EPFL

ETA-Lab
Energy Transport Advances

ME-251: Thermodynamics and energetics I

Thermodynamic Properties

Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering

2025 Fall Semester

Photo Credit: Trougnouf

Last Time

- Apply energy balance to closed systems
- Analyze the energy balance of thermodynamic cycles
- Understand and interpret equation of state (p-T-v surface)

First Law of Thermodynamics for a Closed System

Change in the amount of energy contained within a system during some time interval

=

Net amount of energy transferred **into** the system by heat transfer during the time interval

−

Net amount of energy transferred **out of** the system by work during the time interval

$$\Delta E = Q - W$$

Time rate of change in the amount of energy contained within a system at time *t*

=

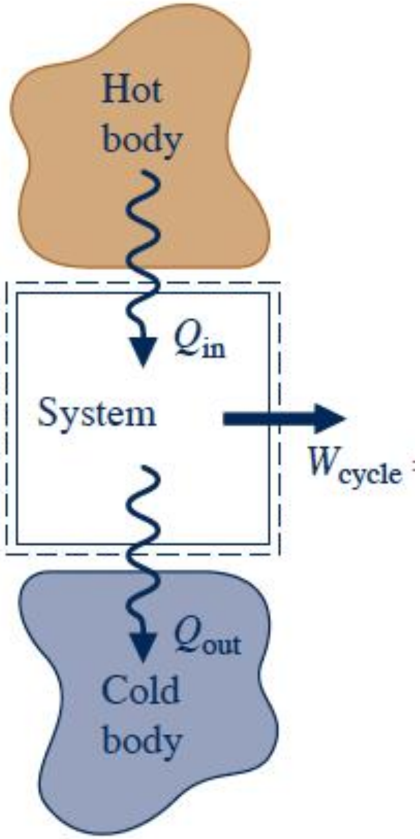
Net rate at which energy is transferred into the system by heat transfer at time *t*

−

Net rate at which energy is transferred out of the system by work at time *t*

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

Thermodynamic Cycles

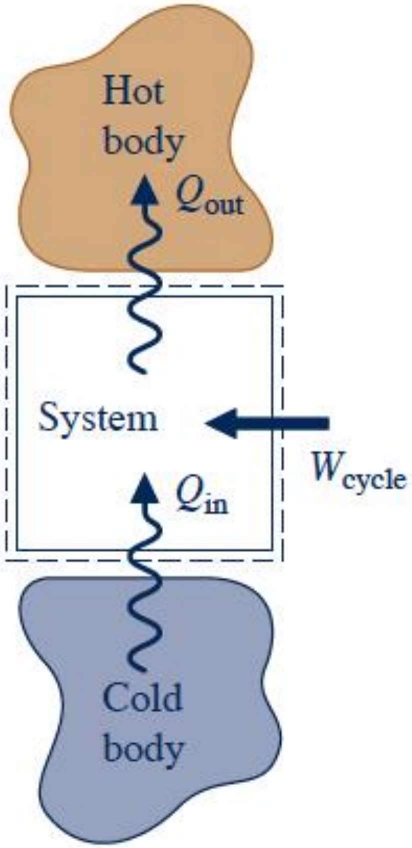


Power cycle

$$W_{cycle} = Q_{in} - Q_{out}$$

Output

$$\eta = \frac{W_{cycle}}{Q_{in}}$$



Refrigeration and heat pump cycle

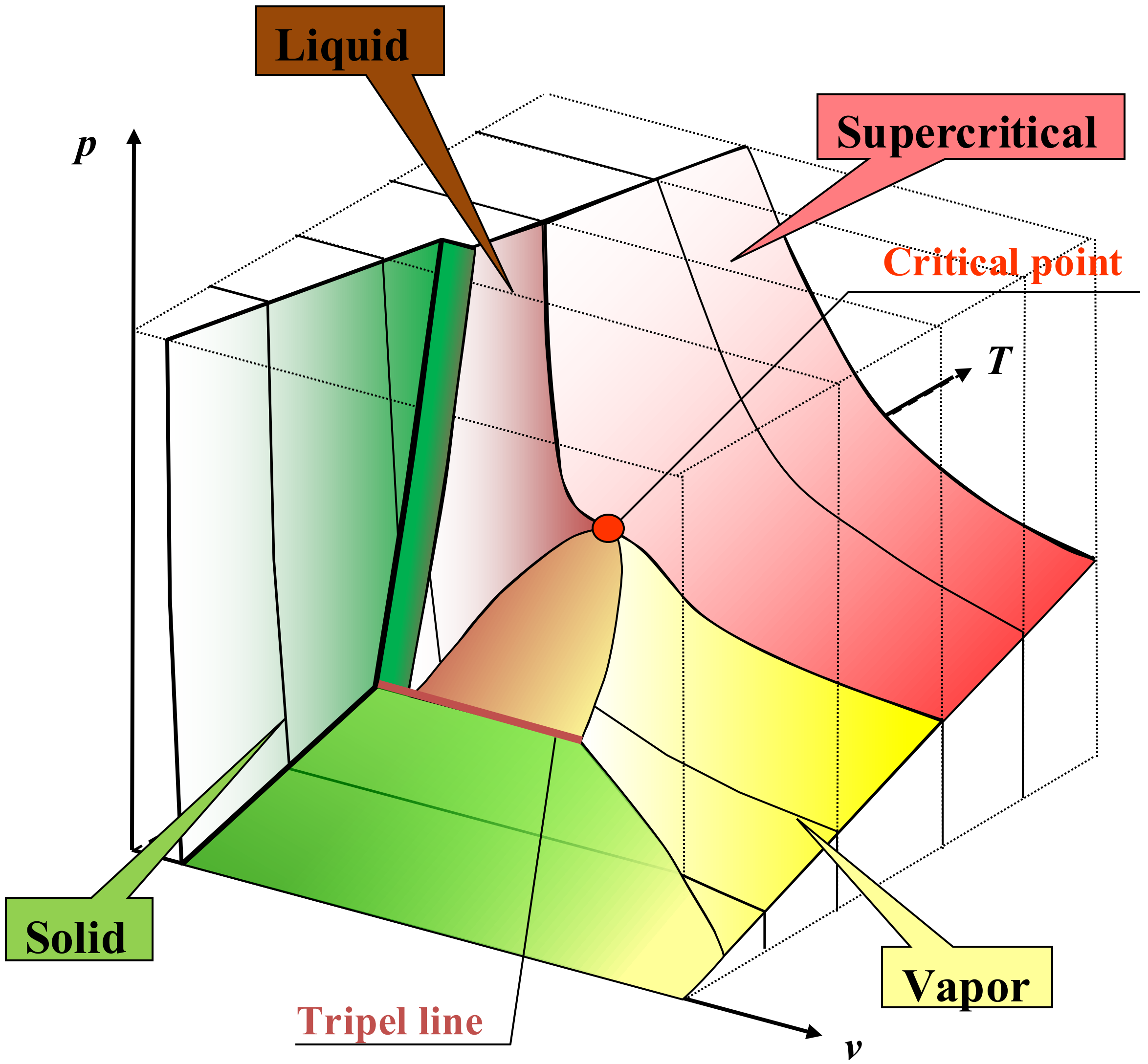
$$W_{cycle} = Q_{out} - Q_{in}$$

Input

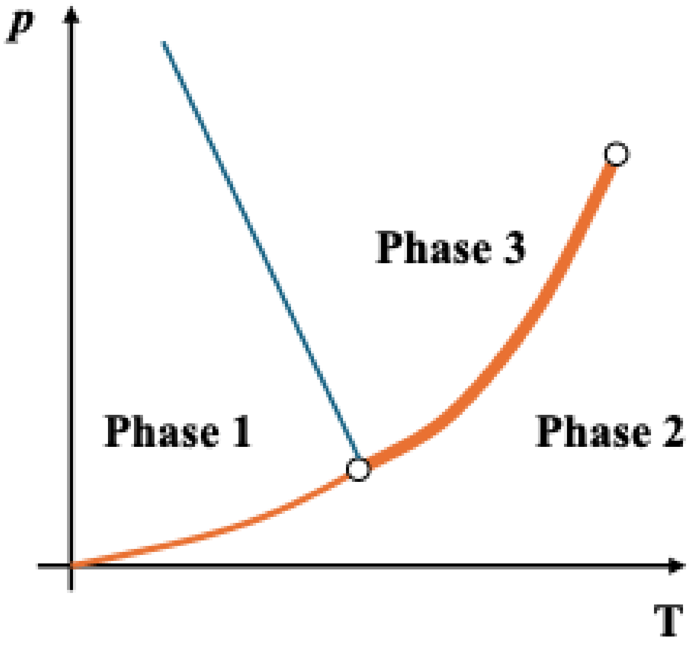
$$\beta_{ACR} = \frac{Q_{in}}{W_{cycle}}$$

$$\gamma_{HP} = \frac{Q_{out}}{W_{cycle}}$$

Pure Substance p-v-T Relation



p-T diagram



Given the p-T diagram for a certain substance shown here, which of the following statements is true when this substance experience phase transition from Phase 1 to Phase 3?

A. The specific volume decreases

B. The specific volume increases

C. The specific volume stays the same

D. The specific volume first increases and then decreases

Scan the QR code with your device
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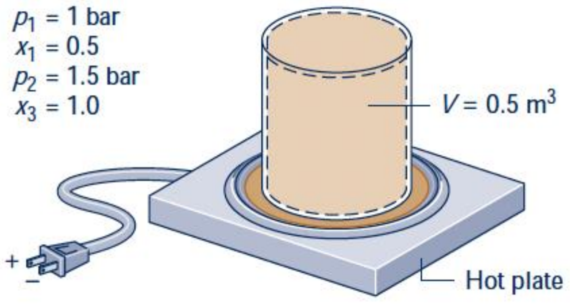
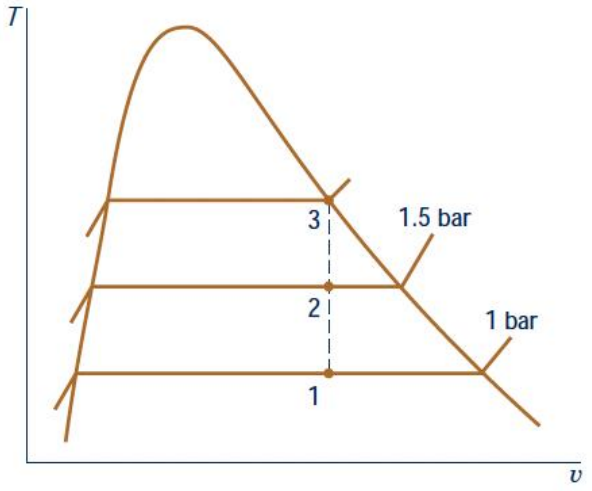
Example 3.2 in Moran

- A closed, rigid container of fixed volume is placed on a hot plate. Initially, at state 1, the container holds a two-phase mixture of saturated liquid water and saturated water vapor at $\boldsymbol{p_1 = 1}$ **bar** with a **quality of 0.5**.
- After heating, at state 2, the pressure in the container is $\boldsymbol{p_2 = 1.5}$ **bar**. Finally, with further heating, at state 3, the container only contains **saturated vapor**.
- **Indicate states 1-3 on a T-v diagram**





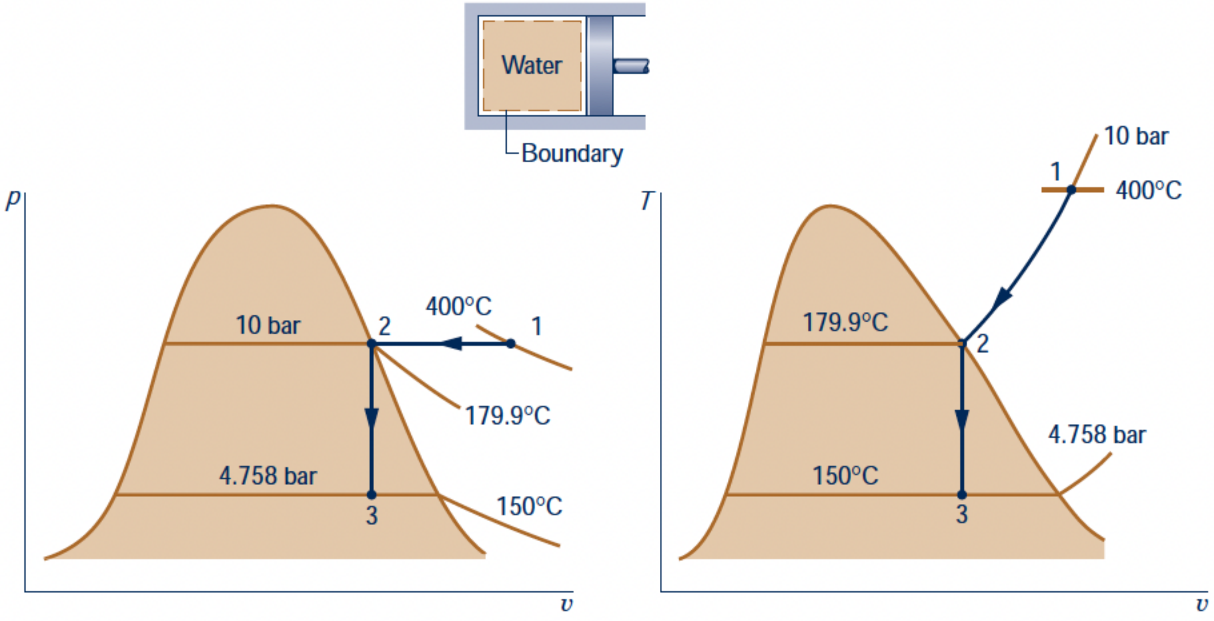
Quality: $x = \frac{m_{vapor}}{m_{liquid}+m_{vapor}}$

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

Example 3.4 in Moran

- Water contained in a piston–cylinder assembly undergoes two processes in series from an initial state where the pressure is 10 bar and the temperature is 400 ℃ (above CP).
  - Process 1–2: The water is cooled as it is compressed at a constant pressure of 10 bar to the saturated vapor state.
  - Process 2–3: The water is cooled at constant volume to 150 ℃.

Sketch both processes on T–v and p–v diagrams.



ILS Today

- Understand the concept of enthalpy
- Understand the concept of specific heat
- Evaluate thermodynamics properties for pure substances using CoolProp

- Reading materials: Moran 3.6, 3.8-3.13

Enthalpy

- A convenient state function for energy balance in open systems; intuitively, it can be understood as the energy needed to create a system in an environment with fixed pressure

- Definition: $H = U + pV$ [J]

- Specific enthalpy: $h = u + pv$ [J/kg]

- Molar enthalpy: $\tilde{h} = \tilde{u} + p\tilde{v}$ [J/mol]

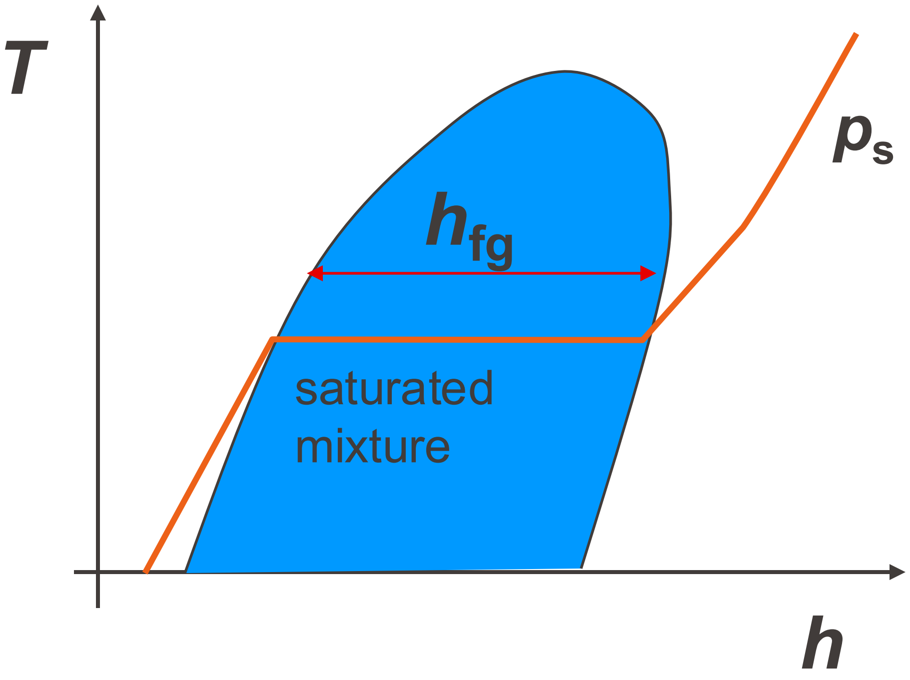
Enthalpy

- Simple systems have two independent properties

- There exists also correlations for enthalpy and internal energy
  - $u(v,T)$
  - $h(p,T)$

- We can also draw diagrams of h or u as a function of p, T, or v (two variables needed)

Enthalpy of Vaporization



- The amount of energy needed to transform liquid into vapor at given pressure or temperature per mass.
- The enthalpy of saturated vapor minus enthalpy of saturated liquid
- It decreases as temperature or pressure increases; it is zero at the critical point

Additional Note on Enthalpy

- The enthalpy, internal energy, and entropy (will be introduced later) cannot be readily measured.

- They are calculated based on measured properties and thermodynamic relations and therefore always given in reference to a point as absolute values are not known.

- E.g. for water the reference is saturated liquid at 0.01°C, i.e. the internal energy and entropy are zero at this condition.

- The 1st law of thermodynamics deals with differences and not absolute values anyway!

Specific Heat

- Amount of heat that must be added to one unit of mass of the substance in order to cause an increase of one unit in temperature under certain conditions.

- Specific heat at a constant volume, c_v [J/kg/K]

$$c_v = \left(\frac{\delta Q}{\partial T}\right)\Big|_v$$

- Specific heat at a constant pressure, c_p [J/kg/K]

$$c_p = \left(\frac{\delta Q}{\partial T}\right)\Big|_p$$

Specific Heat

- Consider a pure substance system where there's no variation in potential and kinetic energy ($\Delta E = \Delta U$) and the only form of work is expansion/compression work (simple compressible system)

- At a constant volume, amount of heat absorbed equals the internal energy increase (no work).

$$c_v = \left(\frac{\partial u}{\partial T}\right)\Big|_v$$

- At a constant pressure, first law requires $du = \delta q - pdv$ (differential intensive form); $\delta q = (du + pdv)|_p = d(u + pv)|_p = dh|_p$

$$c_p = \left(\frac{\partial h}{\partial T}\right)\Big|_p$$

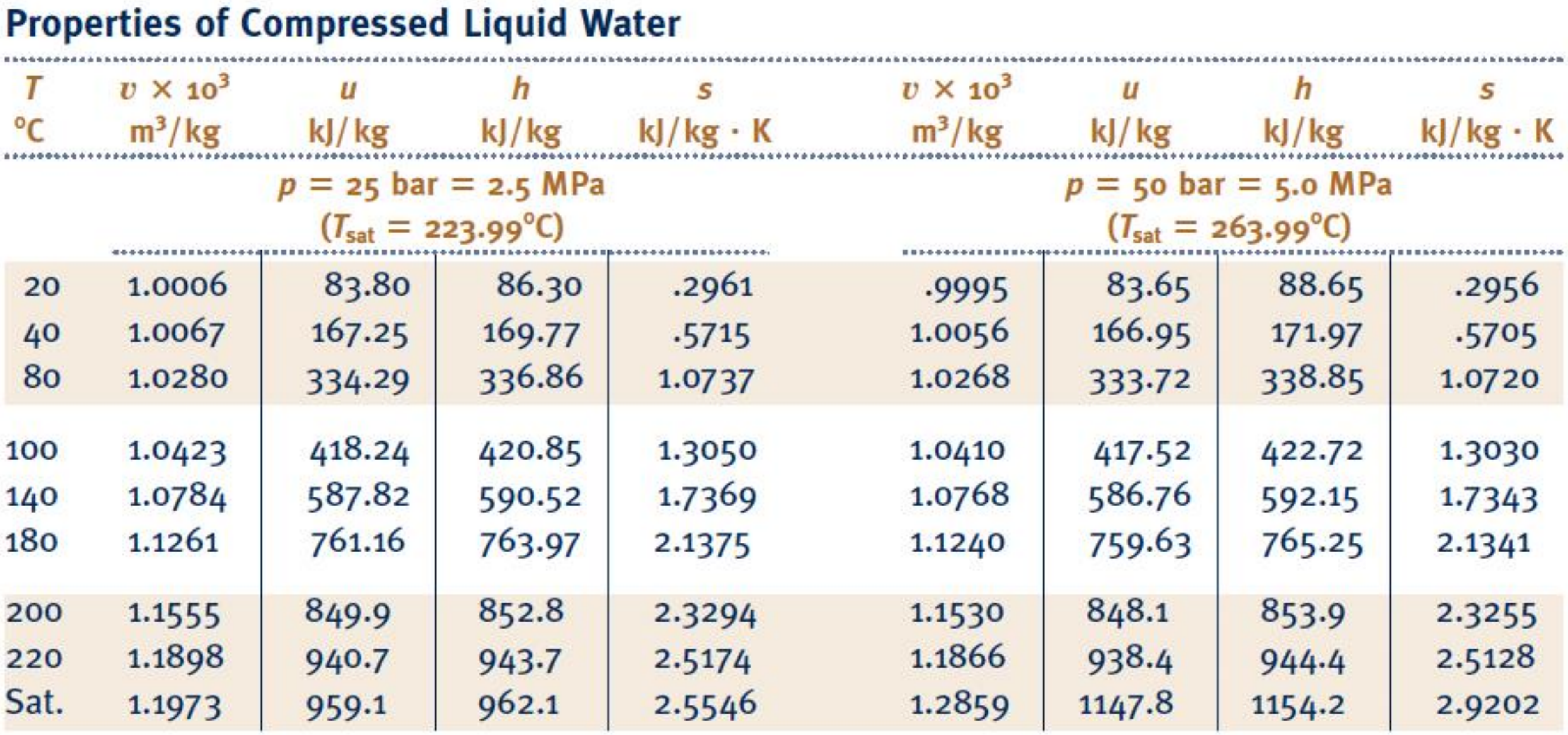
Additional Note on Specific Heat

- Both c_v and c_p are thermodynamics properties, not dependent on processes
- $c_v = \left(\frac{\partial u}{\partial T}\right)|_v$ is a function of T and v
- $c_p = \left(\frac{\partial h}{\partial T}\right)|_p$ is a function of T and p
- $c_v < c_p$ because at a constant pressure, system is allowed to expand when being heated (not all heat are used to raise temperature)
- Specific ratio $k = \frac{c_p}{c_v} > 1$

Property Tables

- Compressed liquid (e.g., Table-A5)
- Superheated vapor (e.g., Table-A2, A3)
- Saturated liquid-vapor mixture (e.g., Table-A4)

Property Tables



Properties of Compressed Liquid Water

T °C	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 25 bar = 2.5 MPa (T_{sat} = 223.99°C)				p = 50 bar = 5.0 MPa (T_{sat} = 263.99°C)			
20	1.0006	83.80	86.30	.2961	.9995	83.65	88.65	.2956
40	1.0067	167.25	169.77	.5715	1.0056	166.95	171.97	.5705
80	1.0280	334.29	336.86	1.0737	1.0268	333.72	338.85	1.0720
100	1.0423	418.24	420.85	1.3050	1.0410	417.52	422.72	1.3030
140	1.0784	587.82	590.52	1.7369	1.0768	586.76	592.15	1.7343
180	1.1261	761.16	763.97	2.1375	1.1240	759.63	765.25	2.1341
200	1.1555	849.9	852.8	2.3294	1.1530	848.1	853.9	2.3255
220	1.1898	940.7	943.7	2.5174	1.1866	938.4	944.4	2.5128
Sat.	1.1973	959.1	962.1	2.5546	1.2859	1147.8	1154.2	2.9202

Property Tables

- How to determine properties from tables:
  - Linear interpolation of desired property (*u*, *v*, *s*, *h*, …) for desired temperature, pressure, … (*z*):

$$f(z) = \frac{f(z_2) - f(z_1)}{z_2 - z_1}(z - z_1) + f(z_1)$$

Moran 3.8.1

- **Instead of tables, we can also use databases online, e.g.:**
  - http://www.coolprop.org/

Sample Code

- https://colab.research.google.com/drive/1x1MU3CXz5fMMe7nZgiKsZopjYz2jvvQ1?usp=sharing

- Read the manual before using the package

http://www.coolprop.org/coolprop/HighLevelAPI.html#propssi-function