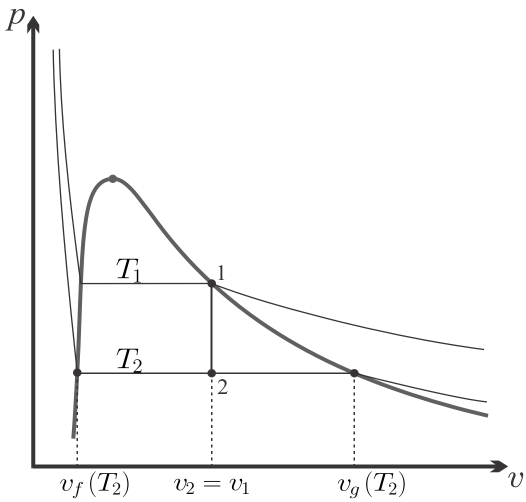

Fig. 6.12 Isochoric cooling of saturated vapor between T_1 and T_2 in the p-v-diagram. The final state 2 is in the two-phase region (mixture of saturated liquid and saturated vapor).

Since $v_2 = v_1 = v_g(T_1)$, the quality of the final state is

$$x_2 = \frac{v_2 - v_f(T_2)}{v_g(T_2) - v_f(T_2)} = \frac{0.03017 - 0.001157}{0.12736 - 0.001157} = 0.23\,.$$

With this value for quality we find the properties at the end point as

$$
\begin{aligned}
p_2 &= p_{\text{sat}}(T_2) = 15.54\,\text{bar}\,, \\
v_2 &= v_1 = 0.03017\frac{\text{m}^3}{\text{kg}}\,, \\
u_2 &= u_f(T_2) + x_2 u_{fg}(T_2) = 1251.7\frac{\text{kJ}}{\text{kg}}\,, \\
h_2 &= h_f(T_2) + x_2 h_{fg}(T_2) = 1298.6\frac{\text{kJ}}{\text{kg}}\,, \\
s_2 &= s_f(T_2) + x_2 s_{fg}(T_2) = 3.274\frac{\text{kJ}}{\text{kg}\,\text{K}}\,.
\end{aligned}
$$

The values for $u_f(T_2), u_{fg}(T_2)$ etc. are taken from the table. The verification of the above results is left to the reader.

We recall that quality *must* have values between 0 and 1. If one computes a quality outside this range, the corresponding state is *not* a saturated state, but either compressed liquid or superheated vapor, for which the property data must be found in the appropriate tables.

6.8 Superheated Vapor

For superheated vapors the equations of state depend on two properties, and are normally laid down in extensive tables, or in computer software. Figure 6.13 shows an excerpt of a table with data for water vapor at some pressures between 10 kPa and 20 MPa.

As an example we consider the adiabatic reversible compression of saturated vapor at $T_1 = 100\,°\text{C}$ to a pressure $p_2 = 3\,\text{MPa}$. From the second law for reversible processes, $\delta q = T ds$ follows that such a process is isentropic (constant entropy), and thus it is a natural choice to draw the process curve in a T-s-diagram as depicted in Fig. 6.14. Clearly, the final state 2 is outside the two phase region, to the right, which means the final state is superheated vapor. The properties of state 1 can be read from the saturation table in Fig. 6.10 as

$$
\begin{aligned}
p_1 &= p_{\text{sat}}(T_1) = 1.014\,\text{bar}\,, \\
v_1 &= v_g(T_1) = 1.673\frac{\text{m}^3}{\text{kg}}\,, \\
u_1 &= u_g(T_1) = 2506.5\frac{\text{kJ}}{\text{kg}}\,, \\
h_1 &= h_g(T_1) = 2676.1\frac{\text{kJ}}{\text{kg}}\,, \\
s_1 &= s_g(T_1) = 7.3549\frac{\text{kJ}}{\text{kg}\,\text{K}}\,.
\end{aligned}
$$

superheated water vapor

deg-C	m3/kg	kJ/kg	kJ/kg	kJ/kg K	m3/kg	kJ/kg	kJ/kg	kJ/kg K	m3/kg	kJ/kg	kJ/kg	kJ/kg K
	p = 0.01 MPa (45.81 °C)				p = 0.10 MPa (99.63 °C)				p = 1.00 MPa (179.91 °C)			
T	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	14.674	2437.9	2584.7	8.1502	1.694	2506.1	2675.5	7.3594	0.19444	2583.6	2778.1	6.5865
50	14.869	2443.9	2592.6	8.1749								
100	17.196	2515.5	2687.5	8.4479	1.696	2506.7	2676.2	7.3614				
150	19.512	2587.9	2783.0	8.6882	1.936	2582.8	2776.4	7.6143				
200	21.825	2661.3	2879.5	8.9038	2.172	2658.1	2875.3	7.8343	0.2060	2621.9	2827.9	6.6940
250	24.136	2736.0	2977.3	9.1002	2.406	2733.7	2974.3	8.0333	0.2327	2709.9	2942.6	6.9247
300	26.445	2812.1	3076.5	9.2813	2.639	2810.4	3074.3	8.2158	0.2579	2793.2	3051.2	7.1229
400	31.063	2968.9	3279.6	9.6077	3.103	2967.9	3278.2	8.5435	0.3066	2957.3	3263.9	7.4651
500	35.679	3132.3	3489.1	9.8978	3.565	3131.6	3488.1	8.8342	0.3541	3124.4	3478.5	7.7622
600	40.295	3302.5	3705.4	10.1608	4.028	3301.9	3704.4	9.0976	0.4011	3296.8	3697.9	8.0290
700	44.911	3479.6	3928.7	10.4028	4.490	3479.2	3928.2	9.3398	0.4478	3475.3	3923.1	8.2731
800	49.526	3663.8	4159.0	10.6281	4.952	3663.5	4158.6	9.5652	0.4943	3660.4	4154.7	8.4996
900	54.141	3855.0	4396.4	10.8396	5.414	3854.8	4396.1	9.7767	0.5407	3852.2	4392.9	8.7118
1000	58.757	4053.0	4640.6	11.0393	5.875	4052.8	4640.3	9.9764	0.5871	4050.5	4637.6	8.9119
1100	63.372	4257.5	4891.2	11.2287	6.337	4257.3	4891.0	10.1659	0.6335	4255.1	4888.6	9.1017
1200	67.987	4467.9	5147.8	11.4091	6.799	4467.7	5147.6	10.3463	0.6798	4465.6	5145.4	9.2822
1300	72.602	4683.7	5409.7	11.5811	7.260	4683.5	5409.5	10.5183	0.7261	4681.3	5407.4	9.4543

	p = 2.00 MPa (212.42 °C)				p = 3.00 MPa (233.90 °C)				p = 5.0 MPa (263.99 °C)			
T	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	0.09963	2600.3	2799.5	6.3409	0.06668	2604.1	2804.2	6.1869	0.03944	2597.1	2794.3	5.9734
225	0.10377	2628.3	2835.8	6.4147								
250	0.11144	2679.6	2902.5	6.5453	0.07058	2644.0	2855.8	6.2872				
300	0.12547	2772.6	3023.5	6.7664	0.08114	2750.1	2993.5	6.5390	0.04532	2698.0	2924.5	6.2084
350	0.13857	2859.8	3137.0	6.9563	0.09053	2843.7	3115.3	6.7428	0.05194	2808.7	3068.4	6.4493
400	0.15120	2945.2	3247.6	7.1271	0.09936	2932.8	3230.9	6.9212	0.05781	2906.6	3195.7	6.6459
500	0.17568	3116.2	3467.6	7.4317	0.11619	3108.0	3456.5	7.2338	0.06857	3091.0	3433.8	6.9759
600	0.19960	3290.9	3690.1	7.7024	0.13243	3285.0	3682.3	7.5085	0.07869	3273.0	3666.5	7.2589
700	0.2232	3470.9	3917.4	7.9487	0.14838	3466.5	3911.7	7.7571	0.08849	3457.6	3900.1	7.5122
800	0.2467	3657.0	4150.3	8.1765	0.16414	3653.5	4145.9	7.9862	0.09811	3646.6	4137.1	7.7440
900	0.2700	3849.3	4389.4	8.3895	0.17980	3846.5	4385.9	8.1999	0.10762	3840.7	4378.8	7.9593
1000	0.2933	4048.0	4634.6	8.5901	0.19541	4045.4	4631.6	8.4009	0.11707	4040.4	4625.7	8.1612
1100	0.3166	4252.7	4885.9	8.7800	0.21098	4250.3	4883.3	8.5912	0.12648	4245.6	4878.0	8.3520
1200	0.3398	4463.3	5142.9	8.9607	0.22652	4460.9	5140.5	8.7720	0.13587	4456.3	5135.7	8.5331
1300	0.3631	4679.0	5405.1	9.1329	0.24206	4676.6	5402.8	8.9442	0.14526	4672.0	5398.2	8.7055

	p = 8.0 MPa (295.06 °C)				p = 12.5 MPa (327.89 °C)				p = 20.0 MPa (365.81 °C)			
T	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	0.02352	2569.8	2758.0	5.7432	0.013495	2505.1	2673.8	5.4624	0.005834	2293.0	2409.7	4.9269
300	0.02426	2590.9	2785.0	5.7906								
350	0.02995	2747.7	2987.3	6.1301	0.016126	2624.6	2826.2	5.7118				
400	0.03432	2863.8	3138.3	6.3634	0.02000	2789.3	3039.3	6.0417	0.009942	2619.3	2818.1	5.5540
450	0.03817	2966.7	3272.0	6.5551	0.02299	2912.5	3199.8	6.2719	0.012695	2806.2	3060.1	5.9017
500	0.04175	3064.3	3398.3	6.7240	0.02560	3021.7	3341.8	6.4618	0.014768	2942.9	3238.2	6.1401
550	0.04516	3159.8	3521.0	6.8778	0.02801	3125.0	3475.2	6.6290	0.016555	3062.4	3393.5	6.3348
600	0.04845	3254.4	3642.0	7.0206	0.03029	3225.4	3604.0	6.7810	0.018178	3174.0	3537.6	6.5048
700	0.05481	3443.9	3882.4	7.2812	0.03460	3422.9	3855.3	7.0536	0.02113	3386.4	3809.0	6.7993
800	0.06097	3636.0	4123.8	7.5173	0.03869	3620.0	4103.6	7.2965	0.02385	3592.7	4069.7	7.0544
900	0.06702	3832.1	4368.3	7.7351	0.04267	3819.1	4352.5	7.5182	0.02645	3797.5	4326.4	7.2830
1000	0.07301	4032.8	4616.9	7.9384	0.04658	4021.6	4603.8	7.7237	0.02897	4003.1	4582.5	7.4925
1100	0.07896	4238.6	4870.3	8.1300	0.05045	4228.2	4858.8	7.9165	0.03145	4211.3	4840.2	7.6874
1200	0.08489	4449.5	5128.5	8.3115	0.05430	4439.3	5118.0	8.0937	0.03391	4422.8	5101.0	7.8707
1300	0.09080	4665.0	5391.5	8.4842	0.05813	4654.8	5381.4	8.2717	0.03636	4638.0	5365.1	8.0442

source: http://www.thermofluids.net/

Fig. 6.13 Excerpt from a property table for superheated water vapor for a variety of pressures. The temperature in brackets is the saturation temperature.

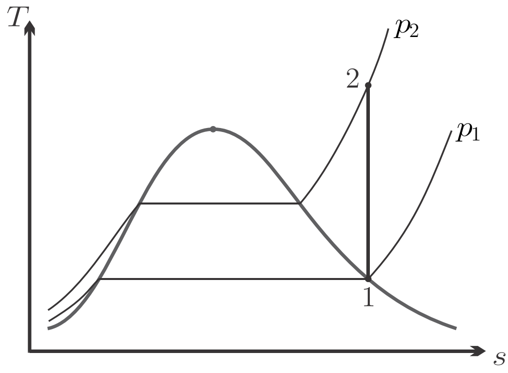

Fig. 6.14 Isentropic compression of saturated vapor from p_1 to p_2 in the T-s - diagram

Two bits of information are required to identify state 2, and here these are its pressure, p_2, and its entropy, since the process is isentropic, $s_2 = s_1 = 7.3549\frac{\mathrm{kJ}}{\mathrm{kg\,K}}$. In the table for superheated water vapor, Fig. 6.13, we have to consider the center box which refers to the pressure 3 MPa. The required value for entropy cannot be found in the table, but lies between values given. The values closest above and below the required value of $s_2 = 7.3549\frac{\mathrm{kJ}}{\mathrm{kg\,K}}$ in the table are

$$s_a = s\left(p_2 = 3\,\mathrm{MPa}, T_a = 500\,^\circ\mathrm{C}\right) = 7.2338\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\ ,$$
$$s_b = s\left(p_2 = 3\,\mathrm{MPa}, T_b = 600\,^\circ\mathrm{C}\right) = 7.5085\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\ .$$

Figure 6.15 shows a sketch of the function $s\left(p_2, T\right)$ in a diagram, with the tabled data points s_a, s_b and the target point s_2 indicated. Assuming that the line $a - 2 - b$ can be well approximated by a straight line, we find the target temperature T_2 by linear interpolation as

$$T_2 = T_a + \frac{s_2 - s_a}{s_b - s_a}\left(T_b - T_a\right) = 543.1\,^\circ\mathrm{C}\ .$$

Correspondingly, the values for volume, internal energy, and enthalpy are computed by interpolation as

$$v_2 = v_a + \frac{s_2 - s_a}{s_b - s_a}\left(v_b - v_a\right) = 0.12337\frac{\mathrm{m}^3}{\mathrm{kg}}\ ,$$
$$u_2 = u_a + \frac{s_2 - s_a}{s_b - s_a}\left(u_b - u_a\right) = 3186.0\frac{\mathrm{kJ}}{\mathrm{kg}}\ ,$$
$$h_2 = h_a + \frac{s_2 - s_a}{s_b - s_a}\left(h_b - h_a\right) = 3556.0\frac{\mathrm{kJ}}{\mathrm{kg}}\ .$$

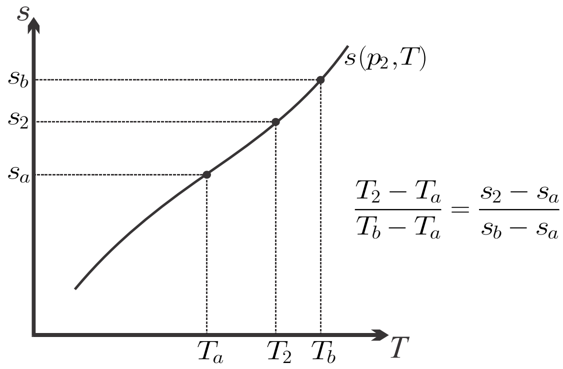

Fig. 6.15 Linear interpolation

Here, $v_a = v(p_2, T_a)$, $u_a = u(p_2, T_a)$ etc. are the appropriate data values from the table.

Since the process is adiabatic, we have $q_{12} = 0$ and the work per unit mass can be computed from the first law as $w_{12} = u_1 - u_2 + q_{12} = -679.5 \frac{\text{kJ}}{\text{kg}}$.

Thermodynamic properties are often listed in tables as discrete values, and interpolation must be frequently used. Typically, tabulated values are spaced such that the assumption of linearity is valid in good approximation.

6.9 Compressed Liquid

For compressed liquid, i.e., the pure liquid state, only few tables are available, Fig. 6.16 shows a table for compressed liquid water.

Most liquids, including water, are almost incompressible for a wider range of pressures, and this allows us to develop useful approximations that relate compressed liquid properties to those of saturated liquid.

For incompressible fluids a change of pressure does not lead to a change of volume, so that the volume can be approximated by the volume of the saturated liquid,

$$v(T,p) \simeq v(T) \simeq v_f(T) \ , \tag{6.10}$$

that is the volume is independent of pressure, but not of temperature. Incompressibility refers to changes at constant temperature, while thermal expansion or contraction are allowed. With this approximation, isothermal lines for the compressed liquid in the p-v-diagram are vertical lines upwards from the saturated liquid line.

Internal energy seen as a function of temperature and volume can then be reduced to its saturated liquid value as well:

$$u(T,v) \simeq u(T, v_f(T)) = u_f(T) \ . \tag{6.11}$$

Compressed Liquid Water (H2O) Table

deg-C	m3/kg	kJ/kg	kJ/kg	kJ/kg K	m3/kg	kJ/kg	kJ/kg	kJ/kg K	m3/kg	kJ/kg	kJ/kg	kJ/kg K
	p = 5 MPa (263.99 C)				p =10 MPa (311.06 C)				p = 15 MPa (342.24 C)			
T	v	u	h	s	v	u	h	s	v	u	h	s
sat.	0.0012859	1147.8	1154.2	2.9202	0.0014524	1393.0	1407.6	3.3596	0.0016581	1585.6	1610.5	3.6848
0	0.0009977	0.0	5.0	0.0001	0.0009952	0.1	10.0	0.0002	0.0009928	0.2	15.1	0.0004
20	0.0009995	83.7	88.7	0.2956	0.0009972	83.4	93.3	0.2945	0.0009950	83.1	98.0	0.2934
40	0.0010056	167.0	172.0	0.5705	0.0010034	166.4	176.4	0.5686	0.0010013	165.8	180.8	0.5666
60	0.0010149	250.2	255.3	0.8285	0.0010127	249.4	259.5	0.8258	0.0010105	248.5	263.7	0.8232
80	0.0010268	333.7	338.9	1.0720	0.0010245	332.6	342.8	1.0688	0.0010222	331.5	346.8	1.0656
100	0.0010410	417.5	422.7	1.3030	0.0010385	416.1	426.5	1.2992	0.0010361	414.7	430.3	1.2955
120	0.0010576	501.8	507.1	1.5233	0.0010549	500.1	510.6	1.5189	0.0010522	498.4	514.2	1.5145
140	0.0010768	586.8	592.2	1.7343	0.0010737	584.7	595.4	1.7292	0.0010707	582.7	598.7	1.7242
160	0.0010988	672.6	678.1	1.9375	0.0010953	670.1	681.1	1.9317	0.0010918	667.7	684.1	1.9260
180	0.0011240	759.6	765.3	2.1341	0.0011199	756.7	767.8	2.1275	0.0011159	753.8	770.5	2.1210
200	0.0011530	848.1	853.9	2.3255	0.0011480	844.5	856.0	2.3178	0.0011433	841.0	858.2	2.3104
220	0.0011866	938.4	944.4	2.5128	0.0011805	934.1	945.9	2.5039	0.0011748	929.9	947.5	2.4953
240	0.0012264	1031.4	1037.5	2.6979	0.0012187	1026.0	1038.1	2.6872	0.0012114	1020.8	1039.0	2.6771
260	0.0012749	1127.9	1134.3	2.8830	0.0012645	1121.1	1133.7	2.8699	0.0012550	1114.6	1133.4	2.8576
280					0.0013216	1220.9	1234.1	3.0548	0.0013084	1212.5	1232.1	3.0393
300					0.0013972	1328.4	1342.3	3.2469	0.0013770	1316.6	1337.3	3.2260
320									0.0014724	1431.1	1453.2	3.4247
340									0.0016311	1567.5	1591.9	3.6546

	p = 20 MPa (365.81 C)				p = 30 Mpa				p = 50 MPa			
T	v	u	h	s	v	u	h	s	v	u	h	s
sat.	0.0020360	1785.6	1826.3	4.0139								
0	0.0009904	0.2	20.0	0.0004	0.0009856	0.3	29.8	0.0001	0.0009766	0.2	49.0	0.0014
20	0.0009928	82.8	102.6	0.2923	0.0009886	82.2	111.8	0.2899	0.0009804	81.0	130.0	0.2848
40	0.0009992	165.2	185.2	0.5646	0.0009951	164.0	193.9	0.5607	0.0009872	161.9	211.2	0.5527
60	0.0010084	247.7	267.9	0.8206	0.0010042	246.1	276.2	0.8154	0.0009962	243.0	292.8	0.8052
80	0.0010199	330.4	350.8	1.0624	0.0010156	328.3	358.8	1.0561	0.0010073	324.3	374.7	1.0440
100	0.0010337	413.4	434.1	1.2917	0.0010290	410.8	441.7	1.2844	0.0010201	405.9	456.9	1.2703
120	0.0010496	496.8	517.8	1.5102	0.0010445	493.6	524.9	1.5018	0.0010348	487.7	539.4	1.4857
140	0.0010678	580.7	602.0	1.7193	0.0010621	576.9	608.8	1.7098	0.0010515	569.8	622.4	1.6915
160	0.0010885	665.4	687.1	1.9204	0.0010821	660.8	693.3	1.9096	0.0010703	652.4	705.9	1.8891
180	0.0011120	751.0	773.2	2.1147	0.0011047	745.6	778.7	2.1024	0.0010912	735.7	790.3	2.0794
200	0.0011388	837.7	860.5	2.3031	0.0011302	831.4	865.3	2.2893	0.0011146	819.7	875.5	2.2634
220	0.0011695	925.9	949.3	2.4870	0.0011590	918.3	953.1	2.4711	0.0011408	904.7	961.7	2.4419
240	0.0012046	1016.0	1040.0	2.6674	0.0011920	1006.9	1042.6	2.649	0.0011702	990.7	1049.2	2.6158
260	0.0012462	1108.6	1133.5	2.8459	0.0012303	1097.4	1134.3	2.8243	0.0012034	1078.1	1138.2	2.7860
280	0.0012965	1204.7	1230.6	3.0248	0.0012755	1190.7	1229.0	2.9986	0.0012415	1167.2	1229.3	2.9537
300	0.0013596	1306.1	1333.3	3.2071	0.0013307	1287.9	1327.8	3.1741	0.0012860	1258.7	1323.0	3.1200
320	0.0014437	1415.7	1444.6	3.3979	0.0013997	1390.7	1432.7	3.3539	0.0013388	1353.3	1420.2	3.2868
340	0.0015684	1539.7	1571.0	3.6075	0.0014920	1501.7	1546.5	3.5426	0.0014032	1452.0	1522.1	3.4557
360	0.0018226	1702.8	1739.3	3.8772	0.0016265	1626.6	1675.4	3.7494	0.0014838	1556.0	1630.2	3.6291
380					0.0018691	1781.4	1837.5	4.0012	0.0015884	1667.2	1746.6	3.8101

source: http://www.thermofluids.net/

Fig. 6.16 Excerpt from a property table for compressed liquid water for a variety of pressures. The temperature in brackets is the saturation temperature.

For consistency, enthalpy needs to be treated differently. Due to the definition $h = u + pv$, the above approximations give in a first step $h(T,p) = u_f(T) + pv_f(T)$. For the saturated liquid at the same temperature we have $h_f(T) = u_f(T) + p_{\text{sat}}(T)\,v_f(T)$. Combining both by eliminating $u_f(T)$, we find the approximation for the enthalpy of compressed liquid as

$$h(T,p) \simeq h_f(T) + (p - p_{sat}(T))\,v_f(T) \ . \tag{6.12}$$

For small enough pressures, the correction term for enthalpy can be ignored, so that $h(T,p) \simeq h_f(T)$.

Finally, entropy can be treated similar to internal energy,

$$s(T,v) \simeq s(T, v_f(T)) = s_f(T) \ . \tag{6.13}$$

With this approximation, isobaric lines for the compressed liquid in the T-s-diagram lie on the saturated liquid line.

As an example, we consider compressed liquid water at $p = 10\,\text{MPa}$ and $T = 200\,°\text{C}$, for which the table in Fig. 6.16 gives

$$v(T,p) = v(200\,°\text{C}, 10\,\text{MPa}) = 0.001148\frac{\text{m}^3}{\text{kg}} \ ,$$
$$u(T,p) = u(200\,°\text{C}, 10\,\text{MPa}) = 844.5\frac{\text{kJ}}{\text{kg}} \ ,$$
$$h(T,p) = h(200\,°\text{C}, 10\,\text{MPa}) = 856.0\frac{\text{kJ}}{\text{kg}} \ ,$$
$$s(T,p) = s(200\,°\text{C}, 10\,\text{MPa}) = 2.3178\frac{\text{kJ}}{\text{kg K}} \ .$$

With the above approximations, we find the corresponding values from the saturation table in Fig. 6.10 as

$$v(T,p) \simeq v_f(T) = v_f(200\,°\text{C}) = 0.001157\frac{\text{m}^3}{\text{kg}} \ ,$$
$$u(T,v) \simeq u_f(T) = u_f(200\,°\text{C}) = 850.65\frac{\text{kJ}}{\text{kg}} \ ,$$
$$h(T,p) \simeq h_f(T) = h_f(200\,°\text{C}) = 852.45\frac{\text{kJ}}{\text{kg}} \ ,$$
$$h(T,p) \simeq h_f(T) + (p - p_{sat}(T))\, v_f(T) = 862.2\frac{\text{kJ}}{\text{kg}} \ ,$$

$$s(T,v) \simeq s_f(T) = s_f(200\,°\text{C}) = 2.3309\frac{\text{kJ}}{\text{kg K}} \ .$$

For this particular example, the approximations yield relative errors below 1%, and even smaller at lower pressures. For higher pressures, however, the relative errors are larger, since compressibility affects all property values, hence these approximations should be used with care. Whenever a full table for compressed liquid states is available, that table should be used. If a table for the liquid states is not available, as is often the case for relatively low pressures, the approximations are quite useful.

6.10 The Ideal Gas

When the temperature of a vapor is sufficiently above the critical temperature or when the pressure is sufficiently below the critical pressure, it will obey the ideal gas law

$$pv = RT \ , \tag{6.14}$$

where $R = \bar{R}/M$ is the gas constant. We have discussed ideal gases already in Sec. 2.15, and used the ideal gas law and the caloric equation of state in examples. We repeat some of the property relations and add new ones.

Experiments and theoretical considerations (see Sec. 16.3) show that for ideal gases internal energy u and enthalpy $h = u + pv = u + RT$ depend on temperature *only*. Therefore, also their derivatives, the specific heats at constant volume, c_v, and at constant pressure, c_p, defined in (3.15, 3.22), depend only on temperature,

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v = \frac{du}{dT} = c_v\left(T\right) \ , \tag{6.15}$$
$$c_p = \left(\frac{\partial h}{\partial T}\right)_p = \frac{dh}{dT} = c_p\left(T\right) \ .$$

Since $h = u + RT$, it follows

$$c_p = c_v + R \ . \tag{6.16}$$

Integration of the specific heats gives energy and enthalpy,

$$u\left(T\right) = \int_{T_0}^{T} c_v\left(T'\right) dT' + u_0 \ , \tag{6.17}$$
$$h\left(T\right) = \int_{T_0}^{T} c_p\left(T'\right) dT' + h_0 \ ,$$

with reference energy u_0 and, for consistency, reference enthalpy $h_0 = u_0 + RT_0$.

The entropy of an ideal gas is determined from integration of the Gibbs equation (6.2). With $dh = c_p dT$ and the ideal gas law, the Gibbs equation assumes the form

$$ds = \frac{c_p}{T} dT - \frac{v}{T} dp = \frac{c_p}{T} dT - \frac{R}{p} dp \ . \tag{6.18}$$

The entropy for the state (T, p) follows by integration between (T, p) and (T_0, p_0) as

$$s\left(T, p\right) = s^0\left(T\right) - R \ln \frac{p}{p_0} \ , \tag{6.19}$$

where we introduced the abbreviation

$$s^0(T) = \int_{T_0}^{T} \frac{c_p(T')}{T'} dT' + s(T_0, p_0) \ . \tag{6.20}$$

The constant of integration is chosen such that $s^0(T)$ is the ideal gas entropy at reference pressure $p_0 = 1\,\text{bar}$. The value of the reference entropy $s(T_0, p_0)$ can be obtained from the third law, which will be discussed later (Sec. 23.6). As long as non-reacting mixtures are considered, its value is unimportant, since it cancels in all calculations. Indeed, only entropy differences are relevant, for which we find

$$s(T_2, p_2) - s(T_1, p_1) = s^0(T_2) - s^0(T_1) - R \ln \frac{p_2}{p_1} \ . \tag{6.21}$$

When one is not interested in entropy as a function of T and p, but as a function of T and v, the ideal gas law can be used to eliminate pressure,

$$s(T_2, v_2) - s(T_1, v_1) = s^0(T_2) - s^0(T_1) - R \ln \frac{T_2 v_1}{T_1 v_2} \ . \tag{6.22}$$

In summary, energy and enthalpy of the ideal gas depend only on temperature, and its entropy depends explicitly on pressure (6.21) or volume (6.22), and on temperature through the function $s^0(T)$. The temperature dependent quantities $u(T), h(T), s^0(T)$ are tabulated.[3]

As an example we consider a property table for air. The molar specific heat of air can be approximated by the Shomate equation

$$\bar{c}_p = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + \frac{a_4}{T^2} \ , \tag{6.23}$$

with (for $T \leq 1000\,\text{K}$)

$$\begin{aligned} a_0 &= 30.0051 \frac{\text{kJ}}{\text{kmol K}} \ , \quad a_1 = -8.86766 \times 10^{-3} \frac{\text{kJ}}{\text{kmol K}^2} \ , \\ a_2 &= 2.21273 \times 10^{-5} \frac{\text{kJ}}{\text{kmol K}^3} \ , \quad a_3 = -1.02450 \times 10^{-8} \frac{\text{kJ}}{\text{kmol K}^4} \ , \\ a_4 &= 838.737 \frac{\text{kJ K}}{\text{kmol}} \ . \end{aligned} \tag{6.24}$$

The mass based specific heats are $c_p = \bar{c}_p / M$ and $c_v = c_p - R$. Internal energy u, enthalpy h and entropy function $s^0(T)$ follow from integration using the formulas above. Figure 6.17 shows the resulting table.

Tables for other gases are widely available, or can be easily produced from the Shomate equation with the appropriate data for the coefficients, which can be found, e.g., from NIST (http://webbook.nist.gov/).

[3] Some tables list molar quantities $\bar{u} = uM$, $\bar{h} = hM$, $\bar{s}^0 = s^0 M$.

Property table for AIR as ideal gas

T	cv [kJ/kg]	cp [kJ/kg]	u [kJ/kg]	h [kJ/kg]	s0 [kJ/kgK]	Pr	Vr
220	0.715	1.002	157.68	220.81	6.826	0.346	636.0
230	0.715	1.002	164.83	230.83	6.870	0.404	569.3
240	0.715	1.002	171.98	240.85	6.913	0.469	512.1
250	0.715	1.002	179.13	250.87	6.954	0.540	462.5
260	0.715	1.002	186.28	260.89	6.993	0.620	419.5
270	0.715	1.002	193.43	270.91	7.031	0.707	381.8
273	0.715	1.002	195.57	273.92	7.042	0.735	371.5
280	0.716	1.003	200.58	280.94	7.067	0.803	348.7
290	0.716	1.003	207.74	290.96	7.103	0.908	319.5
298.15	**0.716**	**1.003**	**213.57**	**299.14**	**7.130**	**1.000**	**298.2**
300	0.716	1.003	214.90	300.99	7.137	1.022	293.6
310	0.717	1.004	222.07	311.03	7.169	1.146	270.5
320	0.718	1.005	229.24	321.08	7.201	1.281	249.9
330	0.718	1.005	236.42	331.13	7.232	1.426	231.4
340	0.719	1.006	243.61	341.18	7.262	1.584	214.7
350	0.720	1.007	250.81	351.25	7.291	1.753	199.6
360	0.721	1.008	258.01	361.33	7.320	1.935	186.0
370	0.722	1.009	265.23	371.42	7.347	2.131	173.6
380	0.724	1.011	272.46	381.52	7.374	2.341	162.3
390	0.725	1.012	279.70	391.63	7.401	2.565	152.0
400	0.726	1.013	286.96	401.75	7.426	2.805	142.6
410	0.727	1.014	294.22	411.89	7.451	3.060	134.0
420	0.729	1.016	301.51	422.04	7.476	3.333	126.0
430	0.730	1.017	308.80	432.21	7.500	3.622	118.7
440	0.732	1.019	316.11	442.39	7.523	3.930	112.0
450	0.734	1.021	323.44	452.59	7.546	4.257	105.71
460	0.735	1.022	330.79	462.80	7.569	4.603	99.93
470	0.737	1.024	338.15	473.03	7.591	4.970	94.56
480	0.739	1.026	345.53	483.28	7.612	5.358	89.58
490	0.741	1.028	352.92	493.55	7.633	5.769	84.94
500	0.743	1.030	360.34	503.83	7.654	6.202	80.62
510	0.744	1.031	367.77	514.14	7.674	6.659	76.59
520	0.746	1.033	375.23	524.46	7.694	7.141	72.82
530	0.749	1.036	382.70	534.81	7.714	7.648	69.30
540	0.751	1.038	390.20	545.17	7.734	8.182	66.00
550	0.753	1.040	397.72	555.56	7.753	8.744	62.90
560	0.755	1.042	405.25	565.97	7.771	9.33	59.99
570	0.757	1.044	412.81	576.40	7.790	9.95	57.26

T	cv [kJ/kg]	cp [kJ/kg]	u [kJ/kg]	h [kJ/kg]	s0 [kJ/kgK]	Pr	Vr
580	0.759	1.046	420.39	586.85	7.808	10.61	54.69
590	0.761	1.048	428.00	597.32	7.826	11.29	52.27
600	0.764	1.051	435.62	607.82	7.844	12.00	49.98
610	0.766	1.053	443.27	618.34	7.861	12.75	47.83
620	0.768	1.055	450.95	628.88	7.878	13.54	45.80
630	0.771	1.058	458.64	639.44	7.895	14.36	43.87
640	0.773	1.060	466.36	650.03	7.912	15.22	42.05
650	0.775	1.062	474.10	660.64	7.928	16.12	40.33
660	0.778	1.065	481.87	671.28	7.944	17.06	38.70
670	0.780	1.067	489.66	681.94	7.960	18.04	37.15
680	0.783	1.070	497.47	692.62	7.976	19.06	35.68
690	0.785	1.072	505.31	703.33	7.992	20.12	34.29
700	0.787	1.074	513.17	714.06	8.007	21.24	32.96
710	0.790	1.077	521.06	724.82	8.023	22.40	31.70
720	0.792	1.079	528.97	735.60	8.038	23.61	30.50
730	0.795	1.082	536.91	746.41	8.053	24.86	29.36
740	0.797	1.084	544.87	757.24	8.067	26.17	28.27
750	0.800	1.087	552.85	768.09	8.082	27.54	27.24
760	0.802	1.089	560.86	778.97	8.096	28.95	26.25
770	0.805	1.091	568.90	789.87	8.111	30.43	25.31
780	0.807	1.094	576.95	800.80	8.125	31.96	24.40
790	0.809	1.096	585.03	811.75	8.139	33.55	23.54
800	0.812	1.099	593.14	822.73	8.152	35.21	22.72
810	0.814	1.101	601.27	833.73	8.166	36.92	21.94
820	0.816	1.103	609.42	844.75	8.180	38.70	21.19
830	0.819	1.106	617.59	855.79	8.193	40.55	20.47
840	0.821	1.108	625.79	866.86	8.206	42.47	19.78
850	0.823	1.110	634.01	877.95	8.219	44.46	19.12
860	0.826	1.112	642.26	889.07	8.232	46.52	18.49
870	0.828	1.115	650.52	900.20	8.245	48.65	17.88
880	0.830	1.117	658.81	911.36	8.258	50.86	17.30
890	0.832	1.119	667.12	922.54	8.271	53.15	16.74
900	0.834	1.121	675.45	933.74	8.283	55.52	16.21
910	0.836	1.123	683.81	944.96	8.295	57.97	15.70
920	0.838	1.125	692.18	956.21	8.308	60.51	15.20
930	0.840	1.127	700.57	967.47	8.320	63.13	14.73
940	0.842	1.129	708.98	978.75	8.332	65.84	14.28
950	0.844	1.131	717.41	990.05	8.344	68.64	13.84

Fig. 6.17 Property data for air: specific heats $c_v(T)$ and $c_p(T)$, internal energy $u(T)$, enthaply $h(T)$ and entropy function $s^0(T)$ as functions of temperature

6.11 Monatomic Gases (Noble Gases)

For monatomic gases, i.e., the noble gases helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and radon (Rn), the specific heats are true constants with the values

$$c_v = \frac{3}{2}R \quad , \quad c_p = c_v + R = \frac{5}{2}R \tag{6.25}$$

and the caloric equation of state follows from straightforward integration as

$$\begin{aligned} u(T) &= c_v(T - T_0) + u_0 \ , \\ h(T) &= c_p(T - T_0) + h_0 \ . \end{aligned} \tag{6.26}$$

With $c_p = const$, the integration in (6.20) can be performed easily, and the entropy becomes

$$s(T, p) = c_p \ln \frac{T}{T_0} - R \ln \frac{p}{p_0} + s_0 \ . \tag{6.27}$$

Since the resulting expressions for the thermodynamic quantities of monatomic gases are rather simple, these are typically not tabulated.

6.12 Specific Heats and Cold Gas Approximation

The value of the specific heat is related to the degrees of freedom of a molecule. Specifically, each degree of freedom contributes $\frac{1}{2}R$ to the specific heat at constant volume (equipartition of energy). The atoms of monatomic gases are essentially spheres that can translate in three directions (up/down, right/left, forward/backward); accordingly, the specific heat of monatomic gases is $c_v = 3 \times \frac{1}{2}R$.

For diatomic gases like oxygen (O_2), nitrogen (N_2), hydrogen (H_2), the molecules are shaped like dumb-bells. At low temperatures these have, in addition to their three translational degrees of freedom, two rotational degrees of freedom for the rotation about two principal axes—there is no rotation around the longitudinal axis. More complex molecules like carbondioxid (CO_2) and water (H_2O) have three translational and three rotational degrees of freedom. Moreover, the molecules can oscillate, the more complicated a molecule is, the more oscillating modes are observed.

At sufficiently low temperatures only translational and rotational modes are excited. With each mode contributing $\frac{1}{2}R$ to the specific heat, we have at low T for a diatomic gas $c_v = \frac{5}{2}R$, $c_p = \frac{7}{2}R$, and for a polyatomic gas $c_v = 3R$, $c_p = 4R$. Oscillatory modes obey quantum mechanical laws; they are not excited at low temperatures and contribute in a temperature dependent manner for higher temperatures. Figure 6.18 shows the molar specific heat $\bar{c}_p = Mc_p$ for a variety of ideal gases. Note the temperature independent value $\bar{c}_p = \frac{5}{2}\bar{R} = 20.8\frac{\text{kJ}}{\text{kg K}}$ for monatomic gases, and the common low temperature value of $\bar{c}_p = \frac{7}{2}\bar{R} = 29.1\frac{\text{kJ}}{\text{kg K}}$ for diatomic gases.

Air, as a mixture of roughly 78% N_2, 21% O_2 and 1% Ar, behaves essentially like a diatomic gas, with the low temperature specific heats $c_v^{air} = \frac{5}{2}R_{air}$, $c_p^{air} = \frac{7}{2}R_{air}$. As air temperatures rises, so do the specific heats.

To simplify computations, one frequently assumes constant specific heats. To not deviate too much from the actual states, one should use suitable average values c_v^{avg}, c_p^{avg} for the temperature interval under consideration, or, alternatively, the values at room temperature. In the latter case one speaks of the *cold-gas-approximation*, or, for air, *cold-air-approximation.* Internal energy, enthalpy and entropy are

$$
\begin{aligned}
u(T) &= c_v^{avg}(T - T_0) + u_0 , \\
h(T) &= c_p^{avg}(T - T_0) + h_0 , \\
s(T,p) &= c_p^{avg} \ln \frac{T_2}{T_0} - R \ln \frac{p_2}{p_0} + s_0 .
\end{aligned}
\tag{6.28}
$$

The cold-gas-approximation, where one uses $c_v^{avg} = c_v(T_0)$, works best for relatively low temperatures (e.g., $T < 600\,\text{K}$ for air), but is highly useful to understand the basic behavior of thermodynamic systems. Constant specific heats allow analytical calculations that give, e.g., explicit expressions for

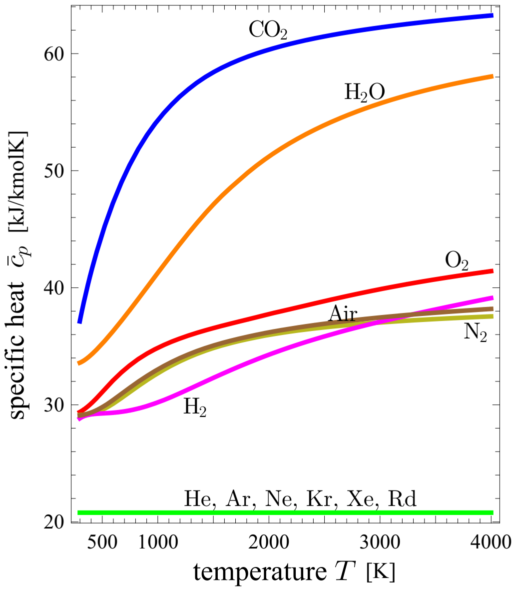

Fig. 6.18 Molar specific heat at constant pressure $\bar{c}_p = Mc_p$ for various ideal gases as function of temperature. Note that specific heat of monatomic gases (noble gases) is constant. Based on specific heat data from NIST.

efficiencies that help to further the understanding. Exact engineering calculations must use variable specific heats, of course, and tabulated data *must* be used, unless the gas is monatomic and the specific heat independent of temperature!

6.13 Real Gases

Gases (or vapors) at relatively high pressures or relatively low temperatures do not obey the ideal gas law. To understand why that is the case, it is helpful to know a little bit about the derivation of the ideal gas law with the tools of *Statistical Thermodynamics*, which relies on two assumptions: (a) Gas particles are mass points, that is their volume can be ignored. (b) There are no long-distance forces between the particles, they only interact in short collisions, and travel most distance between collisions in free flight.

J. D. van der Waals (1837-1923) derived an equation that modifies the ideal gas equation to address both points. The van der Waals equation reads

$$p = \frac{RT}{v-b} - \frac{a}{v^2} \,. \qquad (6.29)$$

The constant b accounts for the volume of the particles, where $v - b$ is the volume accessible to an individual particle. The constant a accounts for long-range attractive forces between the particles, which reduce the pressure. The constants a, b can be obtained from fitting to critical point data. For large values of the specific volume v the equation reduces to the ideal gas law. A deeper discussion of the van der Waals equation can be found in Sec. 16.8, where it will be seen that the equation gives a good qualitative description of real gas effects and liquid-vapor phase change. However, its quantitative agreement with gas behavior is not so good. Therefore, the equation is mainly used as an educational example, but not for simulation of real processes.

Since explicit equations for real gas behavior are useful for simulations and calculations, there exist a wide variety of real gas equations, which can be found in the technical literature (Redlich-Kwong equation, Beattie-Bridgeman equation, virial expansions, etc.).

6.14 Fully Incompressible Solids and Liquids

Also for solids the specific heats depend in general on temperature and volume (or any other pair of properties), and must be collected in tables. Quite often it is possible to treat the solids to be fully incompressible (no change of volume, $v = const$), and to assume constant specific heat. Then, internal energy, enthalpy and entropy are

$$\begin{aligned} u(T) &= c(T - T_0) + u_0 \ , \\ h(T,p) &= c(T - T_0) + v(p - p_0) + h_0 \ , \\ s(T) &= c \ln \frac{T}{T_0} + s_0 \ . \end{aligned} \tag{6.30}$$

As always, u_0, h_0 and s_0 are suitable reference values. Due to incompressibility, the specific heats at constant volume and constant pressure agree, as the following line of equations shows:

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p = \left(\frac{\partial (u + pv)}{\partial T}\right)_p = \left(\frac{\partial u}{\partial T}\right) + \left(v \frac{\partial p}{\partial T}\right)_p = \left(\frac{\partial u}{\partial T}\right) = c_v \ . \tag{6.31}$$

The same approximations can be used for fully incompressible liquids.

Problems

6.1. Property Diagrams and Data (Water)

Draw schematic p-T, p-v, T-v and T-s-diagrams for water, and mark the following points in the diagrams.

CR) critical point	TR) triple point
1) $p = 1\,\text{bar},\ v = 0.85\frac{\text{m}^3}{\text{kg}}$	2) $p = 1\,\text{bar},\ h = 3400\frac{\text{kJ}}{\text{kg}}$
3) $p = 20\,\text{MPa},\ v = 0.0012\frac{\text{m}^3}{\text{kg}}$	4) $h = 2700\frac{\text{kJ}}{\text{kg}},\ x = 1$
5) $p = 20\,\text{MPa}, u = 3100\frac{\text{kJ}}{\text{kg}}$	6) $s = 3\frac{\text{kJ}}{\text{kg K}},\ T = 255\,°\text{C}$

Also, determine temperature, quality, specific internal energy, specific enthalpy, and specific volume for each point, and say whether you have compressed liquid, saturated state, or superheated vapor.

6.2. Property Diagrams and Data (R134a)
Consider cooling fluid R134a. Based on the posted tables, determine temperature, pressure, quality, specific internal energy, specific enthalpy, and specific volume for each point, and say whether you have compressed liquid, saturated state, or superheated vapor. Put all values in a table.

1. $T = -4\,°\text{C}, h = 178.2\frac{\text{kJ}}{\text{kg}}$, 2. $T = -24\,°\text{C}, p = 0.2\,\text{MPa}$,
3. $T = 20\,°\text{C}, s = 0.9883\frac{\text{kJ}}{\text{kg K}}$

6.3. Boiling Temperature
Water in a 5 cm deep pan is observed to boil at 98 °C. At what temperature will the water in a 50 cm deep pan boil? Assume both pans are filled to the rim.

6.4. Food Preservation
To preserve fruit or vegetables (canning), the food is cooked in a jar which is covered by a lid, resting on a rubber seal. As water is evaporated during cooking, vapor escapes and carries air out. After a while, only food, liquid water and vapor are left in the jar. Then cooking stops, and as the jar cools, the pressure in the jar drops, tightly sealing the jar. Consider a jar of 20 cm diameter at 15 °C, and determine the force necessary to pull of the lid.

6.5. Cooling of Steam
2 kg of superheated steam at 2 bar, 300 °C (state 1) are isobarically cooled to the saturated vapor state (state 2). Then, the volume of the container is fixed and the steam is cooled further until the temperature is 20 °C (state 3).

1. Draw the process into a p-v-diagram with respect to saturations lines. Mark the critical point.
2. Compute heat and work exchanged for the processes 1-2 and 2-3.

6.6. Isentropic Expansion of R-134a Vapor
Refrigerant R-134a at 1.2 MPa, 50 °C (state 1) enclosed in a piston-cylinder device expands in an adiabatic reversible (i.e., isentropic) process to 100 kPa (state 2). Determine specific volume, internal energy, enthalpy, entropy at both points. Compute heat and work exchanged between refrigerant and surroundings.

6.7. Evaporation of Water

3 kg of saturated liquid water at 70 °C (state 1) are isobarically heated until the volume reaches 0.921 $\frac{m^3}{kg}$ (state 2). Then, the volume of the container is fixed and the heating continues until all liquid is just evaporated (state 3).

1. Draw the process into a p-v-diagram with respect to saturation lines. Mark the critical point.
2. Compute heat and work exchanged for the processes 1-2, and 2-3.

6.8. Condensation of R134a

500 g of cooling fluid R134a are enclosed in a piston cylinder system at 3.2 bar, 25 °C. The system is isobarically cooled until the cooling fluid assumes a temperature of −8 °C.

1. Draw the process into p-v- and T-s-diagram with respect to saturation lines.
2. Determine heat and work exchanged.
3. Determine the change of entropy.