CAE 208 Thermal-Fluids Engineering I
MMAE 320: Thermodynamics
Fall 2022

October 06, 2022
Energy analysis of closed systems (II)

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ANNOUNCEMENTS

Announcements

- The second problem solving session

Announcements

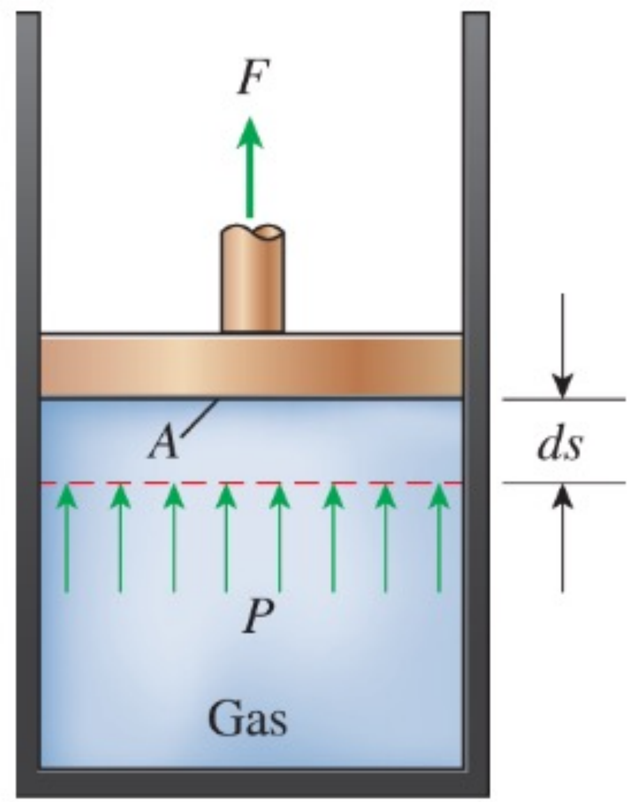
- For the first midterm exam:
  - ❑ I will post the pages that I will provide during the exam (e.g., tables, equations) in advance
  - ❑ The exam is closed book close notes during the class time
  - ❑ The exam is on October 13 in person

RECAP

Recap

- The expansion or compression work is often called *moving boundary work* or simply *boundary work*

$$\delta W_b = F ds = P A ds = P\, dV$$



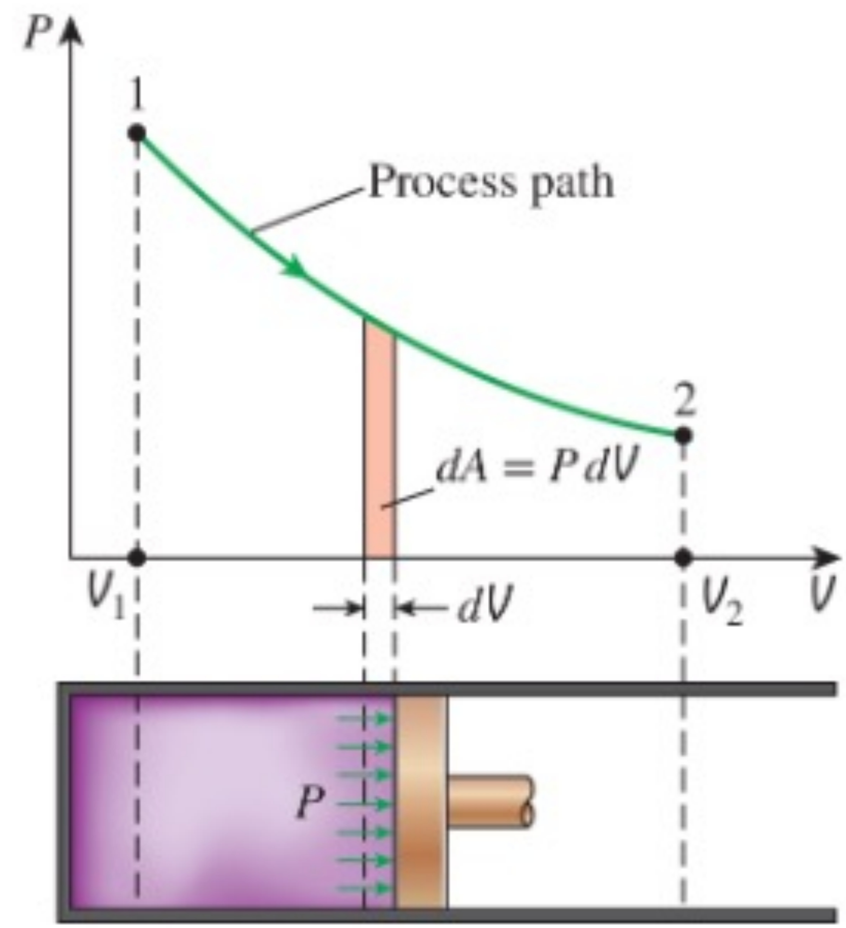
Think about internal combustion engines

Recap

- For a quasi-equilibrium expansion process, we can write:

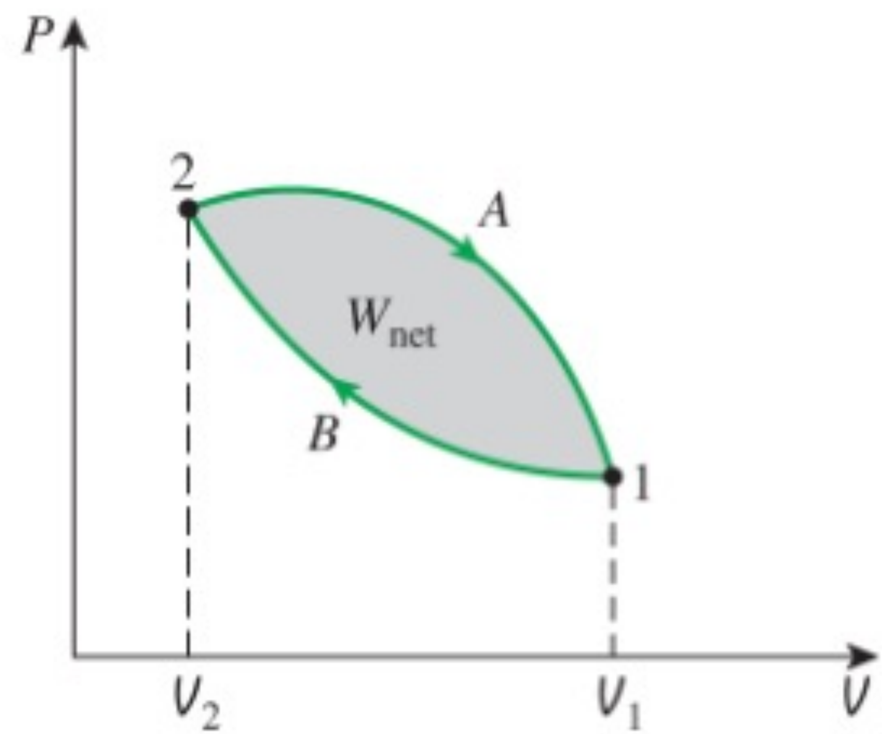
$$Area = A = \int_1^2 dA = \int_1^2 PdV$$

$$W_b = \int_1^2 P_i dV$$



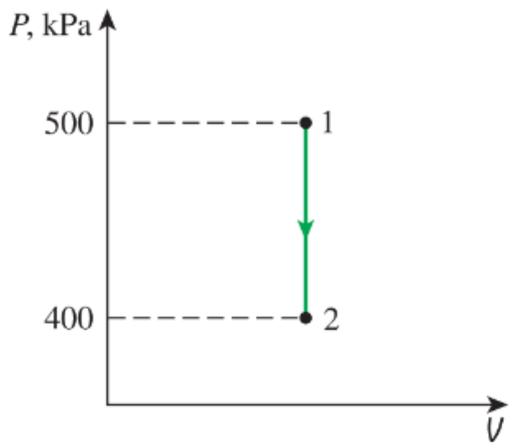
Recap

- The net work done during a cycle is the difference between the work done by the system and the work done on the system:

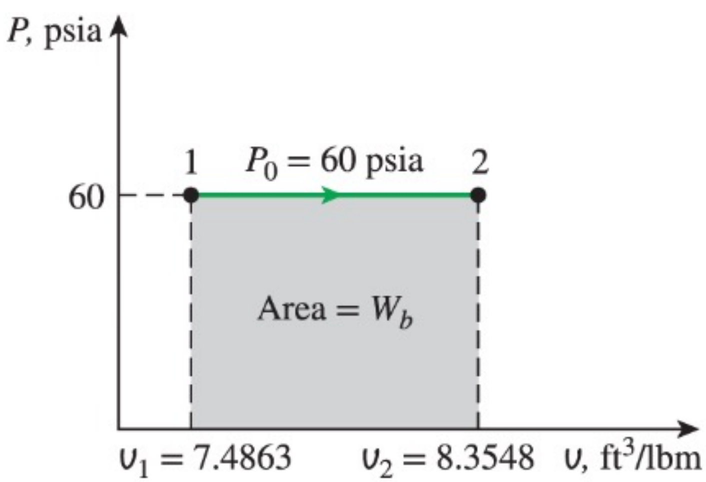


Recap

- Constant Volume



- Constant Pressure



CLASS ACTIVITY

Moving Boundary Work

- Polytropic process

$$P = CV^{-n}$$

$$W_b = \int_1^2 P\,dV = \int_1^2 (CV^{-n})dV = \frac{C\left((V^{-n+1} - V^{-n+1}\right)}{(-n+1)} = \frac{P_2V_2 - P_1V_1}{1-n}$$

Moving Boundary Work

- Polytropic process

$$C = P_1 V_1^n = P_2 V_2^n$$

$$W_b = \frac{mR(T_2 - T_1)}{1 - n} \quad n \neq 1 \ (kJ)$$

Moving Boundary Work

- For the case of n =1

$$W_b = \int_1^2 P dV = \int_1^2 CV^{-1} dV = PV \times Ln(\frac{V_2}{V_1})$$

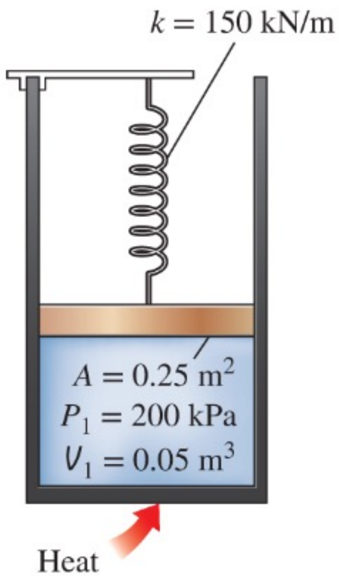
CLASS ACTIVITY

Class Activity

- A piston-cylinder device contains 0.05 m^3 of a gas initially at 200 kPa. At this state, a linear spring that has a spring constant of 150 kN/m is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m^2, determine
  a) The final pressure inside the cylinder
  b) The total work done by the gas
  c) The fraction of this work done against the spring to compress it

Class Activity

- Solution

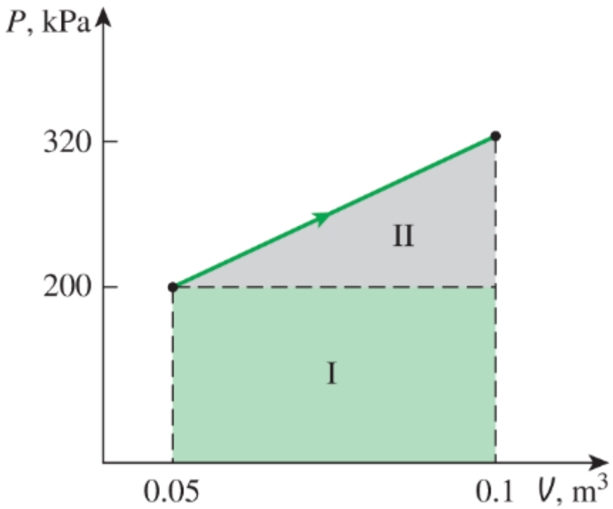


$$V_2 = 2V_1 = 2(0.05\ m^3) = 0.1\ m^3$$

$$x = \frac{\Delta V}{A} = \frac{(0.1 - 0.05)m^3}{0.25\ m^2} = 0.2\ m$$

Class Activity

- Solution



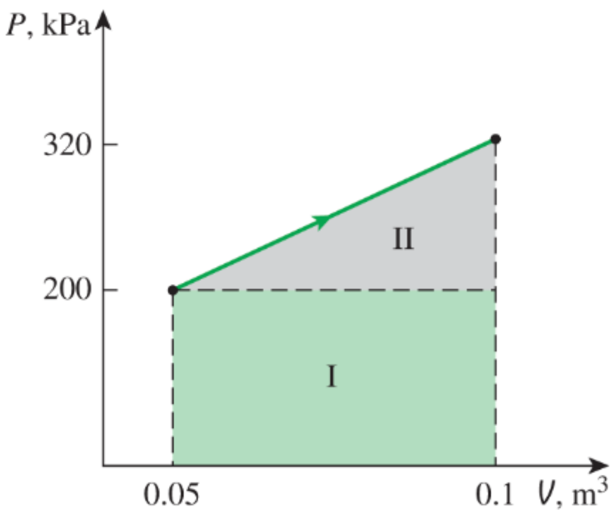
$$F = kx = \left(150\,\frac{kN}{m}\right)(0.2\ m) = 30\ kN$$

$$P = \frac{F}{A} = \frac{30\ kN}{0.25\ m^2} = 120\ kN$$

$$200 + 120 = 320\ kN$$

Class Activity

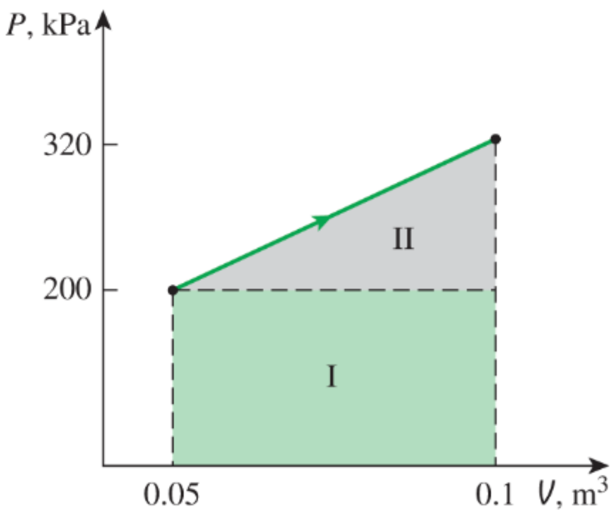
- Solution (b)



$$W = area = \frac{(200 + 320)kPa}{2}[0.1 - 0.05]\left(\frac{1kJ}{1\ kPa.m^2}\right) = 13\ kJ$$

Class Activity

- Solution (c)



$$W_{spring} = \frac{1}{2}[320 - 200]kPa(0.05\, m^3) = 3\ kJ$$

Or

$$W_{spring} = \frac{1}{2}k(x_2^2 - x_1^2) = \frac{1}{2}(150)(0.2^2 - 0^2) = 3\ kJ$$

Moving Boundary Work

- Moving boundary work under different processes

Process	Moving boundary work
Constant volume	0
Constant pressure	$P_0(V_2 - V_1)$
Isothermal	$P_1V_1 \times Ln(\frac{V_2}{V_1})$ $P_1V_1 \times Ln(\frac{P_1}{P_2})$ $mRT_o \times Ln(\frac{V_2}{V_1})$
Polytropic	$\frac{P_2V_2 - P_1V_1}{1-n}$ $\frac{mR(T_2 - T_1)}{1-n}$

ENERGY BALANCE FOR CLOSED SYSTEMS

Energy Balance for Closed Systems

- The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during the process

$$(Total\ energy\ entering\ the\ system) - (Total\ energy\ leaving\ the\ system) = (Change\ in\ the\ total\ energy\ of\ the\ sysem)$$

$$E_{in} - E_{out} = \Delta E_{system}$$

This is known as the energy balance

Energy Balance for Closed Systems

- Energy change of a system ΔE_{system}

$$Energy\ change = Energy\ at\ final\ state\ - Energy\ at\ initial\ state$$

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

Energy is a property, and the value of a property does not change unless the state of the system changes

Energy Balance for Closed Systems

- We can sum the heat, work, and mass, and the heat transfer:

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) += \Delta E_{system}$$

Net energy transfer by heat, work

Change in internal, kinetic, potential, …, energies

Energy Balance for Closed Systems

- We can sum the heat, work, and mass, and the heat transfer in the rate form:

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work}} = \underbrace{\Delta\dot{E}_{system}}_{\text{Rate of change in internal, kinetic, potential, …, energies}}$$

Energy Balance for Closed Systems

- The energy balance can be expressed on a per unit mass basis as

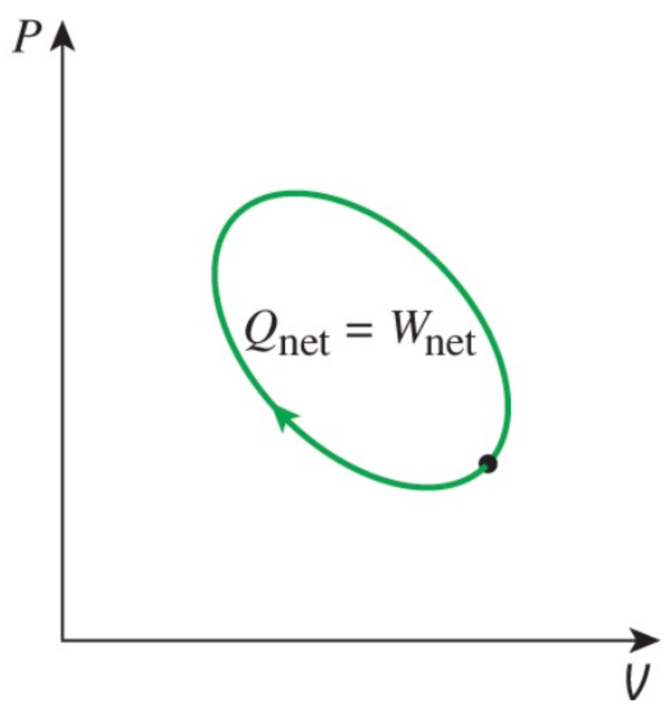
$$e_{in} - e_{out} = \Delta e_{system}$$

Energy Balance for Closed Systems

- For a closed system undergoing a cycle, the initial and final states are identical:

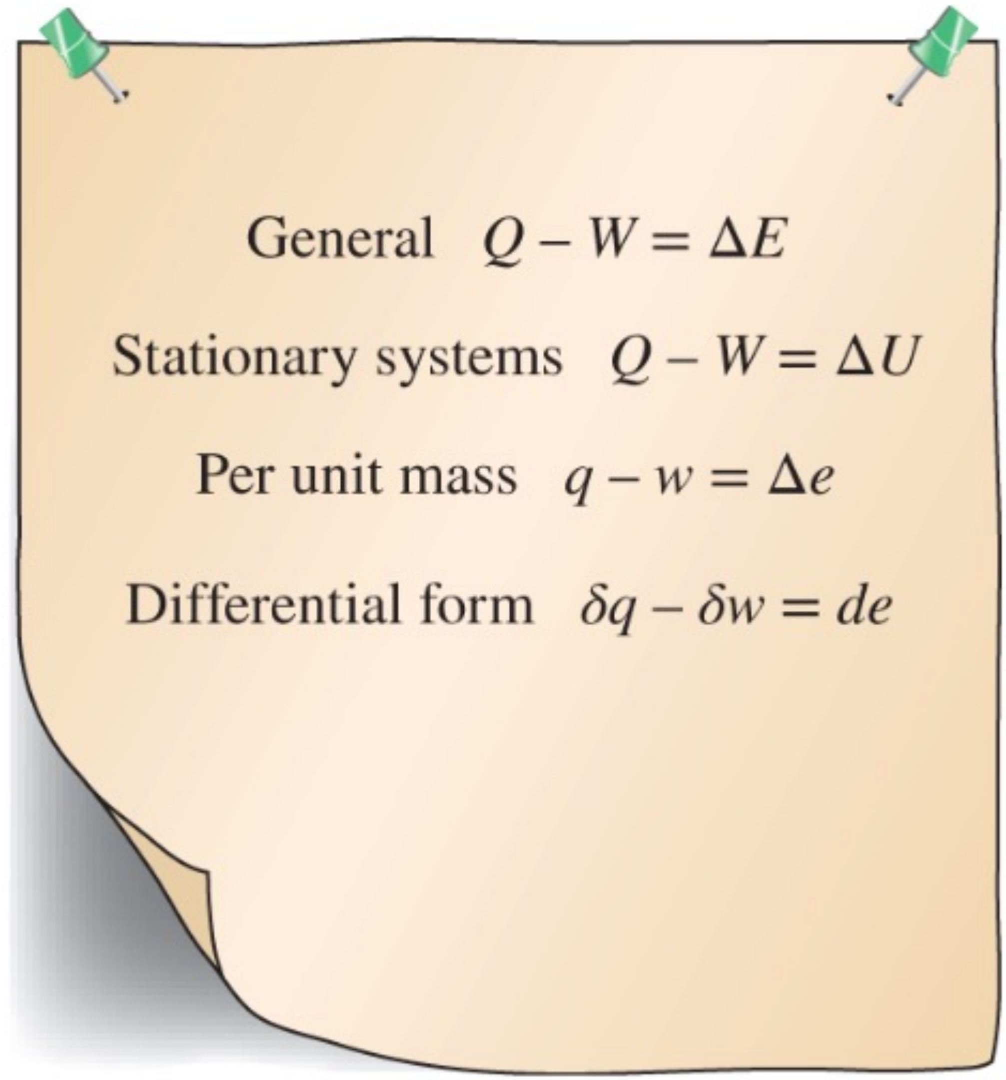
$$\Delta E = E_{in} - E_{out} = 0 \quad \rightarrow E_{in} = E_{out}$$

$$W_{net,out} = Q_{net,in} \quad \rightarrow \dot{W}_{net,out} = \dot{Q}_{net,in}$$



Energy Balance for Closed Systems

- We can write:



CLASS ACTIVITY

Class Activity

- A piston-cylinder device contains 25 g of saturated vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs.
  a) Show that for a closed system the boundary work Wb and the change in internal energy $\Delta \mathrm{U}$ in the first-law relation can be contained into one term ΔH for a constant pressure process
  b) Determine the final temperature of the system

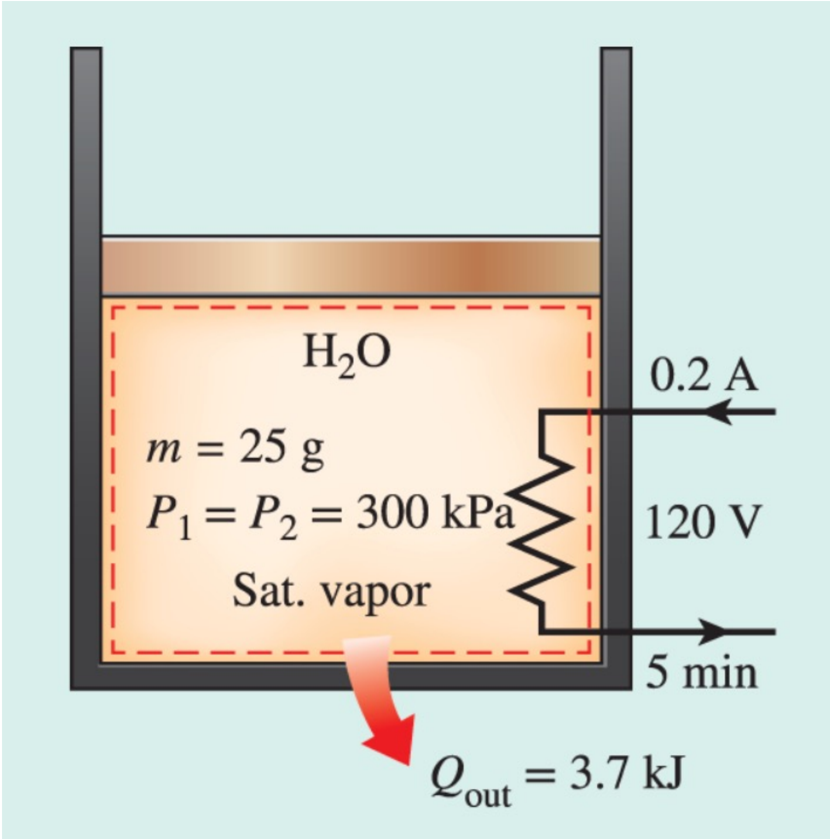
Class Activity

- Solution:

$$E_{in} - E_{out} = \Delta E_{system}$$

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

$$Q - W_{other} - W_b = U_2 - U_1$$



Class Activity

- Solution:

$$W_b = P_0(V_2 - V_1)$$

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

Class Activity

- Solution:

$$P_0 = P_2 = P_1$$

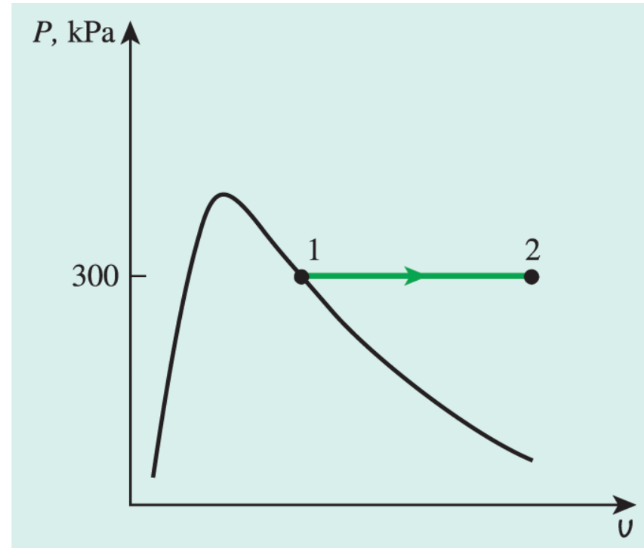
$$Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

$$Q - W_{other} = H_2 - H_1$$

Class Activity

- Solution:

$$@State\ 1: \begin{cases} P_1 = 300\ kPa \\ Sat.vapor \end{cases}$$



APPENDIX 1

PROPERTY TABLES AND CHARTS (SI UNITS)

Class Activity

- Solution:

TABLE A–5

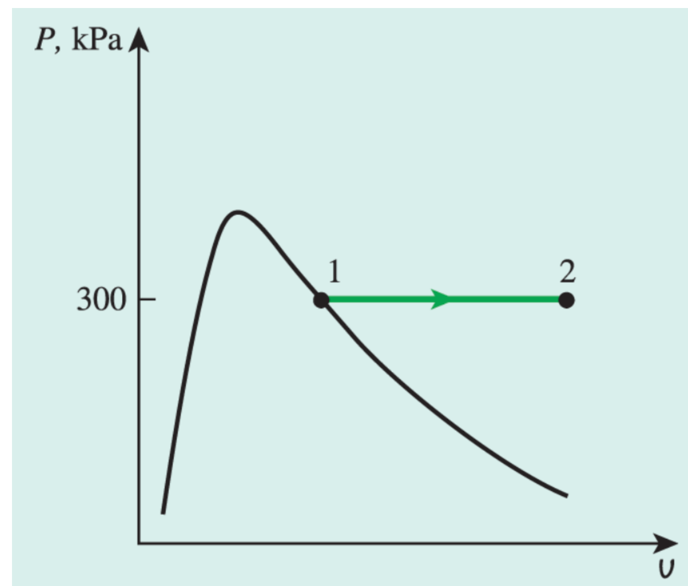
Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	*Specific volume,* m^3/kg Sat. liquid, v_f	Sat. vapor, v_g	*Internal energy,* kJ/kg Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	*Enthalpy,* kJ/kg Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0

Class Activity

- Solution:

$$@State\ 1: \begin{cases} P_1 = 300\ kPa \\ Sat.vapor \end{cases} \qquad h_1 = h_{g\ @300\ kPa} = 2724.9\ \frac{kJ}{kg}$$



Class Activity

- Solution (b):

$$W_e = VI\Delta t = (120\ V)(0.2\ A)(300\ s)\left(\frac{1\ \frac{kJ}{s}}{1000\ VA}\right) = 7.2\ kJ$$

Class Activity

- Solution (b):

$$E_{in} - E_{out} = \Delta E_{system}$$

$$W_{e,in} - Q_{out} - W_b = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta \mathrm{H} = \mathrm{m}(\mathrm{h}_2 - \mathrm{h}_1)$$

Class Activity

- Solution (b):

$$7.2\ kJ - 3.7\ kJ = (0.025\ kg)(h_2 - 2724.9)\ kJ/kg$$

$$h_2 = 2864.9\,\frac{kJ}{kg}$$

Class Activity

- Solution (b):

$$\begin{cases} P_2 = 300\ kPa \\ h_2 = 2865.9\,\dfrac{kJ}{kg} \end{cases} \qquad \mathrm{T}_2 = 200\ °C$$

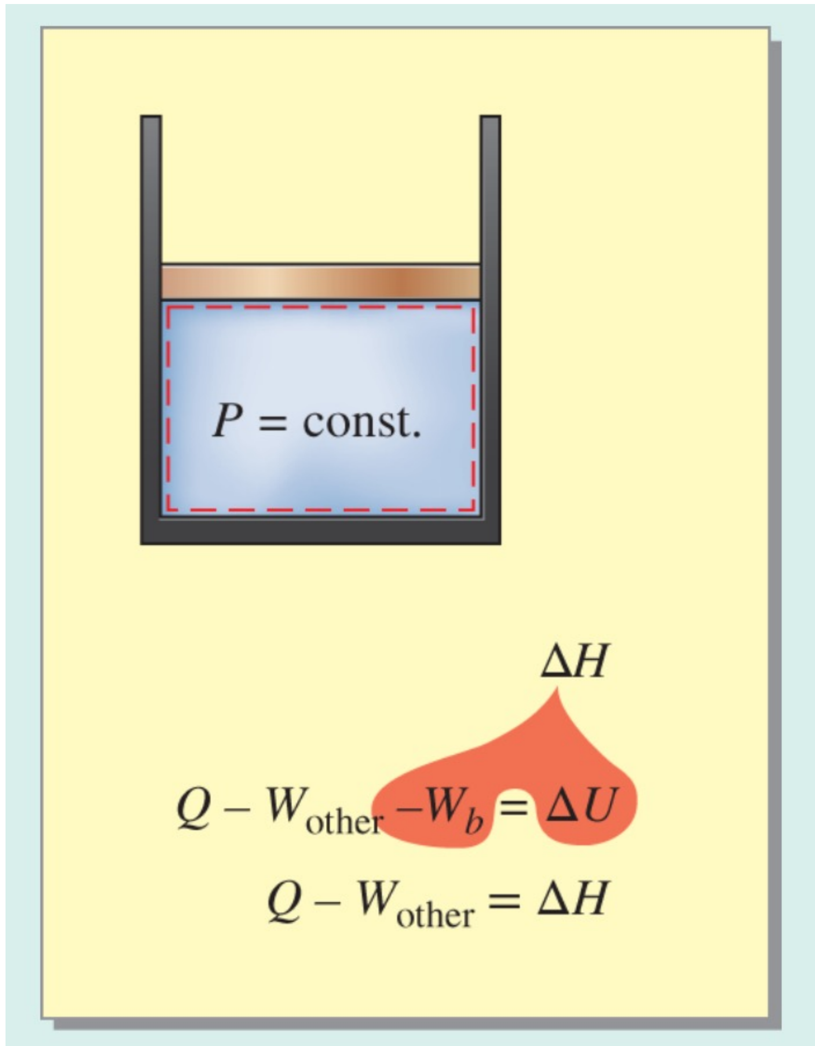
TABLE A–6

Superheated water

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.01 MPa (45.81°C)*				P = 0.05 MPa (81.32°C)			
	P = 0.20 MPa (120.21°C)				P = 0.30 MPa (133.52°C)			
Sat.	0.88578	2529.1	2706.3	7.1270	0.60582	2543.2	2724.9	6.9917
150	0.95986	2577.1	2769.1	7.2810	0.63402	2571.0	2761.2	7.0792
200	1.08049	2654.6	2870.7	7.5081	0.71643	2651.0	2865.9	7.3132
250	1.19890	2731.4	2971.2	7.7100	0.79645	2728.9	2967.9	7.5180
300	1.31623	2808.8	3072.1	7.8941	0.87535	2807.0	3069.6	7.7037
400	1.54934	2967.2	3277.0	8.2236	1.03155	2966.0	3275.5	8.0347
500	1.78142	3131.4	3487.7	8.5153	1.18672	3130.6	3486.6	8.3271

Class Activity

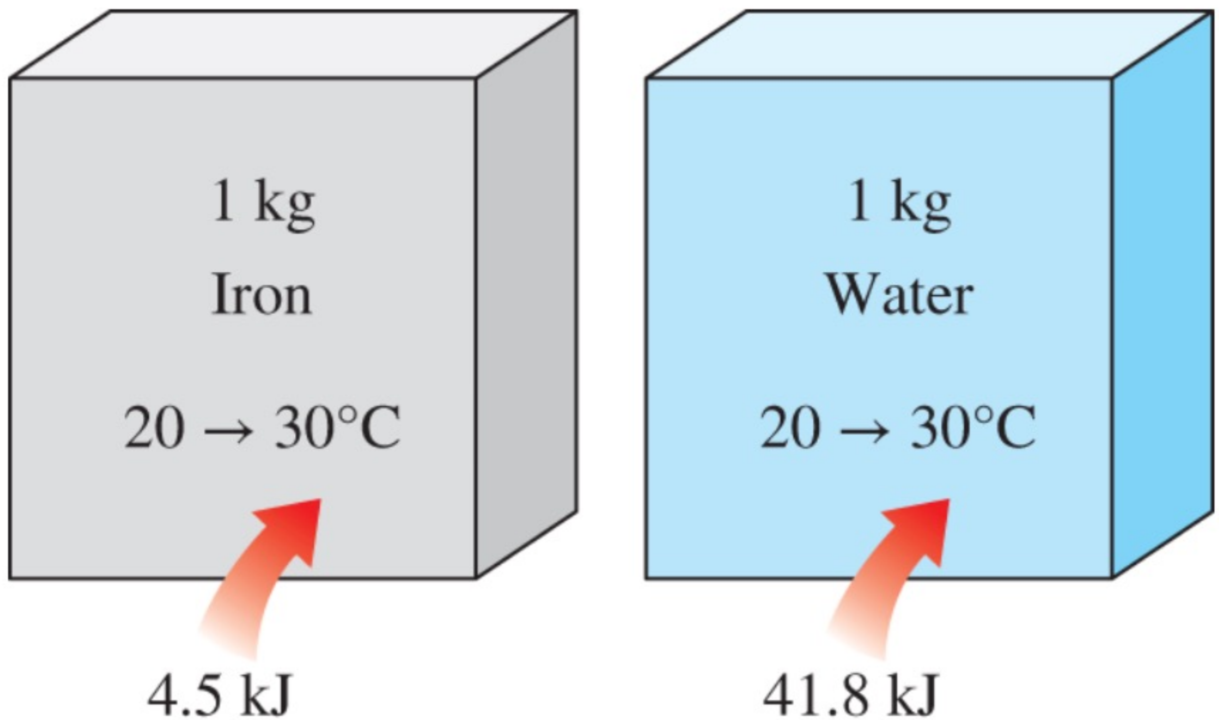
- Summary:



SPECIFIC HEATS

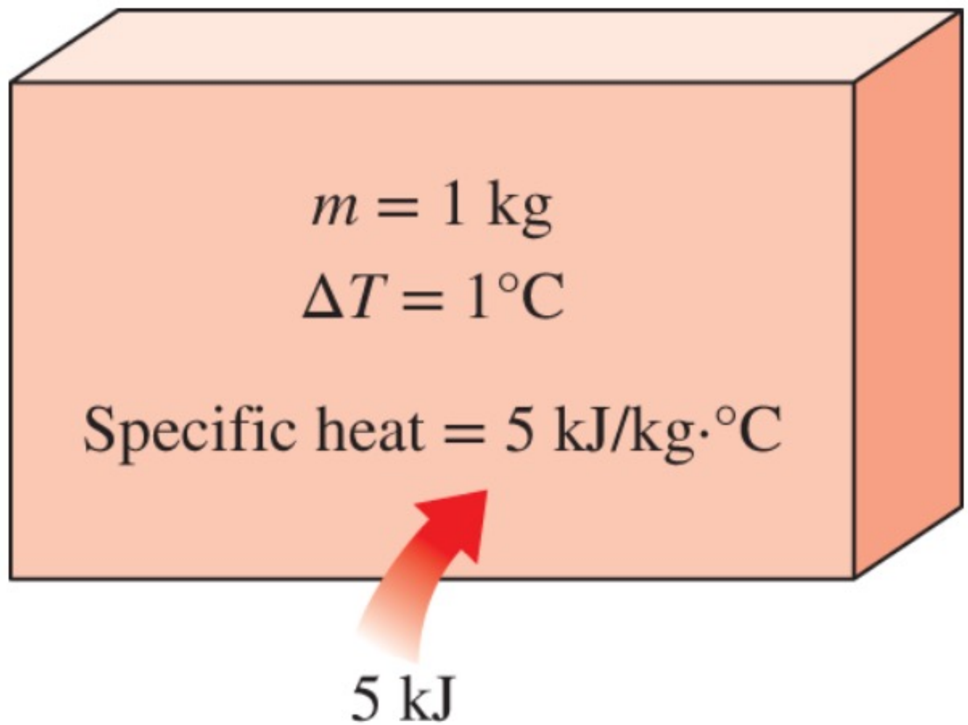
Specific Heats

- How much heat do we need to add to increase temperature of 1 kg iron vs water for 10 °C?



Specific Heats

- Specific heat is defined as the energy required to raise temperature of a unit mass of substance by one degree



Specific Heats

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  - ❑ Specific heat at constant volume (c_v)
  - ❑ Specific heat at constant pressure (c_p)

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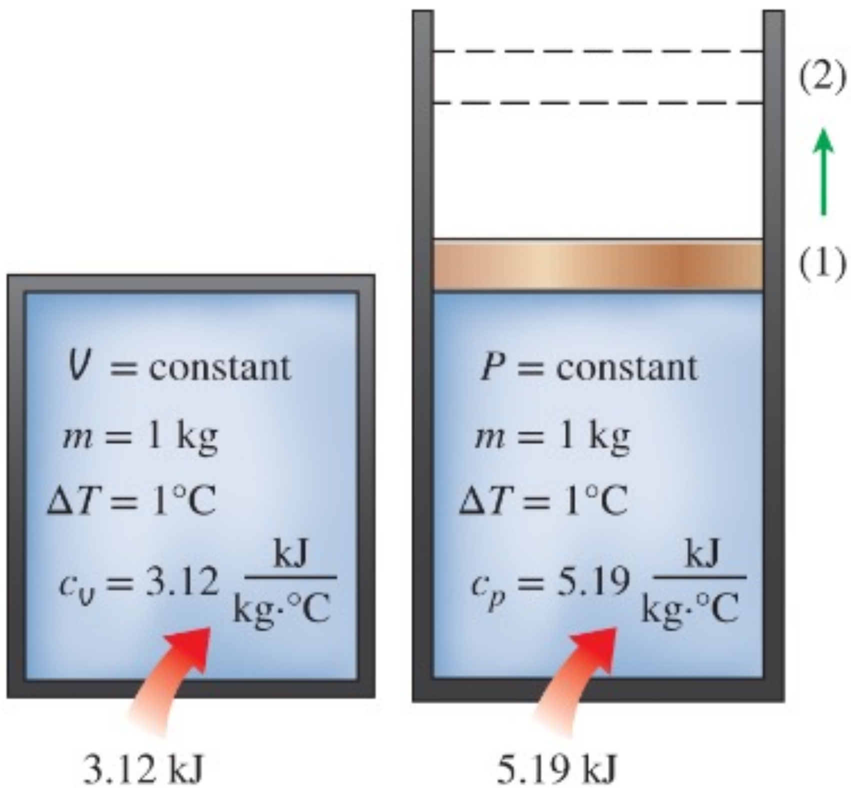

Specific Heats

- Let's start from the fixed mass in a stationary closed system that undergoes a constant volume process

$$\delta e_{in} - \delta e_{out} = du$$

$$c_v dT = du$$

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

Specific Heats

- Similarly, we can write the following for a constant pressure process:

$$c_p = \left(\frac{\partial u}{\partial T}\right)_p$$

Specific Heats