CAE 208 / MMAE 320: Thermodynamics

Fall 2023

October 5, 2023

Energy analysis of closed systems (2)

Built
Environment
Research
@ IIT

Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

Dr. Mohammad Heidarinejad, Ph.D., P.E.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
muh182@iit.edu

ANNOUNCEMENTS

Announcement

Announcements

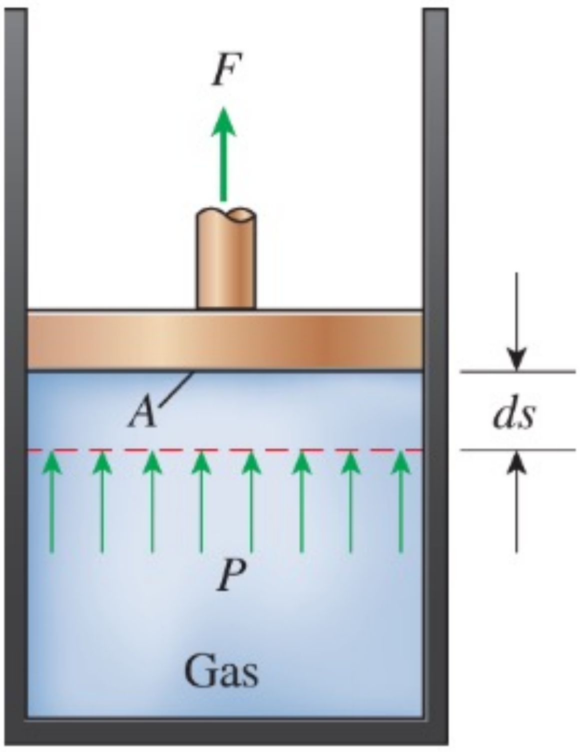
- Midterm is scheduled for October 10:
  - The first part of the exam is closed book (You are allowed to have one page for your cheat sheet to include equations)
  - The second part of the exam is open book (only a thermodynamics book or thermodynamics property tables)

RECAP

Recap

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

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

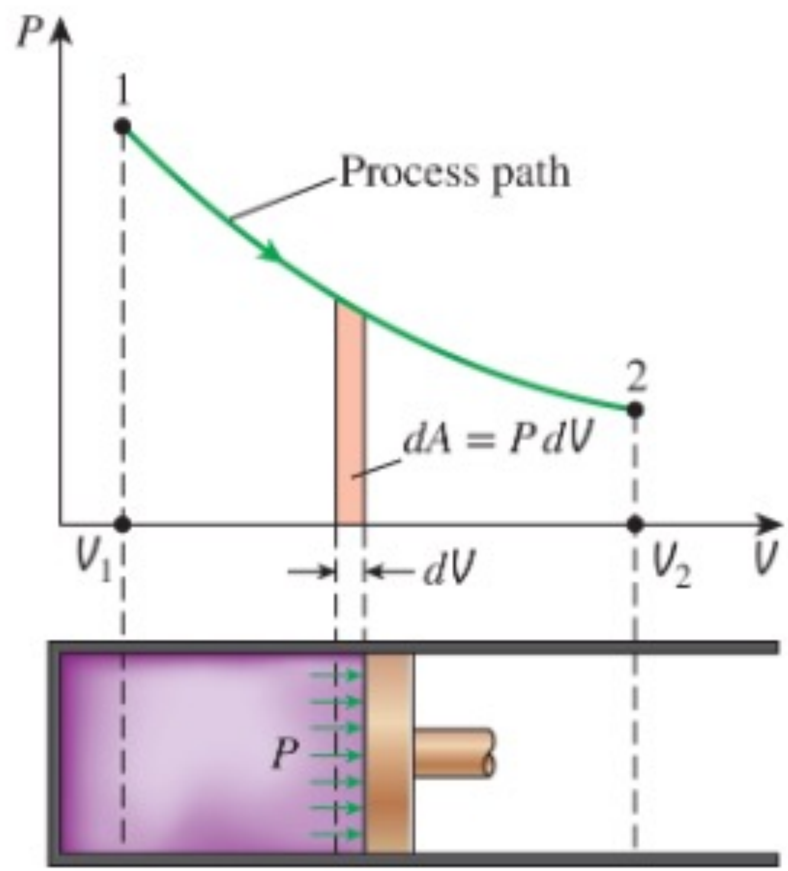


Recap

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

$$Area = A = \int_1^2 dA = \int_1^2 P dV$$

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



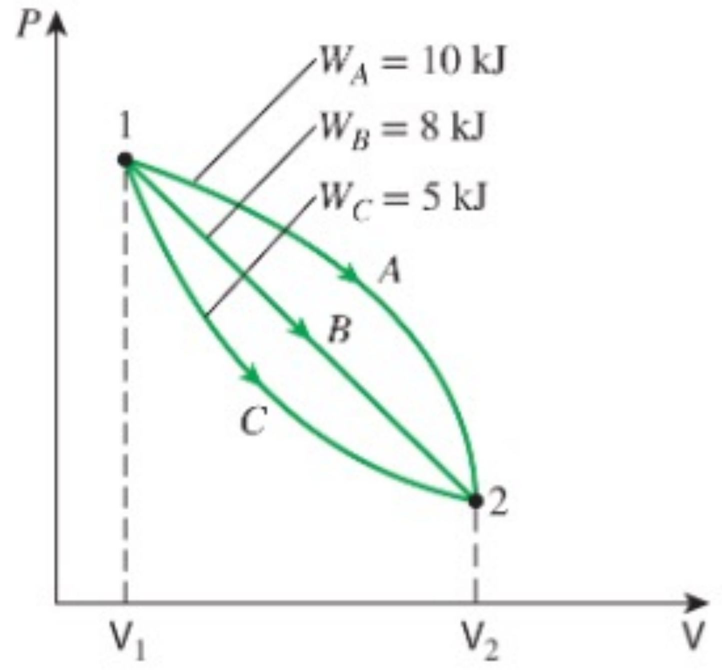
Recap

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

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

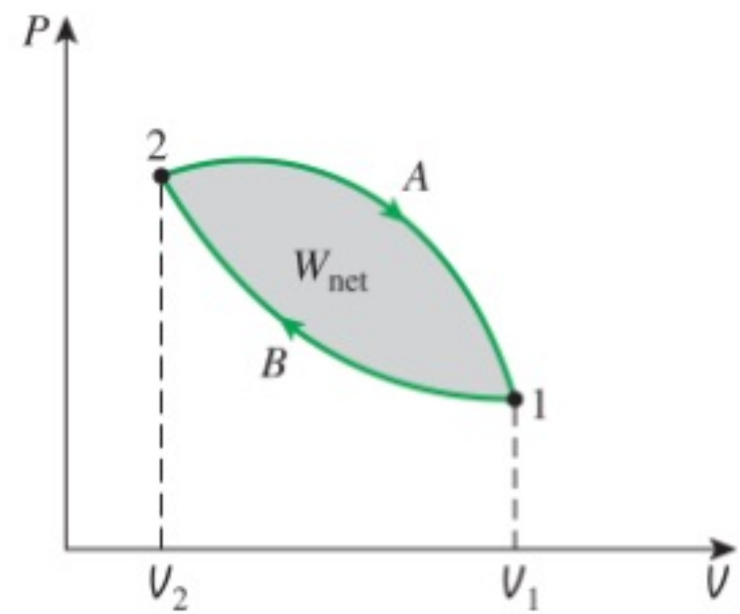
Recap

- The boundary work done during a process depends on the path followed as well as the end states:



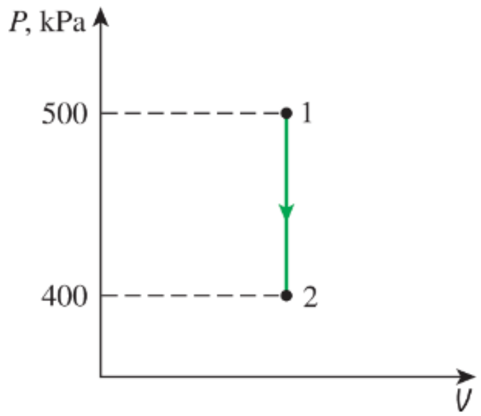
Recap

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

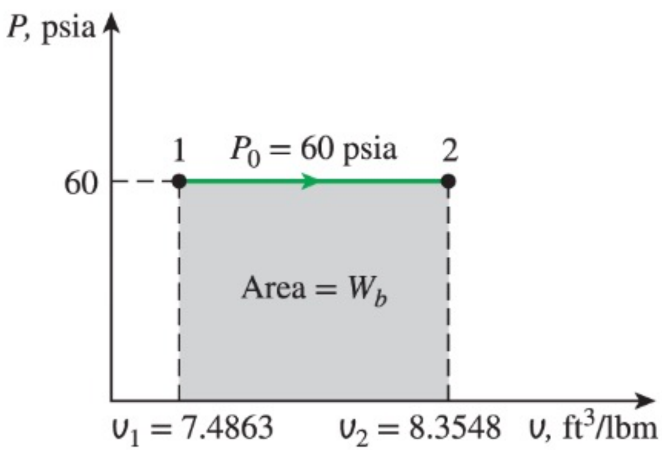


Recap

- Constant Volume



- Constant Pressure



QUIZ

Quiz

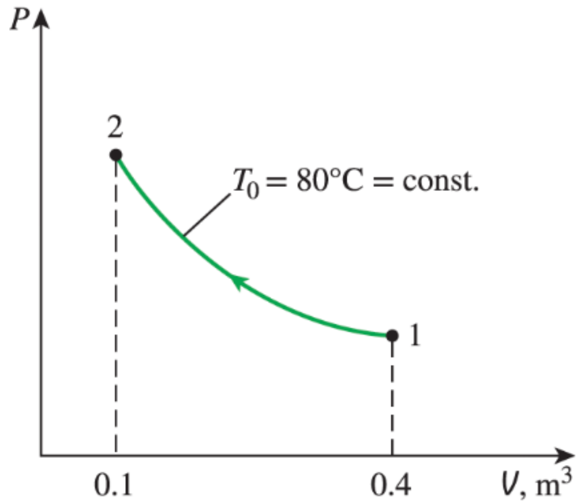
CLASS ACTIVITY

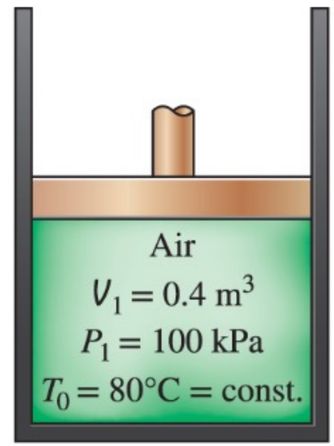
Class Activity

- A piston-cylinder device initially contains 0.4 m^3 of air at 100 kPa and 80 °C. The air is now compressed to 0.1 m^3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process

Class Activity

- Solution:



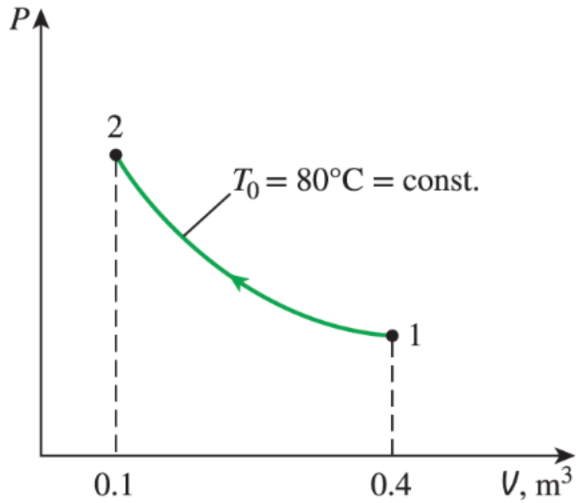


$$PV = mRT_0 \quad \rightarrow \quad P = \frac{C}{V}$$

$$W_b = \int_1^2 P dV = \int_1^2 (\frac{C}{V}) dV = C \int_1^2 (\frac{dV}{V})$$

Class Activity

- Solution:

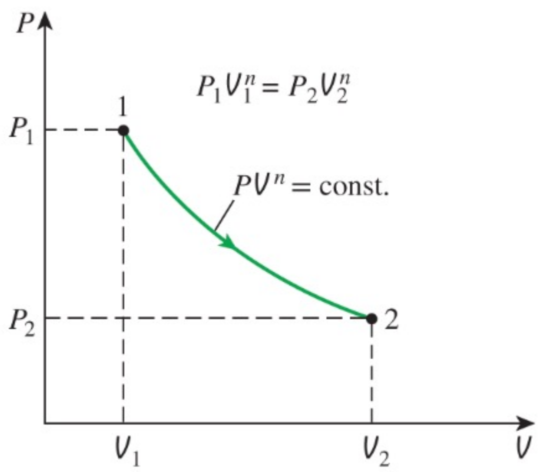


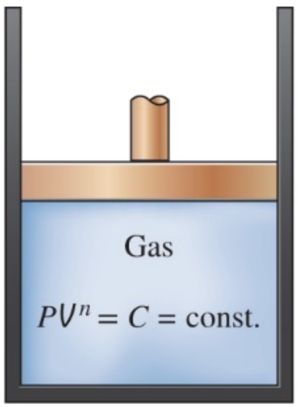
$$W_b = C \times Ln(V)|_{V_1}^{V_2} = C[Ln(V_2) - Ln(V_1)] = P_1V_1 \times Ln(\frac{V_2}{V_1})$$

$$W_b = (100\ kPa)(0.4\ m^3)\left(\text{Ln}\left(\frac{0.1}{0.4}\right)\right)\left(\frac{1kJ}{1\ kPa.m^2}\right) = -55.5\ kJ$$

Moving Boundary Work

- During expansion or compression processes of gases and volume are often related in $PV^n = C$ which is known as a Polytropic process





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

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

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

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	$\frac{P_2V_2 - P_1V_1}{1-n}$ $\frac{mR(T_2 - T_1)}{1-n}$

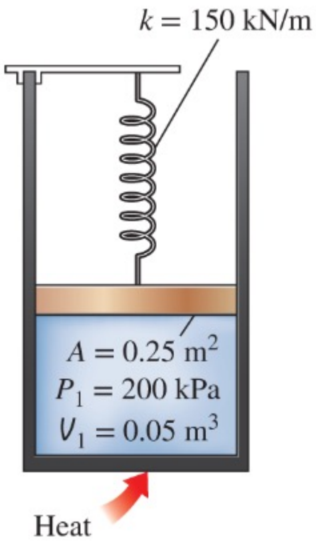
CLASS ACTIVITY

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

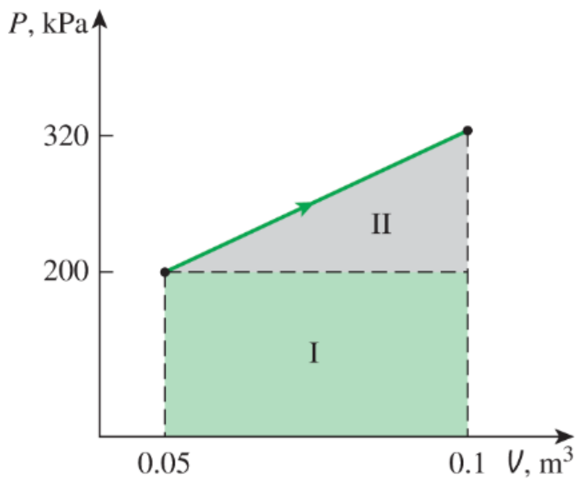


$$V_2 = 2V_1 = 2(0.05\ m^3) = 0.1\ m^3$$

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

Class Activity

- Solution



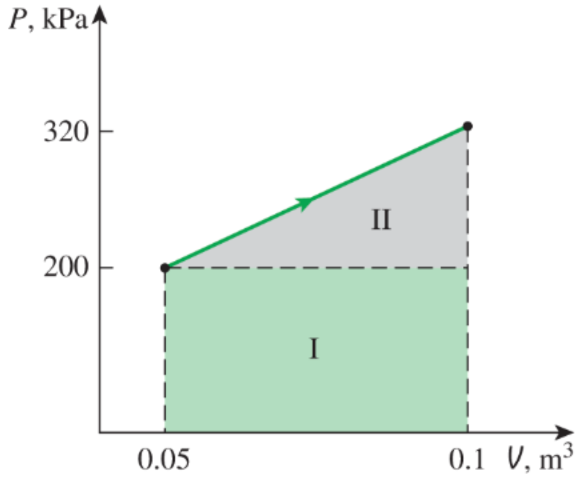
$$F = kx = \left(150\,\frac{kN}{m}\right)(0.2\,m) = 30\,kN$$

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

$$200 + 120 = 320\,kN$$

Class Activity

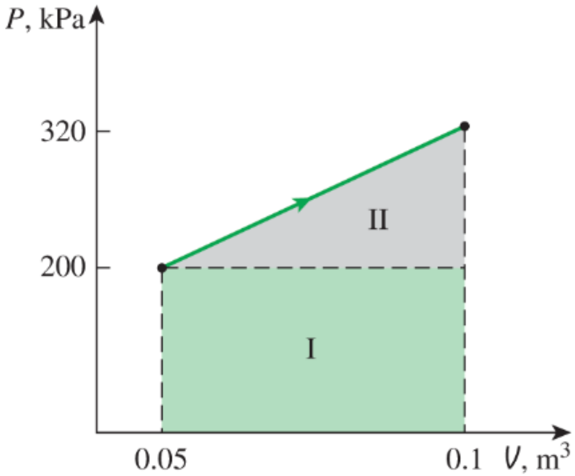
- Solution (b)



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

Class Activity

- Solution (c)



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

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

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:

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

Rate of net energy transfer by heat, work

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 constant rates, we can write:

$$Q = \dot{Q}\Delta t$$

$$W = \dot{W}\Delta t$$

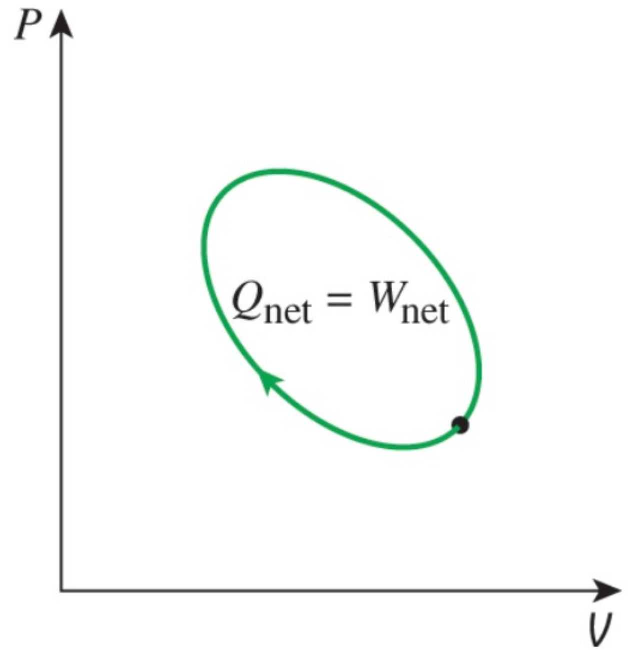
$$E = \left(\frac{dE}{dt}\right)\Delta t$$

Energy Balance for Closed Systems

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

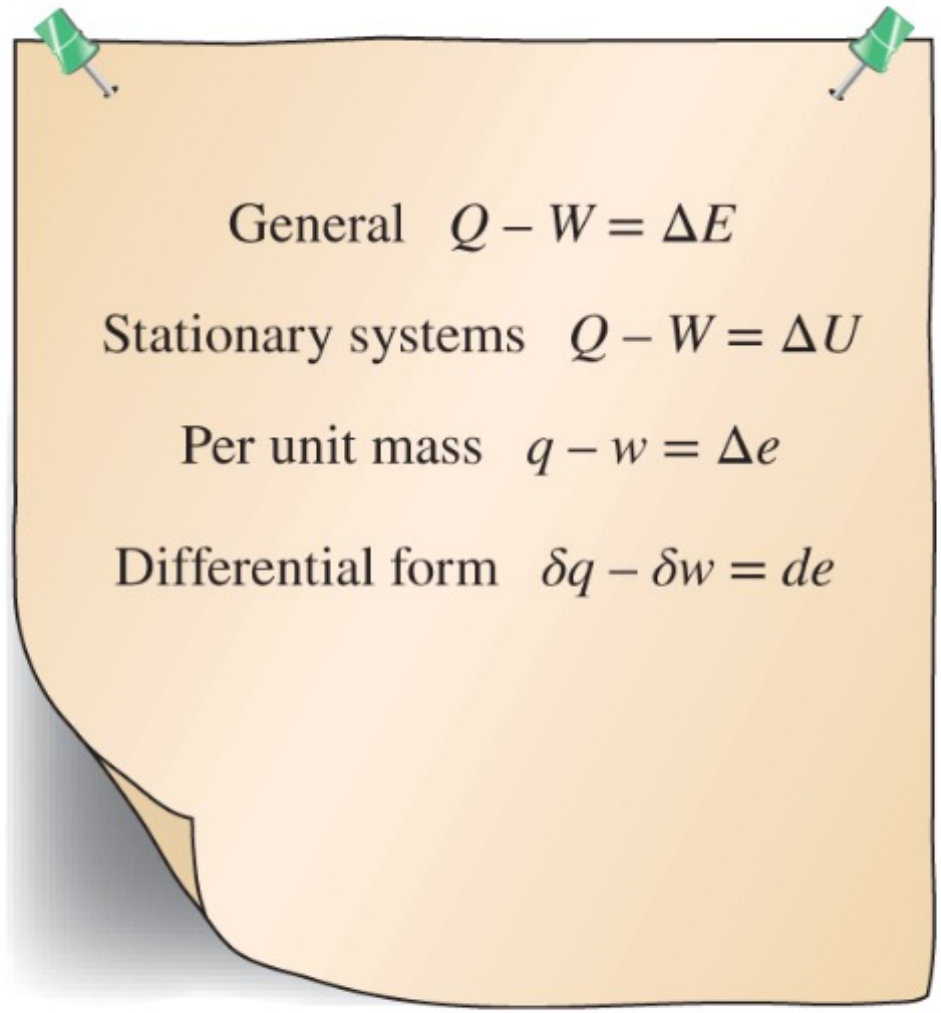
$$\Delta E = E_{in} - E_{out} = 0 \quad \rightarrow E_{in} = E_{out}$$

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



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 W_b and the change in internal energy ΔU 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

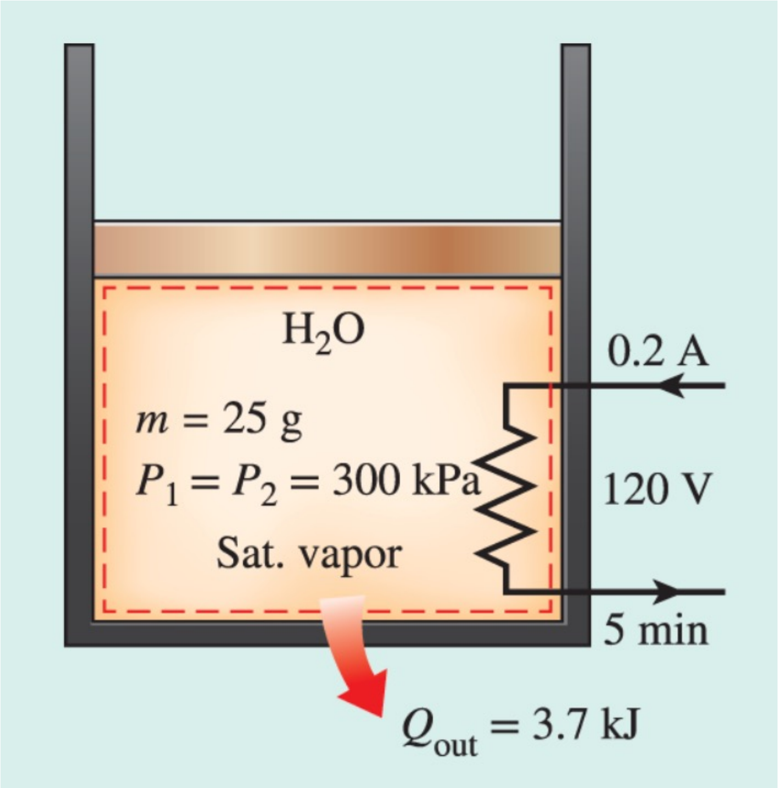
Class Activity

- 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:

$$P_0 = P_2 = P_1$$

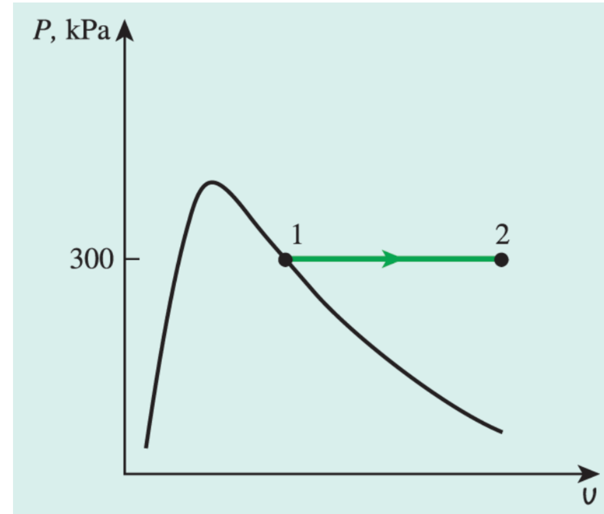
$$Q - W_{other} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

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

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

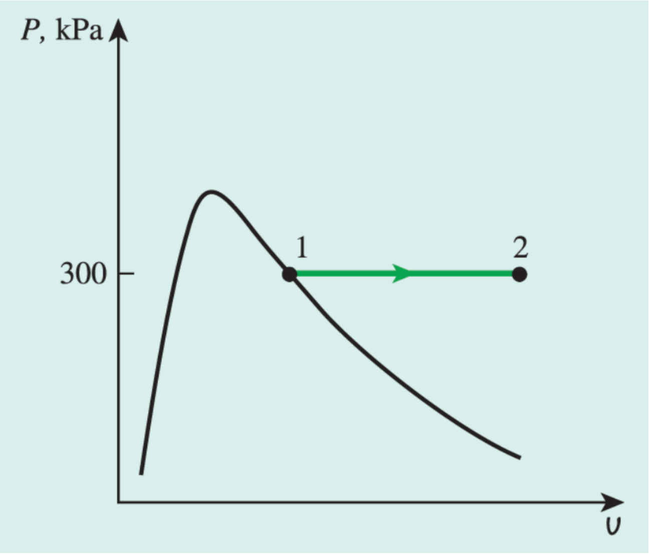
Saturated water—Pressure table

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):

$$\begin{cases} P_2 = 300\ kPa \\ h_2 = 2865.9\,\dfrac{kJ}{kg} \end{cases} \qquad T_2 = 200\ °C$$

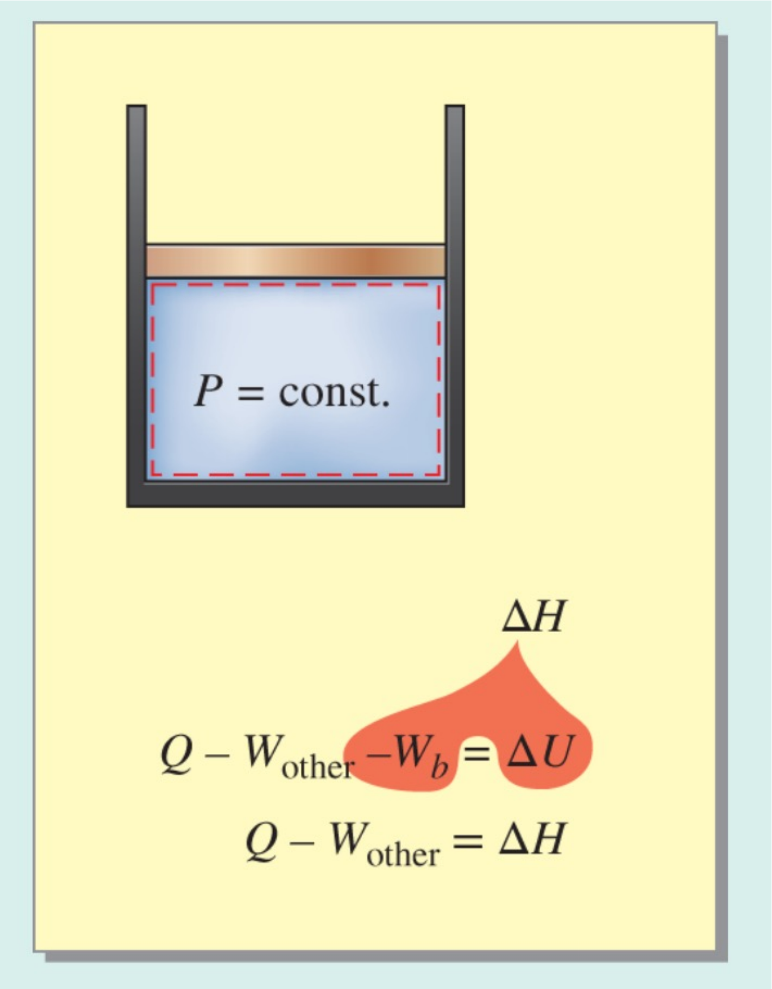
TABLE A–6

Superheated water

T °C	υ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	υ m³/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

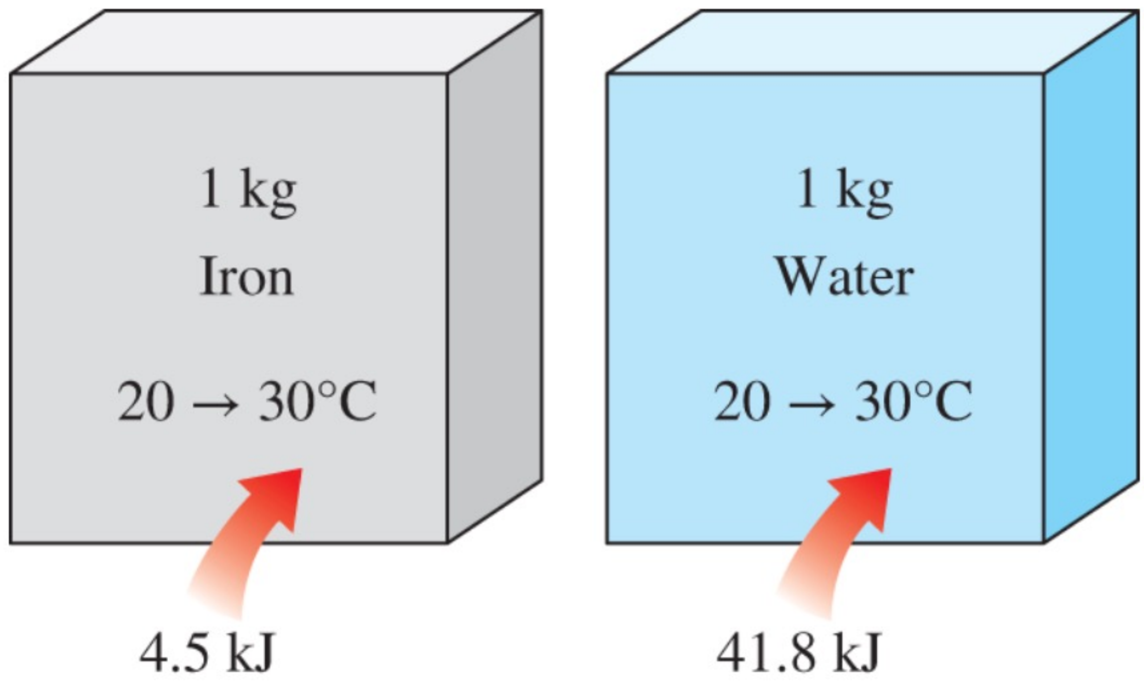
- Summary:



SPECIFIC HEATS

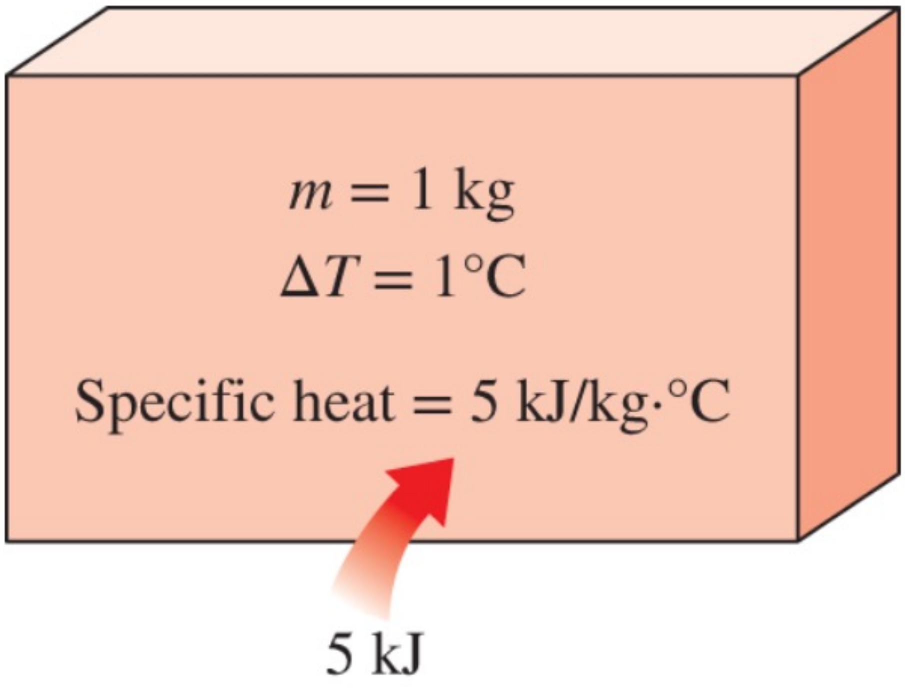
Specific Heats

- 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

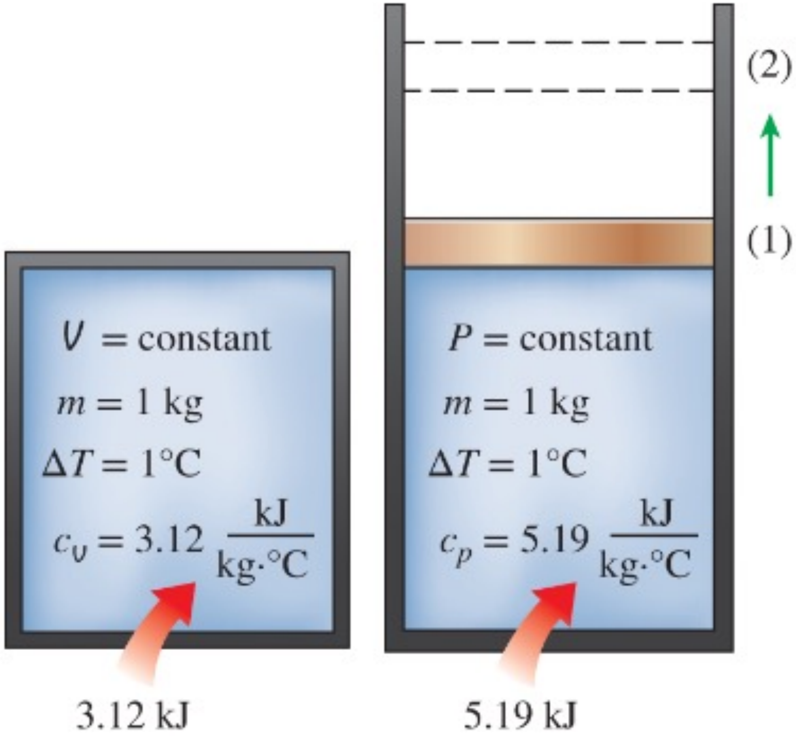


Specific Heats

- Specific heat is defined as the energy required to raise temperature of a unit mass of substance by one degree
  - Specific heat at constant volume (c_v)
  - Specific heat at constant pressure (c_p)

Specific Heats

- Specific heat is defined as the energy required to raise temperature of a unit mass of substance by one degree
  - Specific heat at constant volume (c_v)
  - Specific heat at constant pressure (c_p)



Specific Heats

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

$$\delta e_{in} - \delta e_{out} = dU + dKE + dPE = \delta Q - \delta W$$

$$\delta Q = dU + \delta W = dU + PdV$$

$$c_v = \frac{1}{m}\left(\frac{\delta Q}{\delta T}\right)_v = \frac{1}{m}\left(\frac{\partial U}{\partial T}\right)_v = \left(\frac{\partial u}{\partial T}\right)_v$$

$$c_v dT = du$$

Specific Heats

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

$$\delta Q = dU + \delta W = dU + PdV$$

$$c_p = \frac{1}{m}\left(\frac{\delta Q}{\delta T}\right)_p = \frac{1}{m}\left(\frac{\partial H}{\partial T}\right)_p = \left(\frac{\partial h}{\partial T}\right)_p$$

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

Specific Heats