Thermodynamics ENME 333
Chapter 5
First Law of Thermodynamics
(Energy Equation)

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Outline

- First law for a cycle
- First law for control mass
- Internal energy
- Enthalpy
- Specific heats

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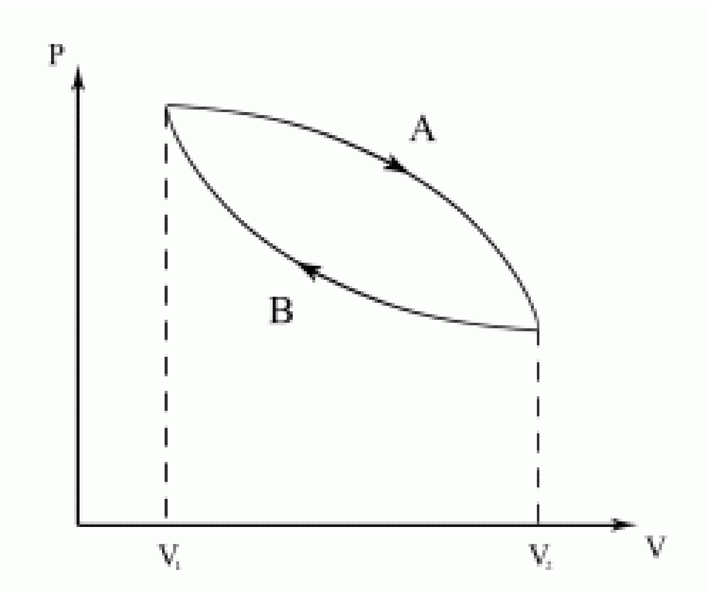
First law for a thermodynamic cycle

- Based on experimental evidence, first law for a thermodynamic cycle is given as in eqn 5.2 p.97.

$$\oint \delta Q = \oint \delta W$$

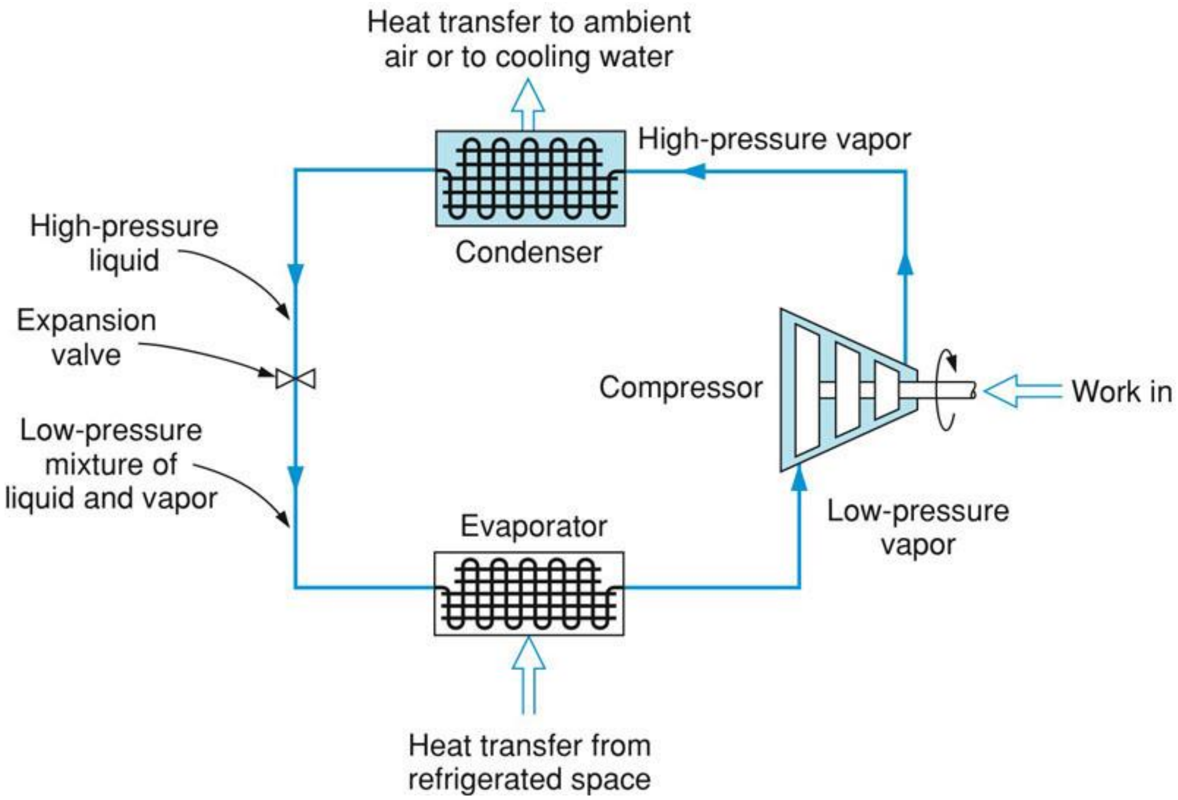
- The total heat transfer around the cycle equals the total work around the cycle.
- As an exercise apply the first law to the thermodynamic cycle of the simple steam power plant, and the vapor compression cycles in chapter one. You should take into consideration the sign for both work and heat.



Vapor compression cycle

$$\oint \delta Q = \oint \delta W$$

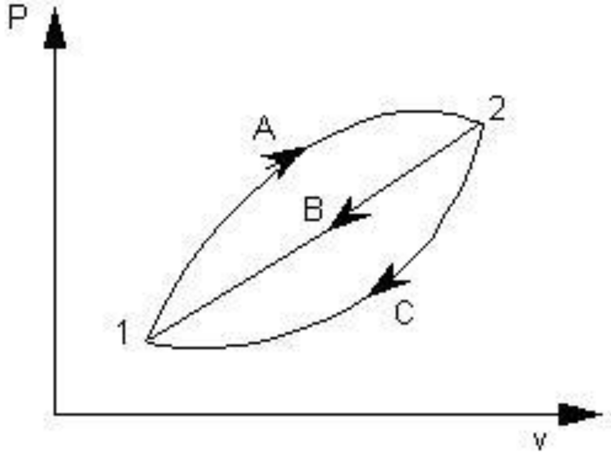
- $-Q_{\text{condenser}} + Q_{\text{evaporator}} = -W_{\text{compressor}}$
- $Q_{\text{condenser}} - Q_{\text{evaporator}} = W_{\text{compressor}}$



First law for a process

Undergoes a cycle changing from state 1 to 2 by process A and returning from state 2 to 1 by process B

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$$



The system changing from State 1 to 2 by process A and returning to state 1 by process C

$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_C = \int_1^2 \delta W_A + \int_2^1 \delta W_C$$

Subtracting the equations we get:

$$\int_1^2 \delta Q_B - \int_2^1 \delta Q_C = \int_2^1 \delta W_B - \int_2^1 \delta W_C$$

$$\int_2^1 (\delta Q - \delta W)_B = \int_2^1 (\delta Q - \delta W)_C$$

Energy of the system

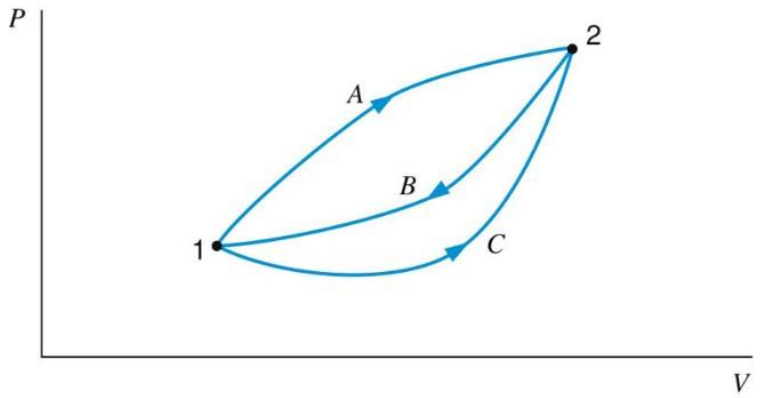
- the quantity (dQ -dW) is the same for all processes between states 1 and 2

- Therefore, (dQ -dW) depends only on the initial and final states and not on the path followed between the two states.
- That is this quantity is a *point function,* which means that it is a *property* of the system,
- It is called the *energy* of the system and is given symbol E

First law for a change of state of a control mass

- By choosing an arbitrary cycles A-B and A-C as shown in figure 5.2 p.98 and applying first law to them you conclude that the difference between heat and work is constant or path independent as given in eqn 5.3,

$$dE = \delta Q - \delta W$$



- This new path independent function is called the total energy of the system E, hence first law for the control mass is given by eqn 5.4 as differential form or eqn 5.5 in the integrated form.

- $E2 - E1 = 1Q2 - 1W2$

First law for a change of state of a control mass

- dE/dt = + energy in – energy out
- Integrating from 1 to 2
- Energy in and out with flowing material also across boundary in form of work and heat.
- E2-E1 = Energy transfer in – energy transfer out= Q –W
- Energy added as heat is positive while energy added by work is negative according to the sign convention.

Total Energy

- The total energy as given in eqn 5.6 consists of the potential energy PE, the kinetic energy KE and the internal energy U,
- E = KE+PE +Internal energy
- dE=d(KE)+d(PE)+dU
- Now first law is written as in eqn 5.7 $dE = \delta Q - \delta W$

$$\delta Q = dU + d(KE) + d(PE) + \delta W$$

- But KE = (½)mV^2, PE = mgz

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First law for cm

- However when the known forms of PE and KE are substituted in the first law we obtain the integrated form of the first law in eqn 5.11 p. 101.

$$1Q2 = U2 - U1 + \frac{m(V2^2 - V1^2)}{2} + mg(Z2 - Z1) + 1W2$$

Internal energy

- Nature of the internal energy, U, is well explained in chapter two pp.24-26.
- In summary you make think of internal energy in microscopic level as the energy of molecules and this energy is of two parts: kinetic and potential energies. Kinetic energy of molecules takes different forms as translation kinetic energy when molecules move, rotational energy as they rotate and vibration energy of the bonds between atoms, more atoms means more vibration modes and larger kinetic energy.
- The specific internal energy or internal energy per unit mass u is a property of substance similar to temperature, pressure and specific volume. Hence it can be tabulated along with the other properties.

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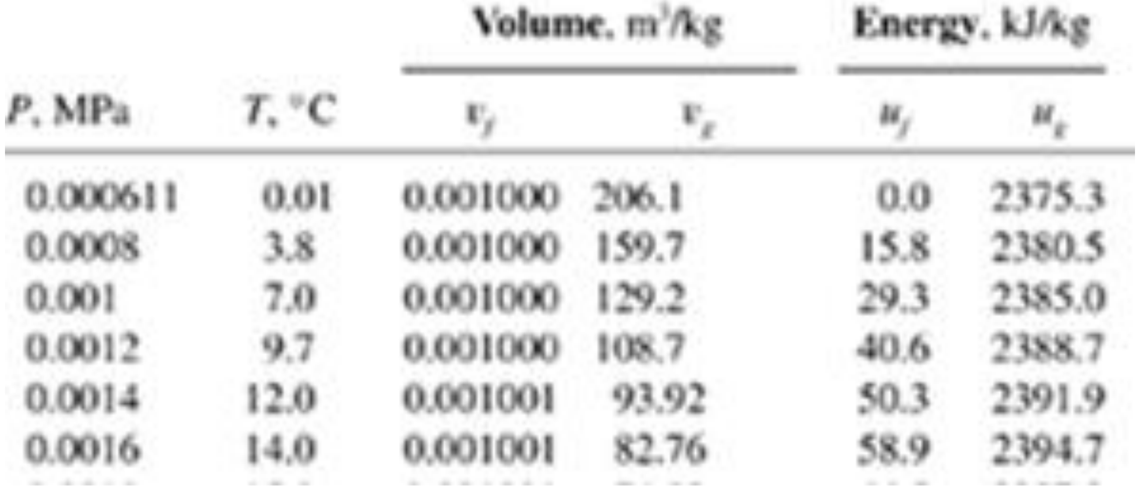
Internal energy

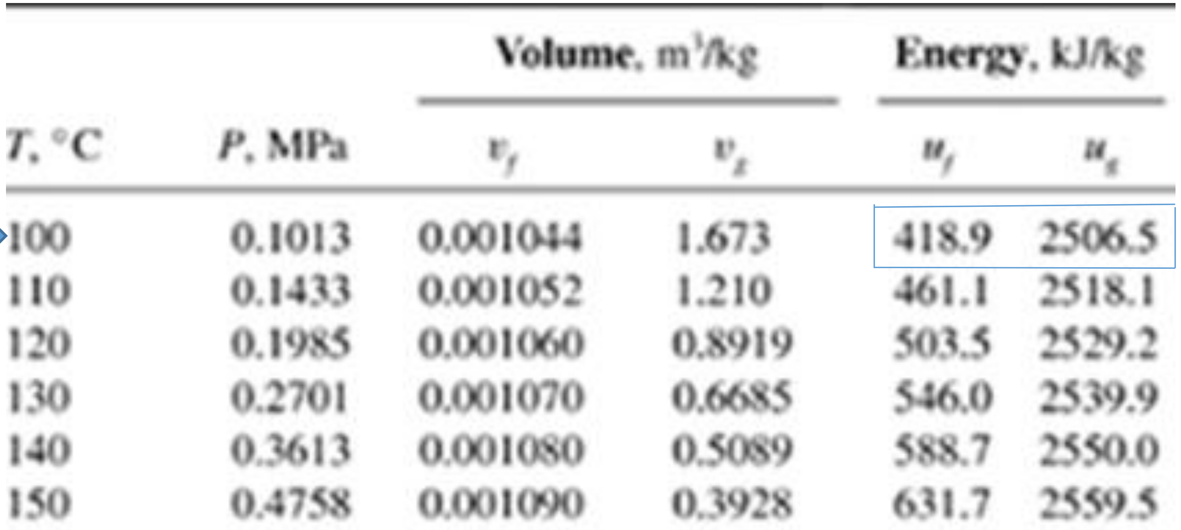
- See tables in appendix B. In saturation region internal energy of saturated liquid is given as u_f and internal energy of saturated vapor as u_g.

$$u = u_f + xu_{fg}$$

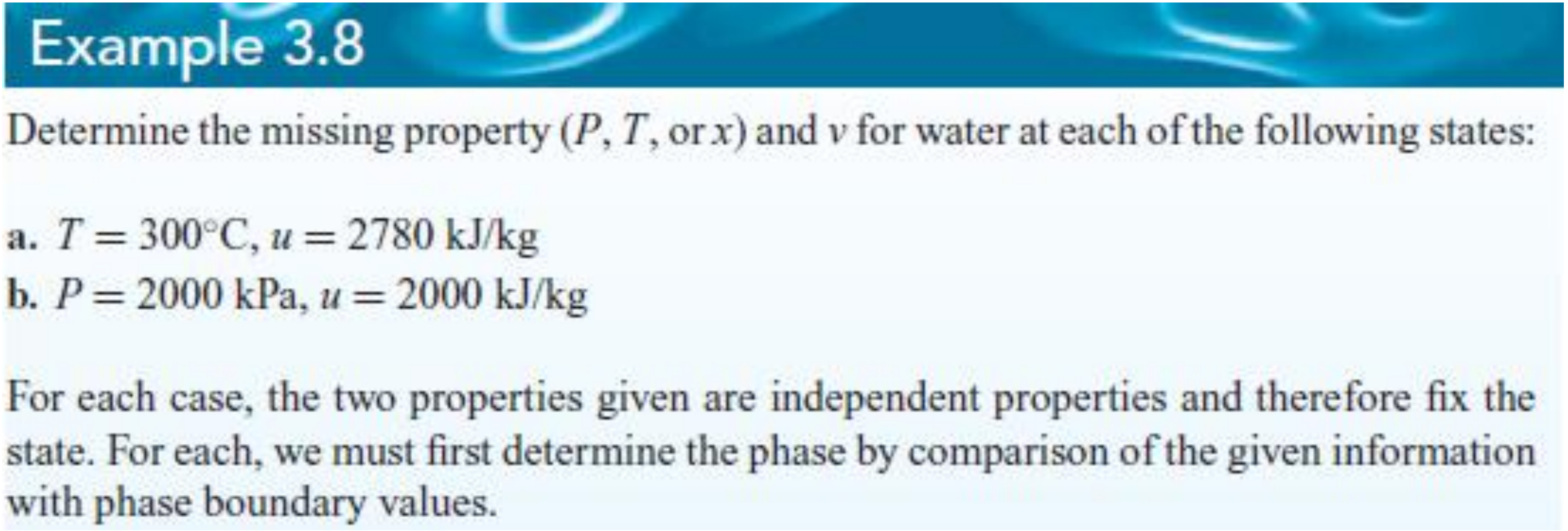
- As an exercise determine the internal energy of steam with 90% quality at 100 ^oC.
- See e.g 5.4 p. 125.



		Volume, m³/kg		Energy, kJ/kg	
P, MPa	T, °C	v_f	v_g	u_f	u_g
0.000611	0.01	0.001000	206.1	0.0	2375.3
0.0008	3.8	0.001000	159.7	15.8	2380.5
0.001	7.0	0.001000	129.2	29.3	2385.0
0.0012	9.7	0.001000	108.7	40.6	2388.7
0.0014	12.0	0.001001	93.92	50.3	2391.9
0.0016	14.0	0.001001	82.76	58.9	2394.7



		Volume, m³/kg		Energy, kJ/kg	
T, °C	P, MPa	v_f	v_g	u_f	u_g
100	0.1013	0.001044	1.673	418.9	2506.5
110	0.1433	0.001052	1.210	461.1	2518.1
120	0.1985	0.001060	0.8919	503.5	2529.2
130	0.2701	0.001070	0.6685	546.0	2539.9
140	0.3613	0.001080	0.5089	588.7	2550.0
150	0.4758	0.001090	0.3928	631.7	2559.5

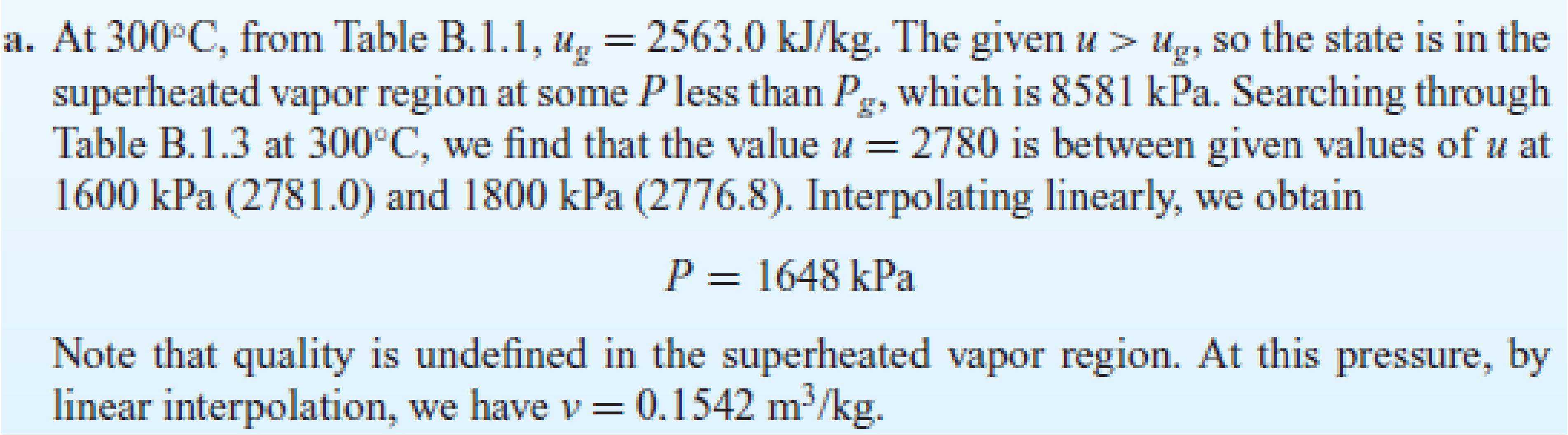


Example 3.8

Determine the missing property (P, T, or x) and v for water at each of the following states:

a. $T = 300°\text{C}$, $u = 2780$ kJ/kg
b. $P = 2000$ kPa, $u = 2000$ kJ/kg

For each case, the two properties given are independent properties and therefore fix the state. For each, we must first determine the phase by comparison of the given information with phase boundary values.



a. At 300°C, from Table B.1.1, $u_g = 2563.0$ kJ/kg. The given $u > u_g$, so the state is in the superheated vapor region at some P less than P_g, which is 8581 kPa. Searching through Table B.1.3 at 300°C, we find that the value $u = 2780$ is between given values of u at 1600 kPa (2781.0) and 1800 kPa (2776.8). Interpolating linearly, we obtain

$$P = 1648 \text{ kPa}$$

Note that quality is undefined in the superheated vapor region. At this pressure, by linear interpolation, we have $v = 0.1542\ \text{m}^3/\text{kg}$.

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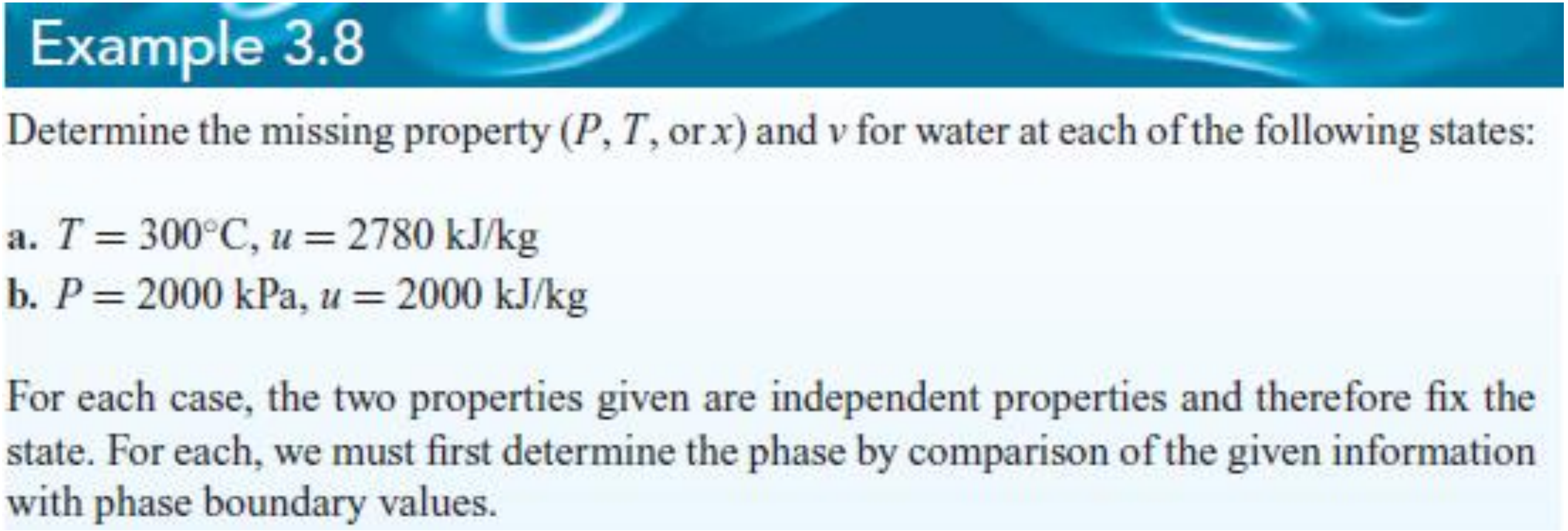

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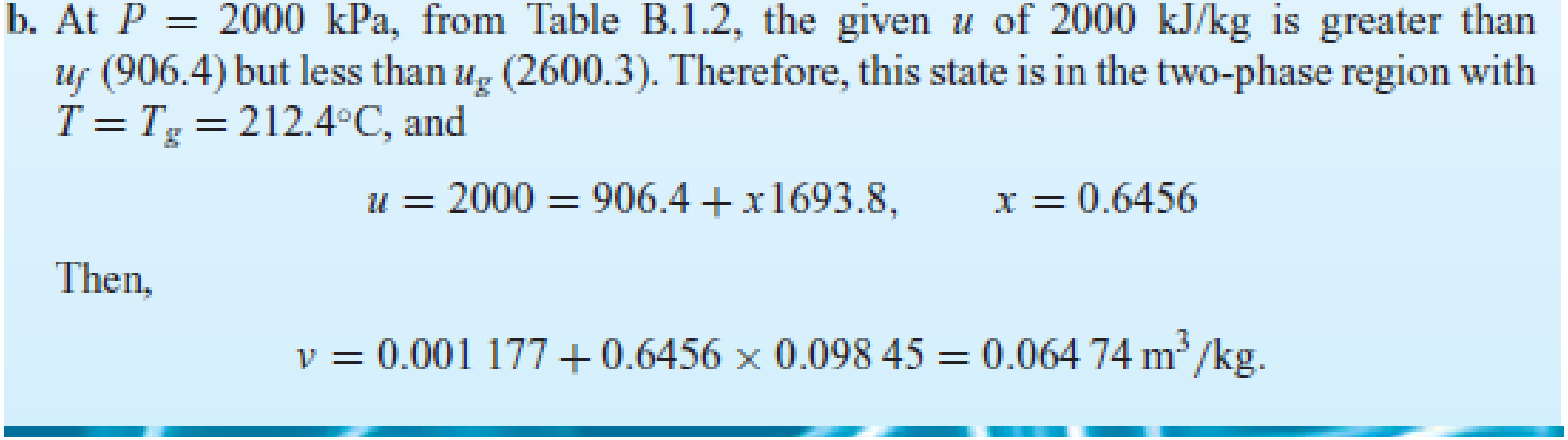

b. At $P = 2000$ kPa, from Table B.1.2, the given u of 2000 kJ/kg is greater than u_f (906.4) but less than u_g (2600.3). Therefore, this state is in the two-phase region with $T = T_g = 212.4°\text{C}$, and

$$u = 2000 = 906.4 + x1693.8, \qquad x = 0.6456$$

Then,

$$v = 0.001\,177 + 0.6456 \times 0.098\,45 = 0.064\,74 \text{ m}^3/\text{kg}.$$

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Problem Analysis & solution technique

- Draw schematic of system
- Show boundary of the system (c.v or c.m)
- Show flow of mass, if any, and of energy heat and work
- Write initial and final states if given
- Draw T-v or P-v diagrams showing all states and processes
- Properties model steam and refrigerant tables , ideal gas and so on.
- Equations including mass conservation and energy equation for c.m or c.v
- Solution technique finding all states , finding heat and work etc.

- Work e.g 5.5 p. 127
- Work e.g 5.6 p.132

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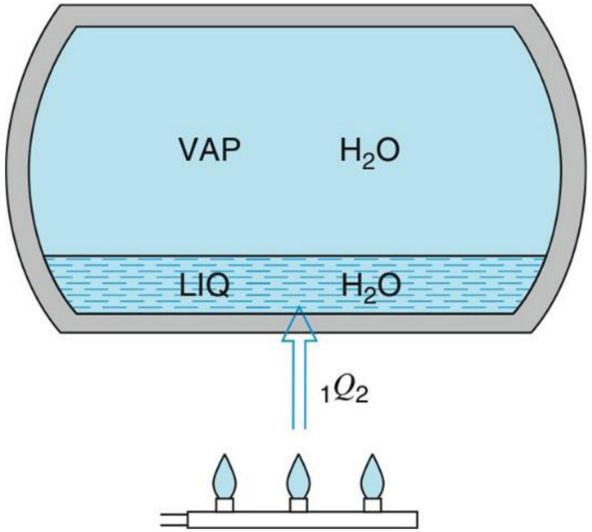
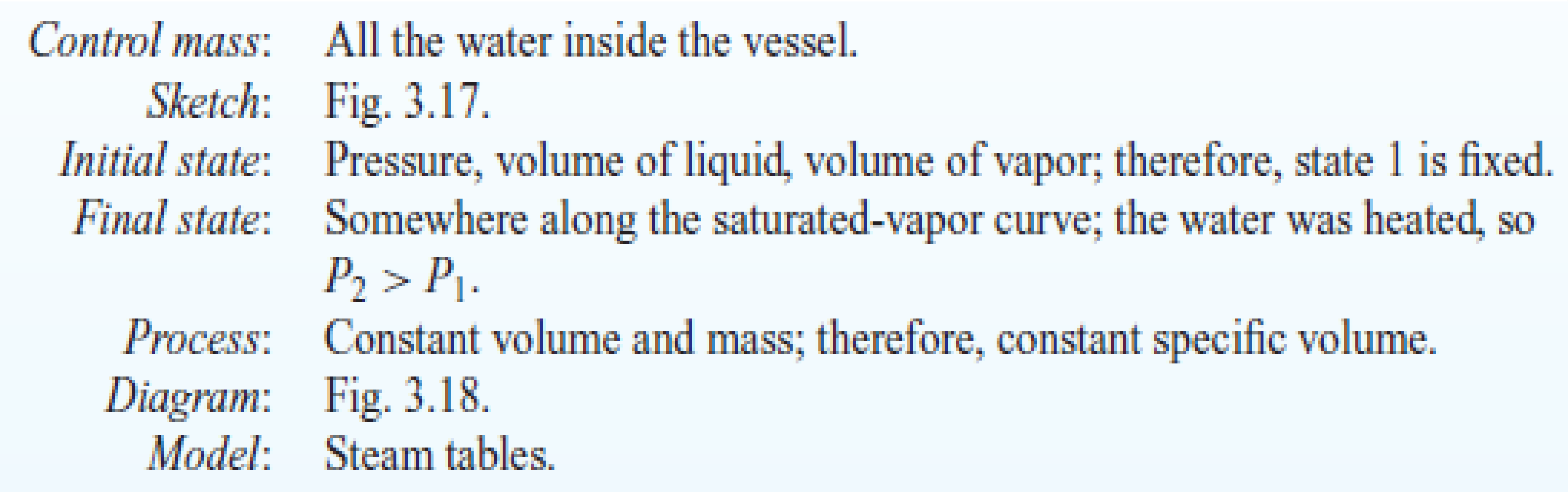
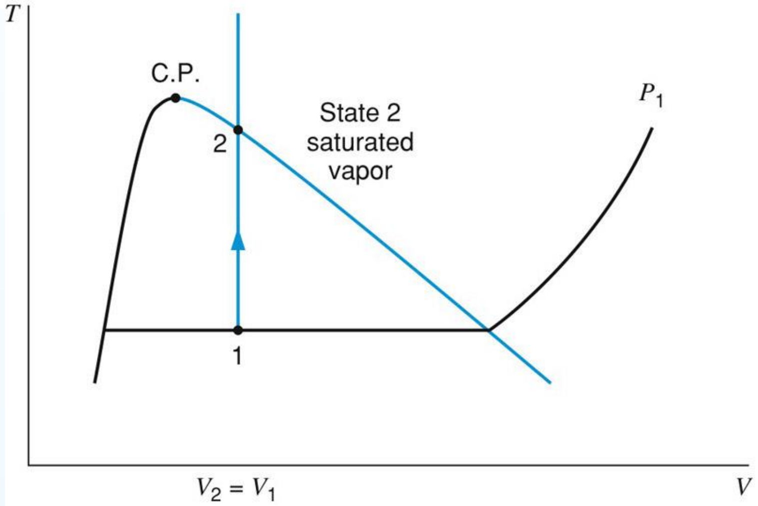
Example 5.5 p.127

- A vessel having a volume of 5 m3 contains 0.05 m3 of saturated liquid water and rest of saturated vapor at 0.1MPa. Heat is transferred until the vessel is filled with saturated vapor. Determine the heat transfer for this process.





Control mass: All the water inside the vessel.
Sketch: Fig. 3.17.
Initial state: Pressure, volume of liquid, volume of vapor; therefore, state 1 is fixed.
Final state: Somewhere along the saturated-vapor curve; the water was heated, so $P_2 > P_1$.
Process: Constant volume and mass; therefore, constant specific volume.
Diagram: Fig. 3.18.
Model: Steam tables.



From the energy equation we have

$$U_2 - U_1 + m\frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} + mg(Z_2 - Z_1) = {}_1Q_2 - {}_1W_2$$

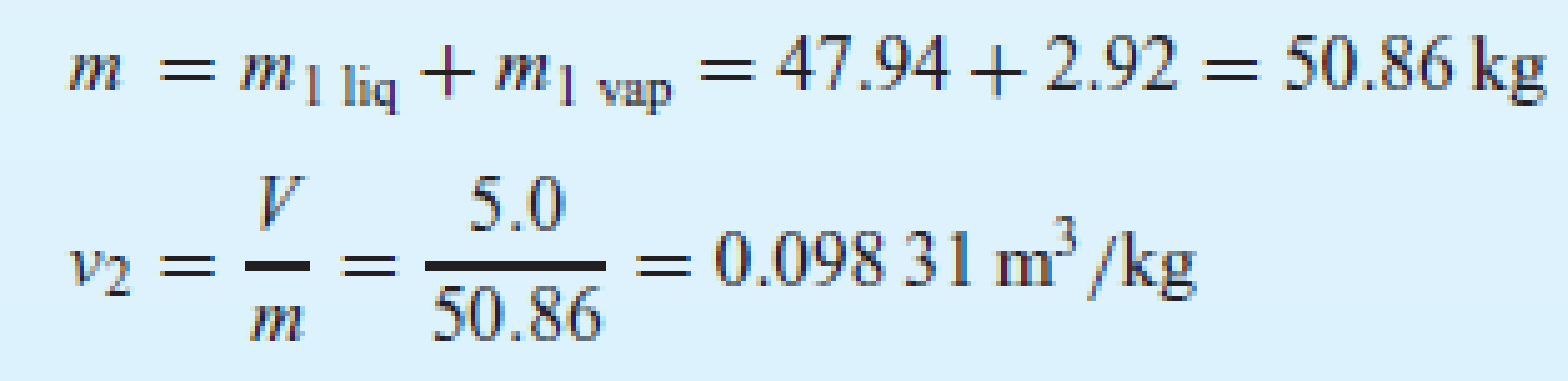
$${}_1Q_2 = U_2 - U_1$$

$$m_{1\,\text{liq}} = \frac{V_{\text{liq}}}{v_f} = \frac{0.05}{0.001\,043} = 47.94\text{ kg}$$

$$m_{1\,\text{vap}} = \frac{V_{\text{vap}}}{v_g} = \frac{4.95}{1.6940} = 2.92\text{ kg}$$

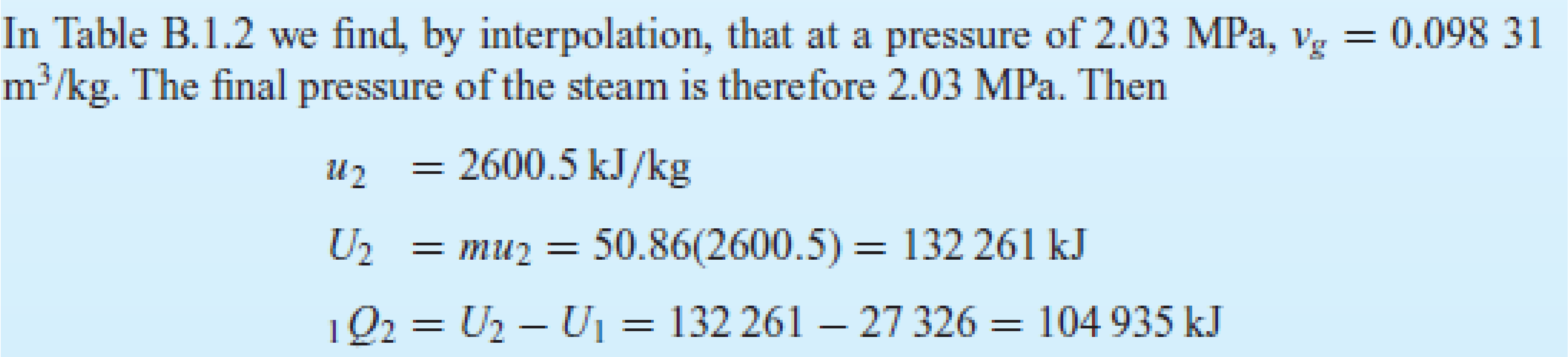
$$U_1 = m_{1\,\text{liq}}u_{1\,\text{liq}} + m_{1\,\text{vap}}u_{1\,\text{vap}}$$

$$= 47.94(417.36) + 2.92(2506.1) = 27\,326\text{ kJ}$$



$$m = m_{1\,\text{liq}} + m_{1\,\text{vap}} = 47.94 + 2.92 = 50.86\ \text{kg}$$

$$v_2 = \frac{V}{m} = \frac{5.0}{50.86} = 0.098\,31\ \text{m}^3/\text{kg}$$



In Table B.1.2 we find, by interpolation, that at a pressure of 2.03 MPa, $v_g = 0.098\,31$ m^3/kg. The final pressure of the steam is therefore 2.03 MPa. Then

$$u_2 = 2600.5\ \text{kJ/kg}$$

$$U_2 = mu_2 = 50.86(2600.5) = 132\,261\ \text{kJ}$$

$$_1Q_2 = U_2 - U_1 = 132\,261 - 27\,326 = 104\,935\ \text{kJ}$$

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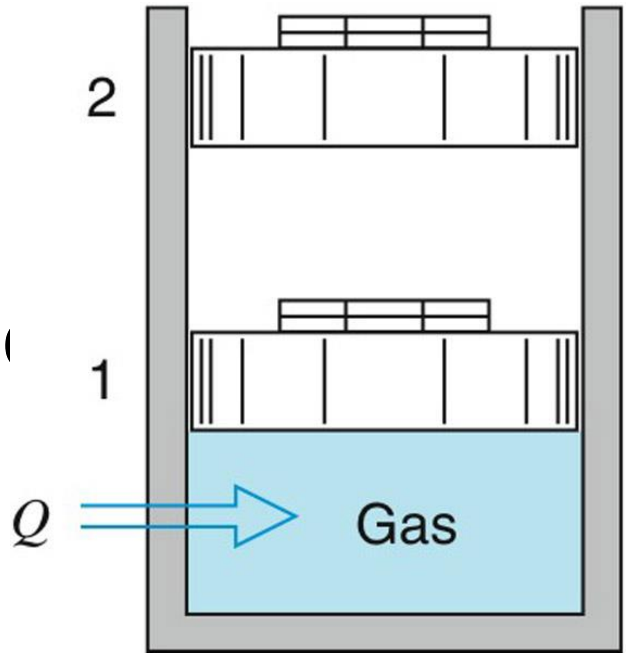
Example 5.6

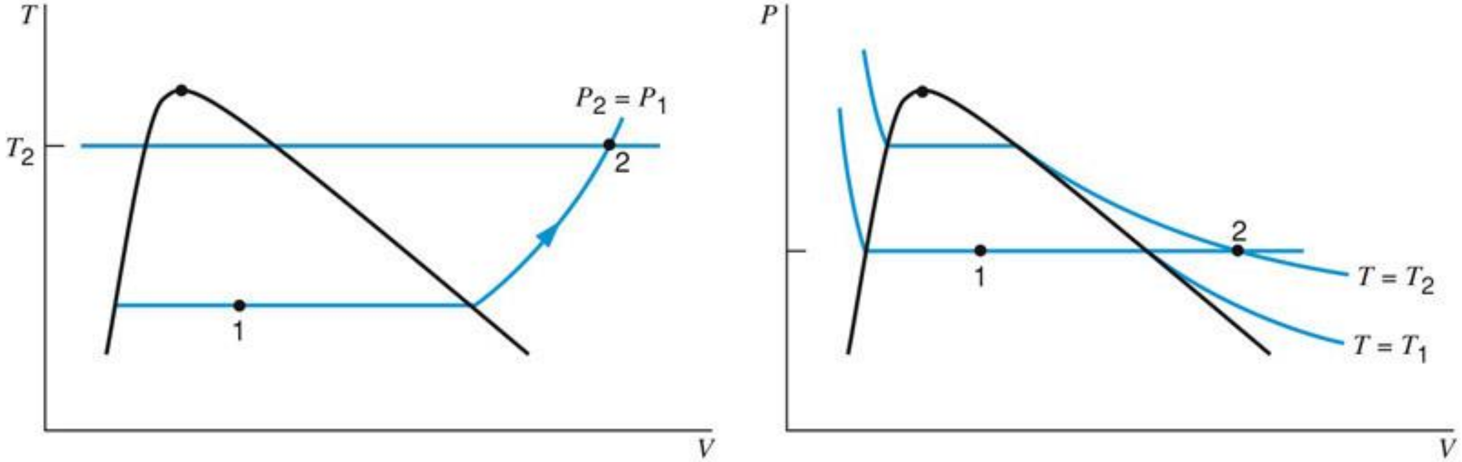


- A cylinder fitted with a piston has a volume of 0.1 m^3 and contains 0.5 kg of steam at 0.4 MPa. Heat is transferred to the steam until the temperature is 300 $^{\circ}$ while the pressure remains constant. Determine the heat transfer and the work for this process.

$$1Q2 = U2 - U1 + \frac{m(V2^2 - V1^2)}{2} + mg(Z2 - Z1) + 1W2$$

$W = P(V2 - V1)$=P(mv2-V1)

$U2 - U1 = m(u2 - u1)$



Find v1= V1/m then x1 then u1 at 0.4MPa,

State 2: 0.4MPa , 300^{o}C

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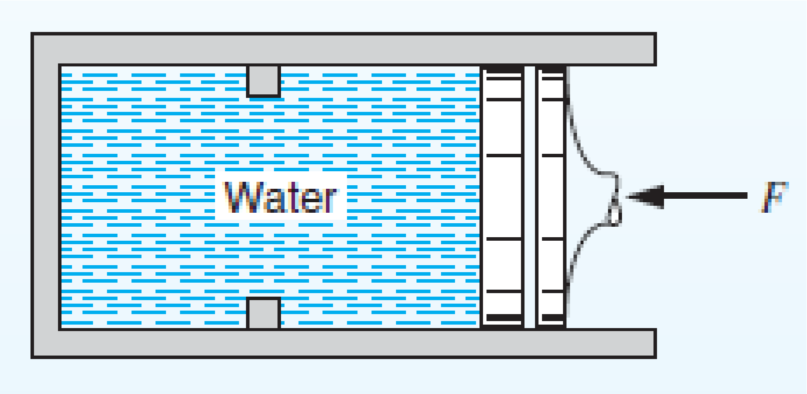
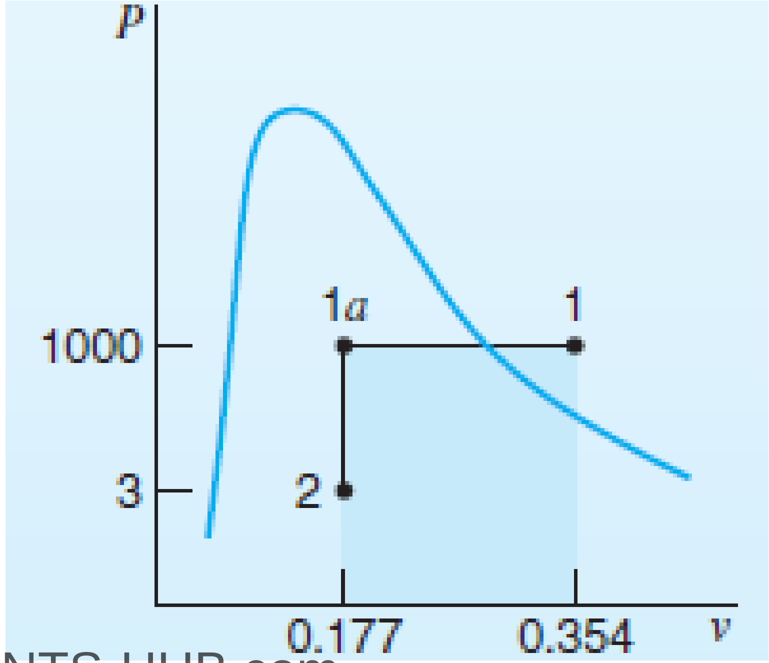
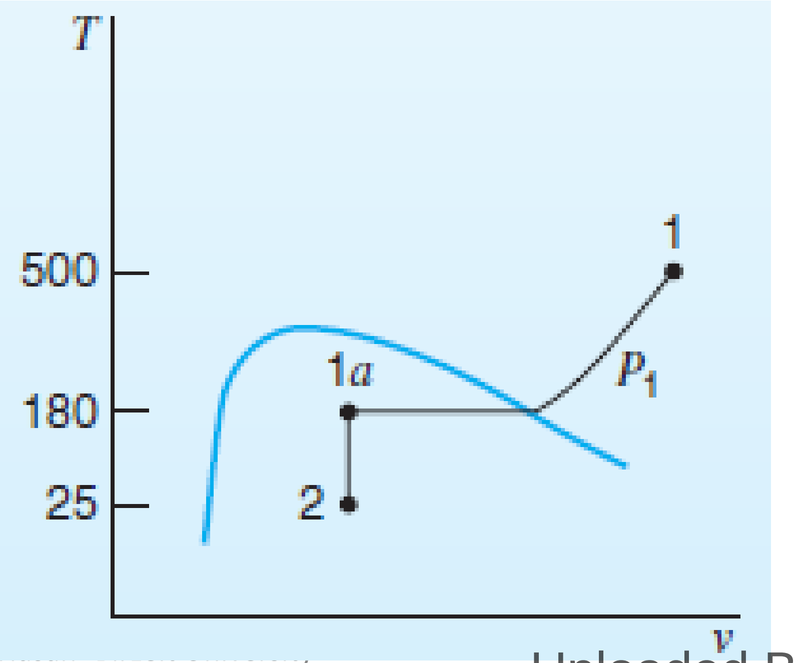
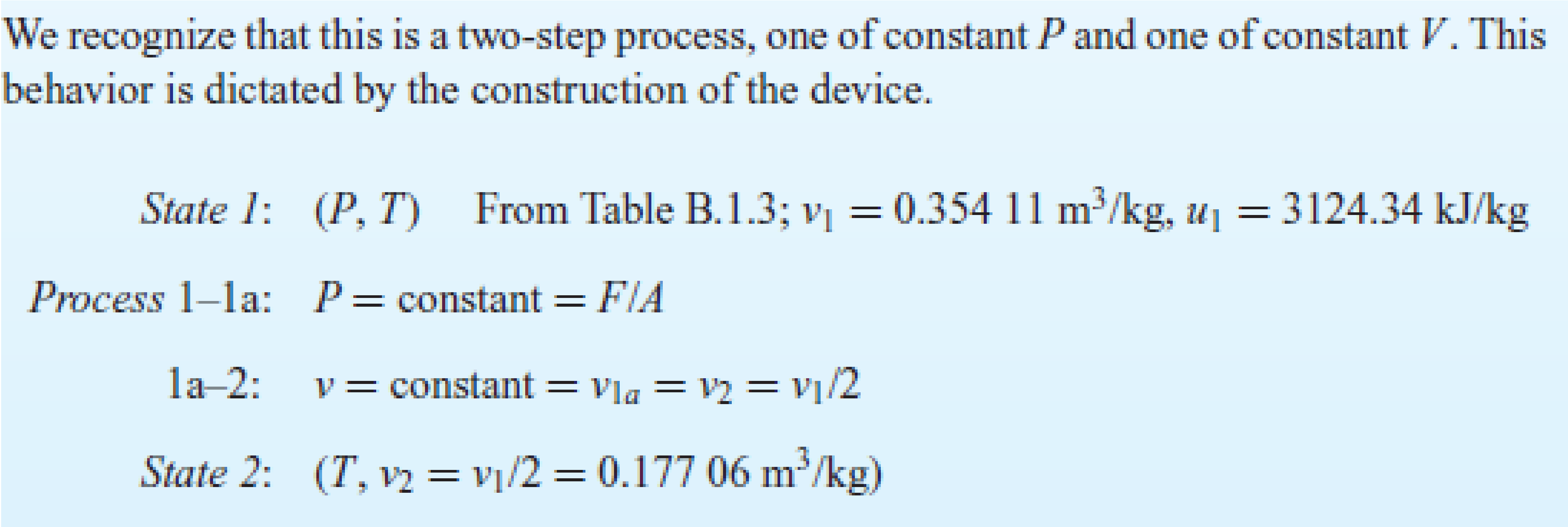
Example 3.11

The piston/cylinder setup shown in Fig. 3.20 contains 0.1 kg of water at 1000 kPa, 500◦C. The water is now cooled with a constant force on the piston until it reaches half of the initial volume. After this it cools to 25◦C while the piston is against the stops. Find the final water pressure and the work and heat transfer in the overall process, and show the process in a P–v diagram.









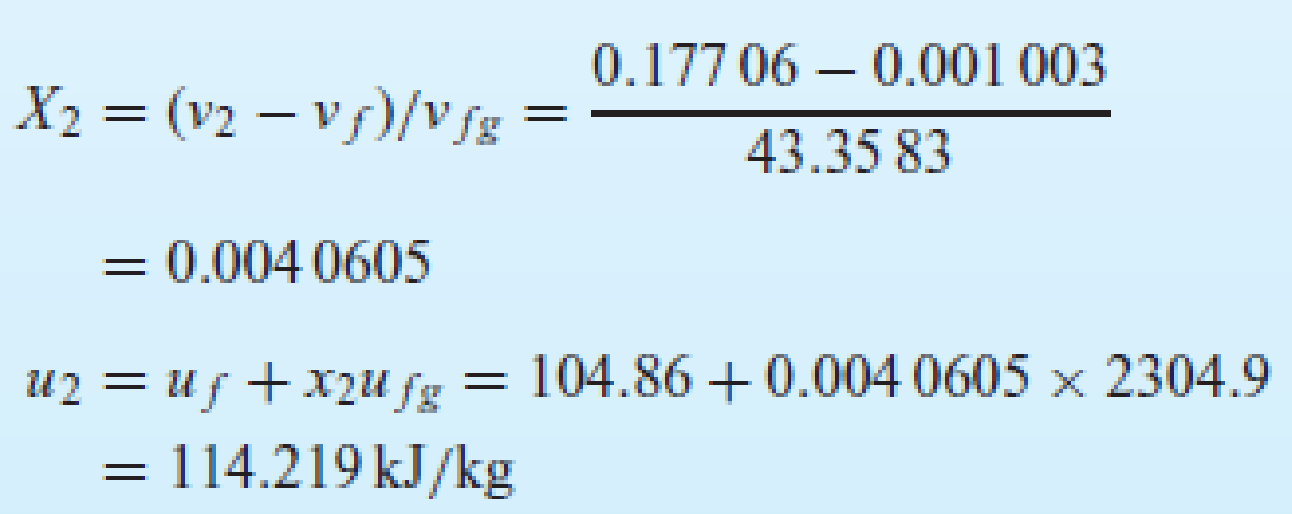
We recognize that this is a two-step process, one of constant P and one of constant V. This behavior is dictated by the construction of the device.

State 1: (P, T) From Table B.1.3; $v_1 = 0.354\,11\ \mathrm{m^3/kg}$, $u_1 = 3124.34\ \mathrm{kJ/kg}$

Process 1–1a: $P = \text{constant} = F/A$

1a–2: $v = \text{constant} = v_{1a} = v_2 = v_1/2$

State 2: $(T, v_2 = v_1/2 = 0.177\,06\ \mathrm{m^3/kg})$



$$X_2 = (v_2 - v_f)/v_{fg} = \frac{0.177\,06 - 0.001\,003}{43.35\,83}$$

$$= 0.004\,0605$$

$$u_2 = u_f + x_2 u_{fg} = 104.86 + 0.004\,0605 \times 2304.9$$
$$= 114.219\ \mathrm{kJ/kg}$$

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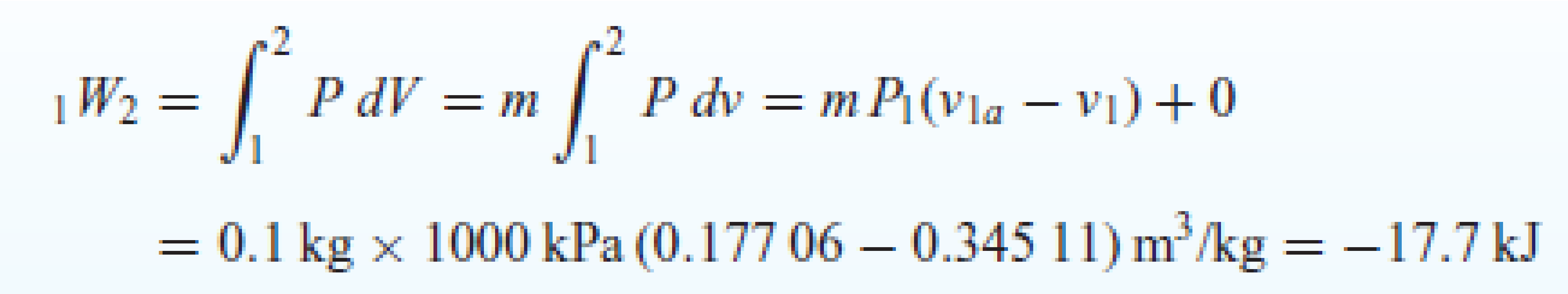
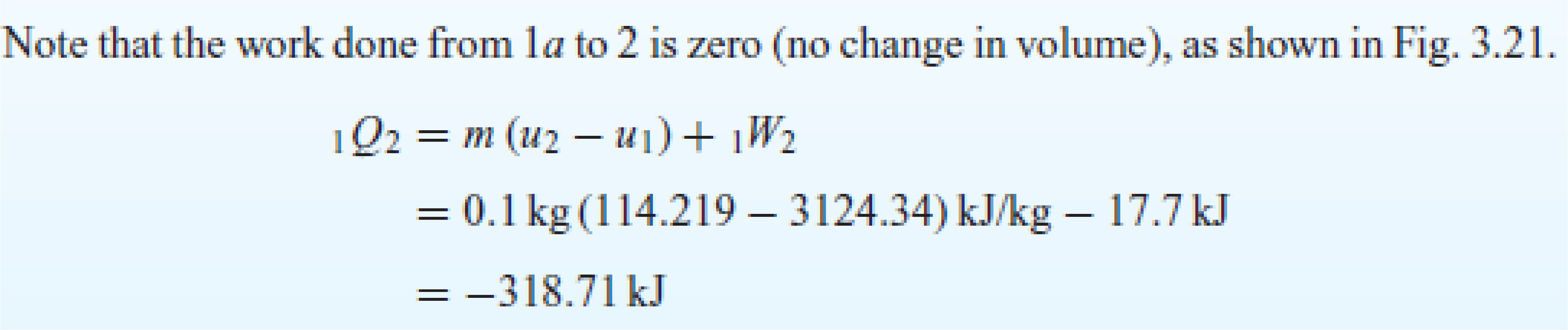


$$ {}_1W_2 = \int_1^2 P\,dV = m\int_1^2 P\,dv = mP_1(v_{1a} - v_1) + 0 $$

$$ = 0.1\ \mathrm{kg} \times 1000\ \mathrm{kPa}\,(0.177\,06 - 0.345\,11)\ \mathrm{m^3/kg} = -17.7\ \mathrm{kJ} $$



Note that the work done from 1*a* to 2 is zero (no change in volume), as shown in Fig. 3.21.

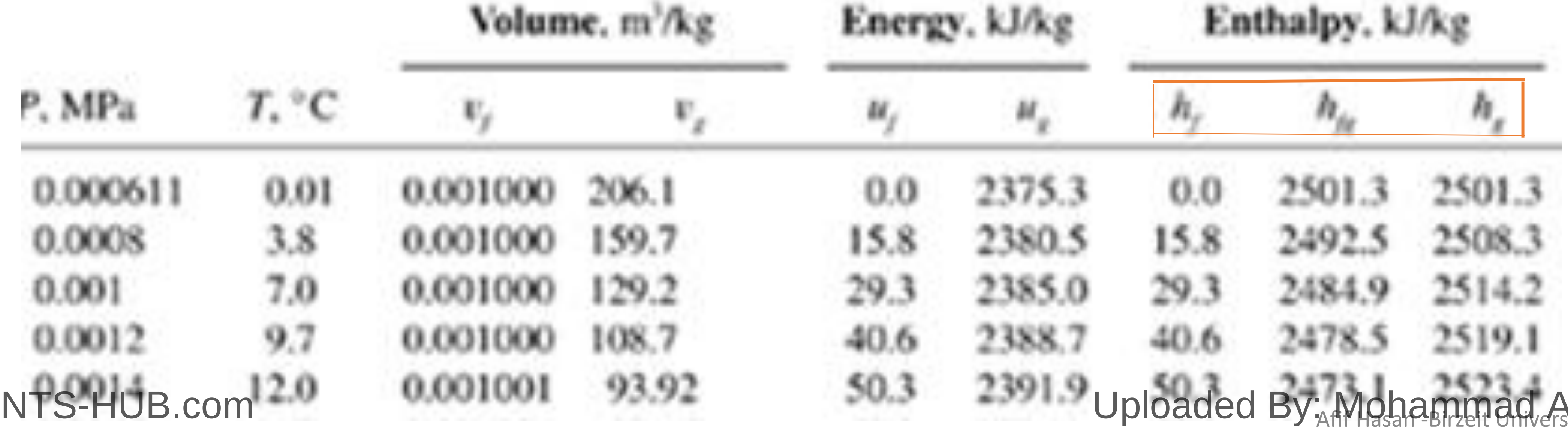
$$ {}_1Q_2 = m(u_2 - u_1) + {}_1W_2 $$

$$ = 0.1\ \mathrm{kg}\,(114.219 - 3124.34)\ \mathrm{kJ/kg} - 17.7\ \mathrm{kJ} $$

$$ = -318.71\ \mathrm{kJ} $$

Thermodynamic property enthalpy

- Combination of thermodynamic properties forms another thermodynamic property, enthalpy is one example of such property. Total enthalpy is H and specific enthalpy is h and it is defined as
- H= U + PV and h = u + Pv
- Refer to appendix B to get values of enthalpy. Note in saturation region enthalpy of saturated liquid h_f and enthalpy of saturated vapor h_g , h_{fg} for evaporation or latent heat



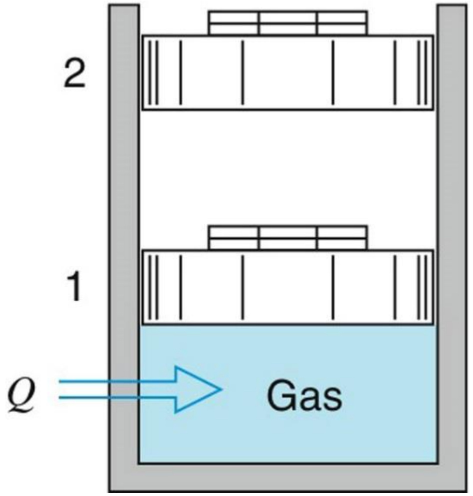
		Volume, m³/kg		Energy, kJ/kg		Enthalpy, kJ/kg		
P, MPa	T, °C	v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g
0.000611	0.01	0.001000	206.1	0.0	2375.3	0.0	2501.3	2501.3
0.0008	3.8	0.001000	159.7	15.8	2380.5	15.8	2492.5	2508.3
0.001	7.0	0.001000	129.2	29.3	2385.0	29.3	2484.9	2514.2
0.0012	9.7	0.001000	108.7	40.6	2388.7	40.6	2478.5	2519.1
0.0014	12.0	0.001001	93.92	50.3	2391.9	50.3	2473.1	2523.4

Enthalpy

- Enthalpy of mixture of liquid and vapor : $h = h_f + xh_{fg}$
- An example of how the enthalpy appears in problems is the isobaric expansion of simple compressible control mass. Refer to p. 108 for development of such example.
- Question: Find enthalpy for the following:

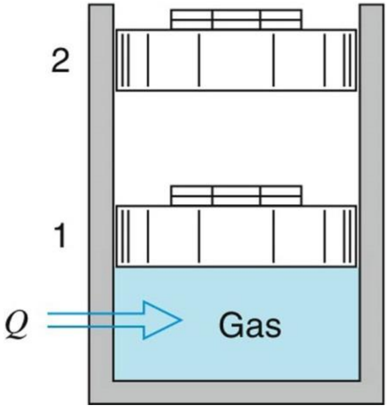
  Water 200 ^{o}C, 1 MPa; R-12 10 ^{o}C , 70% quality; and water at critical point.
- Internal energy u may be calculated from the enthalpy values as,

  u = h-Pv
- Question: Calculate internal energy of superheated ammonia vapor at 1200 kPa , 100^{o}C.



Example 3.12

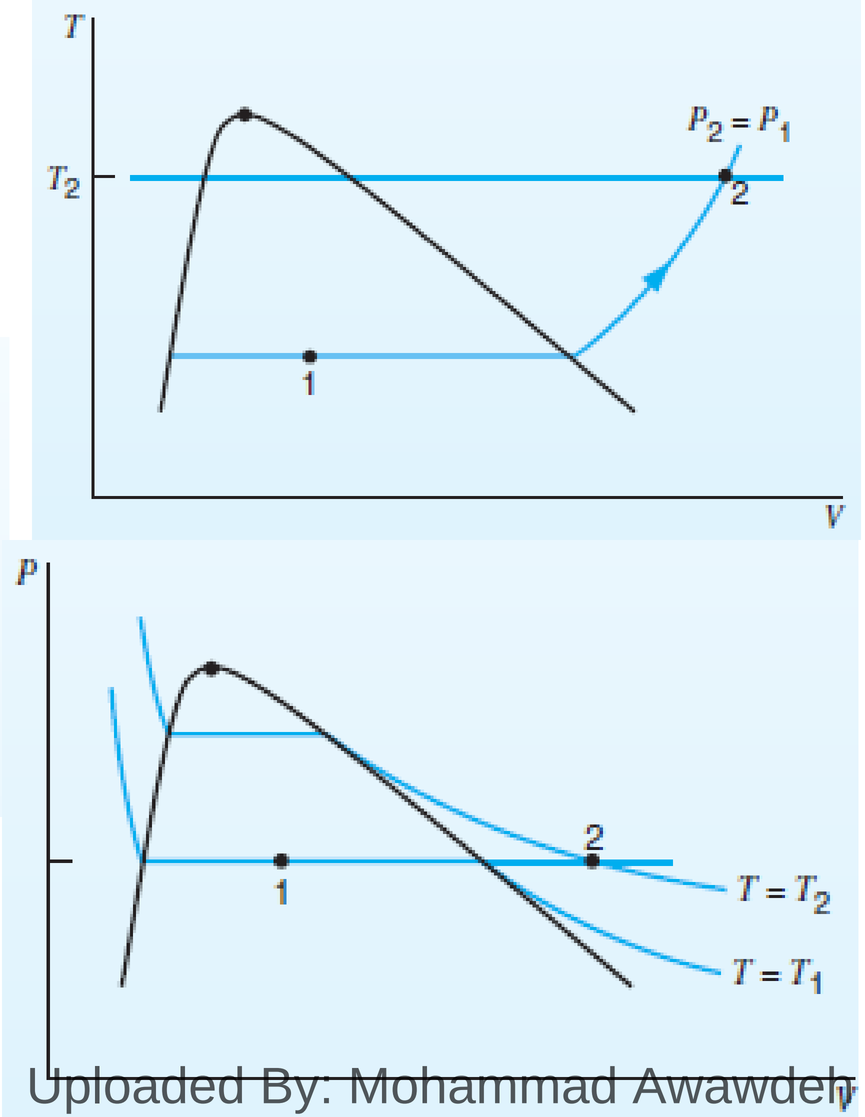
A cylinder fitted with a piston has a volume of 0.1 m3 and contains 0.5 kg of steam at 0.4MPa. Heat is transferred to the steam until the temperature is 300◦C,while the pressure remains constant. Determine the heat transfer



Control mass:	Water inside cylinder.
Process:	Constant pressure, $P_2 = P_1$
Initial state:	P_1, V_1, m; therefore, v_1 is known, state 1 is fixed (at P_1, v_1, check steam tables—two-phase region).
Final state:	P_2, T_2; therefore, state 2 is fixed (superheated).
Diagram:	Fig. 3.23.
Model:	Steam tables.

$$ {}_1Q_2 = m(u_2 - u_1) + {}_1W_2 $$

$$ {}_1W_2 = \int_1^2 P\,dV = P\int_1^2 dV = P(V_2 - V_1) = m(P_2v_2 - P_1v_1) $$



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$$
\begin{aligned}
{}_1Q_2 &= m(u_2 - u_1) + {}_1W_2 \\
&= m(u_2 - u_1) + m(P_2v_2 - P_1v_1) = m(h_2 - h_1)
\end{aligned}
$$

$$v_1 = \frac{V_1}{m} = \frac{0.1\ m^3}{0.5\ \text{kg}} = 0.2 = (0.001\,084 + x_1 0.4614)\frac{m^3}{\text{kg}}$$

$$x_1 = \frac{0.1989}{0.4614} = 0.4311$$

$$
\begin{aligned}
h_1 &= h_f + x_1 h_{fg} \\
&= 604.74 + 0.4311 \times 2133.8 = 1524.7\ \text{kJ/kg}
\end{aligned}
$$

$$h_2 = 3066.8\ \text{kJ/kg}$$

$${}_1Q_2 = 0.5\ \text{kg}\,(3066.8 - 1524.7)\ \text{kJ/kg} = 771.1\ \text{kJ}$$

$${}_1W_2 = mP(v_2 - v_1) = 0.5 \times 400(0.6548 - 0.2) = 91.0\ \text{kJ}$$

Constant –volume and constant –pressure specific heats

- Specific heat is defined as heat added per unit mass per degree.
  specific heat = dq/dT
- In general the temperature is related to pressure and volume by state equation, but T =f (P, V).
- When heating you may fix P or V.
- Specific volume at constant volume C_v is the heat added per unit mass per degree keeping volume constant.
- Specific heat at constant pressure C_p is the heat added per unit mass while keeping pressure constant.

Constant –volume and constant –pressure specific heats

- First law per unit mass: du = dq- dw also dw= Pdv
- Then at fixed volume C_v =dq/dT=du/dT

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v$$

- At constant pressure recall dq = dh
- Then C_p = dq/dT = dh/dT

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p$$

- Specific heats as function of temperature are given in table A.6 while specific heats of gases at 300 K is given in table A.5.
- For solids and liquids only one value of specific heat, since raising temperature does not effect significantly pressure and volume.
- Specific heats for various solids and liquids are listed in Tables A.3 and A.4 in the appendix

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Internal energy, enthalpy and specific heat of ideal gases

- Recall the ideal gas eqn

  $Pv = RT$

- It can be shown that for an ideal gas the internal energy is a function of temperature only. This was demonstrated the first time by Joule in 1843, see Joule experiment and analysis in p. 135.
- Sine internal energy of ideal gas is a function of temperature only

  $u = f(T)$ only

- then the specific heat at constant volume $C_v = dq/dT = du/dT$

$C_{vo} = du/dT \Rightarrow du = C_{vo}dT$, the subscript o denotes specific heat of ideal gas

Integrate to get

$\Delta u = \int_{T1}^{T2} C_{vo} dT$ Function of C_{vo} is given in table A.6

Joule experiment

- Two chambers one gas a second vacuum, water bath
- Open valve and gas expands into both chambers, no change in temperature.
- No heat transfer, no work, why? Hence no change in u
- Now pressure and volume changed however u did not change meaning u is not a function of P,V. results it is function of T only.
- For ideal gas u=f(T) only

Specific heat at constant pressure

- Similarly it can be shown that enthalpy of ideal gas is a function of temperature only (prove this using definition of enthalpy).

  $h = u + Pv = f(T) + RT$

- The specific heat at constant pressure for ideal gas $C_p = dq/dT = dh/dT$ becomes $C_{po} = dh/dT$ then

  $dh = C_{po}\, dT$

Integrate to get

$\Delta h = \int_{T1}^{T2} C_{po} dT$ see table A.6 for the function

$$h_2 - h_1 = \int_{T0}^{T2} C_{po} dT - \int_{T0}^{T1} C_{po} dT = h_{T2} - hT_1$$

For h_T see table A.7 for air and A.8 for other gases

TABLE A.5

Properties of Various Ideal Gases at 25°C, 100 kPa*[a] *(SI Units)

Gas	Chemical Formula	Molecular Mass (kg/kmol)	R (kJ/kg-K)	ρ (kg/m^3)	C_{p0} (kJ/kg-K)	C_{v0} (kJ/kg-K)	$k = \frac{C_p}{C_v}$
Steam	H_2O	18.015	0.4615	0.0231	1.872	1.410	1.327
Acetylene	C_2H_2	26.038	0.3193	1.05	1.699	1.380	1.231
Air	—	28.97	0.287	1.169	1.004	0.717	1.400
Ammonia	NH_3	17.031	0.4882	0.694	2.130	1.642	1.297
Argon	Ar	39.948	0.2081	1.613	0.520	0.312	1.667
Butane	C_4H_{10}	58.124	0.1430	2.407	1.716	1.573	1.091
Carbon dioxide	CO_2	44.01	0.1889	1.775	0.842	0.653	1.289
Carbon monoxide	CO	28.01	0.2968	1.13	1.041	0.744	1.399
Ethane	C_2H_6	30.07	0.2765	1.222	1.766	1.490	1.186
Ethanol	C_2H_5OH	46.069	0.1805	1.883	1.427	1.246	1.145
Ethylene	C_2H_4	28.054	0.2964	1.138	1.548	1.252	1.237
Helium	He	4.003	2.0771	0.1615	5.193	3.116	1.667
Hydrogen	H_2	2.016	4.1243	0.0813	14.209	10.085	1.409
Methane	CH_4	16.043	0.5183	0.648	2.254	1.736	1.299
Methanol	CH_3OH	32.042	0.2595	1.31	1.405	1.146	1.227
Neon	Ne	20.183	0.4120	0.814	1.03	0.618	1.667
Nitric oxide	NO	30.006	0.2771	1.21	0.993	0.716	1.387
Nitrogen	N_2	28.013	0.2968	1.13	1.042	0.745	1.400
Nitrous oxide	N_2O	44.013	0.1889	1.775	0.879	0.690	1.274
n-Octane	C_8H_{18}	114.23	0.07279	0.092	1.711	1.638	1.044
Oxygen	O_2	31.999	0.2598	1.292	0.922	0.662	1.393
Propane	C_3H_8	44.094	0.1886	1.808	1.679	1.490	1.126
R-12	CCl_2F_2	120.914	0.06876	4.98	0.616	0.547	1.126
R-22	$CHClF_2$	86.469	0.09616	3.54	0.658	0.562	1.171
R-32	CF_2H_2	52.024	0.1598	2.125	0.822	0.662	1.242
R-125	CHF_2CF_3	120.022	0.06927	4.918	0.791	0.722	1.097
R-134a	CF_3CH_2F	102.03	0.08149	4.20	0.852	0.771	1.106
R-410a	—	72.585	0.11455	2.967	0.809	0.694	1.165
Sulfur dioxide	SO_2	64.059	0.1298	2.618	0.624	0.494	1.263
Sulfur trioxide	SO_3	80.053	0.10386	3.272	0.635	0.531	1.196

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TABLE A7.1

Ideal Gas Properties of Air, Standard Entropy at 0.1-MPa (1-Bar) Pressure

T (K)	u (kJ/kg)	h (kJ/kg)	s_T^0 (kJ/kg-K)	T (K)	u (kJ/kg)	h (kJ/kg)	s_T^0 (kJ/kg-K)
200	142.77	200.17	6.46260	1100	845.45	1161.18	8.24449
220	157.07	220.22	6.55812	1150	889.21	1219.30	8.29616
240	171.38	240.27	6.64535	1200	933.37	1277.81	8.34596
260	185.70	260.32	6.72562	1250	977.89	1336.68	8.39402
280	200.02	280.39	6.79998	1300	1022.75	1395.89	8.44046
290	207.19	290.43	6.83521	1350	1067.94	1455.43	8.48539
298.15	213.04	298.62	6.86305	1400	1113.43	1515.27	8.52891
300	214.36	300.47	6.86926	1450	1159.20	1575.40	8.57111
320	228.73	320.58	6.93413	1500	1205.25	1635.80	8.61208
340	243.11	340.70	6.99515	1550	1251.55	1696.45	8.65185
360	257.53	360.86	7.05276	1600	1298.08	1757.33	8.69051
380	271.99	381.06	7.10735	1650	1344.83	1818.44	8.72811
400	286.49	401.30	7.15926	1700	1391.80	1879.76	8.76472
420	301.04	421.59	7.20875	1750	1438.97	1941.28	8.80039
440	315.64	441.93	7.25607	1800	1486.33	2002.99	8.83516
460	330.31	462.34	7.30142	1850	1533.87	2064.88	8.86908
480	345.04	482.81	7.34499	1900	1581.59	2126.95	8.90219
500	359.84	503.36	7.38692	1950	1629.47	2189.19	8.93452
520	374.73	523.98	7.42736	2000	1677.52	2251.58	8.96611
540	389.69	544.69	7.46642	2050	1725.71	2314.13	8.99699
560	404.74	565.47	7.50422	2100	1774.06	2376.82	9.02721
580	419.87	586.35	7.54084	2150	1822.54	2439.66	9.05678
600	435.10	607.32	7.57638	2200	1871.16	2502.63	9.08573
620	450.42	628.38	7.61090	2250	1919.91	2565.73	9.11409
640	465.83	649.53	7.64448	2300	1968.79	2628.96	9.14189
660	481.34	670.78	7.67717	2350	2017.79	2692.31	9.16913
680	496.94	692.12	7.70903	2400	2066.91	2755.78	9.19586
700	512.64	713.56	7.74010	2450	2116.14	2819.37	9.22208
720	528.44	735.10	7.77044	2500	2165.48	2883.06	9.24781
740	544.33	756.73	7.80008	2550	2214.93	2946.86	9.27308

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Constant specific heats

- Assuming C_{vo} is constant then

  $$u_2 - u_1 = C_{vo} (T_2 - T_1)$$

- Assuming C_{po} constant then

  $$h_2 - h_1 = C_{po} (T_2 - T_1)$$

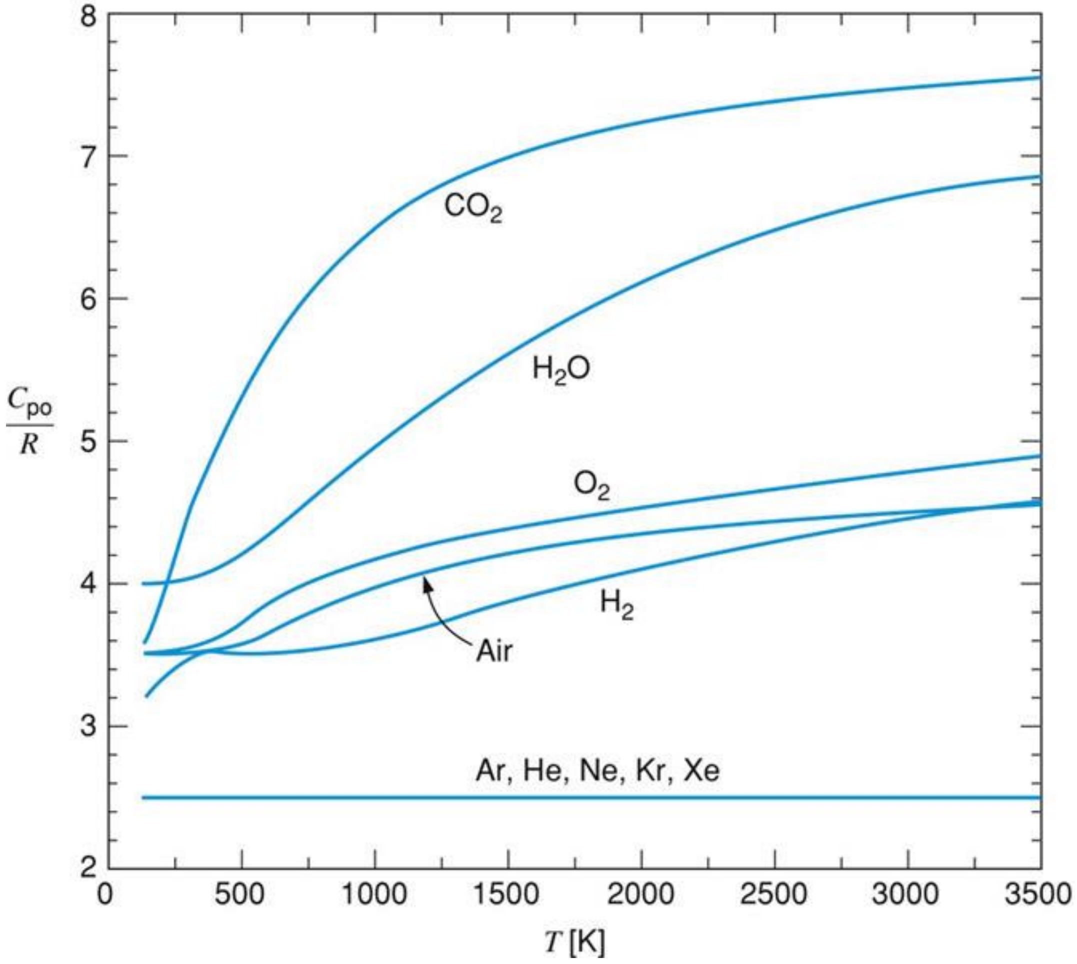
- Constant specific heats are given in table A.5 at 100kPa and 25 ^oC

  For air $C_{po} = 1.004 kJ/kg.K$, $C_{vo} = 0.717\ kJ/kg.K$

- Question: find the change of internal energy and enthalpy for nitrogen as it is heated from 300 to 360 K.

Dependence of specific heat on temperature

- Dependence of specific heat on temperature is illustrated in figure 5.11 p.137, from the figure note the following:
    - Monoatomic gases such as the noble gases specific heat is constant regardless of temperature.
    - Diatomic gases such oxygen nitrogen and air weak dependence of specific heat on temperature, and for most applications it can be assumed as constant specific heat specially in narrow temperature ranges.
    - Polyatomic gases such as water and carbon dioxide specific heat dependence on temperature is strong.



Dependence of specific heat on temperature

- temperature specific heat dependence can be explained in relation to the modes of vibration of the molecules.
- As more atoms means more bonds and more vibration modes and stronger temperature dependence on the internal energy and hence the specific heats.

Relation between specific heats

- From h = u +Pv = u + RT , the differential with T

  $dh = du + RdT$, but $du = C_{vo}dT$, $dh = C_{po}\,dT$ then

  $C_{po}\,dT = C_{vo}dT + RdT$ divide by dT to get

  $C_{po} = C_{vo} + R$ or

  $C_{po} - C_{vo} = R$

Check for air R= 0.287 , C_{po} = 1.004kJ/kg.K , C_{vo} = 0.717 kJ/kg.K

- For mole basis

  $$\overline{C_{po}} - \overline{C_{vo}} = \bar{R}$$

- See example 5.7 p. 139
- Work e.g 5.8 p. 140

Example 5.7 p. 139

- Calculate the change of enthalpy as one kg of oxygen is heated from 300 to 1500K, assume ideal gas behavior.
- Most accurate using ideal gas tables A.8

  h2 – h1 = 1540.2 – 273.2 = 1267 kJ/kg

Integration of specific heat as function of temperature will give a good result. Table A.6 for Cp(T)

- Assuming constant specific heat gives a reasonable but not accurate result. Cpo at 300 K from table A.2

  h2-h1 = Cpo (T2- T1) = 0.922* 1200 = 1106.4 kJ/kg

  which is low by 12.7%

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Example 5.8

- Cylinder fitted with a piston has an initial volume of 0.1 m^3 and contains nitrogen at 150 kPa, 25 ^{o} C. The piston is moved , compressing the nitrogen until the pressure is 1MPa and temperature is 150 ^{o} C. During process heat is transferred from the nitrogen and the work is done on the nitrogen is 20 kJ. Determine the amount of this heat transfer.
- $1Q2 = m(u2 - u1) + 1W2$
- $m = \frac{PV}{RT} = \frac{150X0.1}{0.2968} * 298.1 = 0.1695kg.$
- $1Q2 = mCvo(T2 - T1) + 1W2$
- $1Q2 = 0.1695X0.745X(150 - 25) - 20 = -4.2kJ$

The first law as a rate equation

- The first law as a rate equation is given

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

- such form will be used when applying first law to control volume in the next chapter.
- See key concepts and formula page 145.

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The first law as a rate equation

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

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- See key concepts and formula page 145.

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KEY CONCEPTS AND FORMULAS

Total energy	$E = U + \text{KE} + \text{PE} = mu + \frac{1}{2}m\mathbf{V}^2 + mgZ$
Kinetic energy	$\text{KE} = \frac{1}{2}m\mathbf{V}^2$
Potential energy	$\text{PE} = mgZ$
Specific energy	$e = u + \frac{1}{2}\mathbf{V}^2 + gZ$
Enthalpy	$h \equiv u + Pv$
Two-phase mass average	$u = u_f + xu_{fg} = (1-x)u_f + xu_g$ $h = h_f + xh_{fg} = (1-x)h_f + xh_g$
Specific heat, heat capacity	$C_v = \left(\frac{\partial u}{\partial T}\right)_v$; $C_p = \left(\frac{\partial h}{\partial T}\right)_p$
Solids and liquids	Incompressible, so v = constant $\cong v_f$ (or v_i) and v small $C = C_v = C_p$ [Tables A.3 and A.4 (F.2 and F.3)] $u_2 - u_1 = C(T_2 - T_1)$ $h_2 - h_1 = u_2 - u_1 + v(P_2 - P_1)$ (Often the second term is small.) $h = h_f + v_f(P - P_{\text{sat}})$; $u \cong u_f$ (saturated at same T)

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Ideal gas	$h = u + Pv = u + RT$ (only functions of T)
	$C_v = \frac{du}{dT};\ C_p = \frac{dh}{dT} = C_v + R$
	$u_2 - u_1 = \int C_v\, dT \cong C_v(T_2 - T_1)$
	$h_2 - h_1 = \int C_p\, dT \cong C_p(T_2 - T_1)$
Energy equation rate form	$\dot{E} = \dot{Q} - \dot{W}$ (rate = +in − out)
Energy equation integrated	$E_2 - E_1 = {}_1Q_2 - {}_1W_2$ (change = +in − out)
	$m(e_2 - e_1) = m(u_2 - u_1) + \frac{1}{2}m(\mathbf{V}_2^2 - \mathbf{V}_1^2) + mg(Z_2 - Z_1)$
Multiple masses, states	$E = m_A e_A + m_B e_B + m_C e_C + \cdots$
Work	Energy in transfer: mechanical, electrical, and chemical
Heat	Energy in transfer caused by ΔT

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Displacement work	$W = \int_1^2 F\,dx = \int_1^2 P\,dV = \int_1^2 \mathcal{S}\,dA = \int_1^2 T\,d\theta$
Specific work	$w = W/m$ (work per unit mass)
Power, rate of work	$\dot{W} = F\mathbf{V} = P\dot{V} = T\omega$ ($\dot{V}$ displacement rate)
	Velocity $\mathbf{V} = r\omega$, torque $T = Fr$, angular velocity $= \omega$
Polytropic process	$PV^n = \text{constant}$ or $Pv^n = \text{constant}$
Polytropic process work	${}_1W_2 = \frac{1}{1-n}(P_2V_2 - P_1V_1)$ (if $n \neq 1$)
	${}_1W_2 = P_1V_1 \ln\frac{V_2}{V_1}$ (if $n = 1$)
Conduction heat transfer	$\dot{Q} = -kA\frac{dT}{dx} \simeq kA\frac{\Delta T}{L}$
Conductivity	k (W/m K)
Convection heat transfer	$\dot{Q} = hA\,\Delta T$
Convection coefficient	h (W/m^2 K)
Radiation heat transfer (net to ambient)	$\dot{Q} = \varepsilon\sigma A(T_s^4 - T_{\text{amb}}^4)$ ($\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4)
Rate integration	${}_1Q_2 = \int \dot{Q}\,dt \approx \dot{Q}_{\text{avg}}\,\Delta t$

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End of First Law for CM

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