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

October 03, 2022
Energy analysis of closed systems (I)

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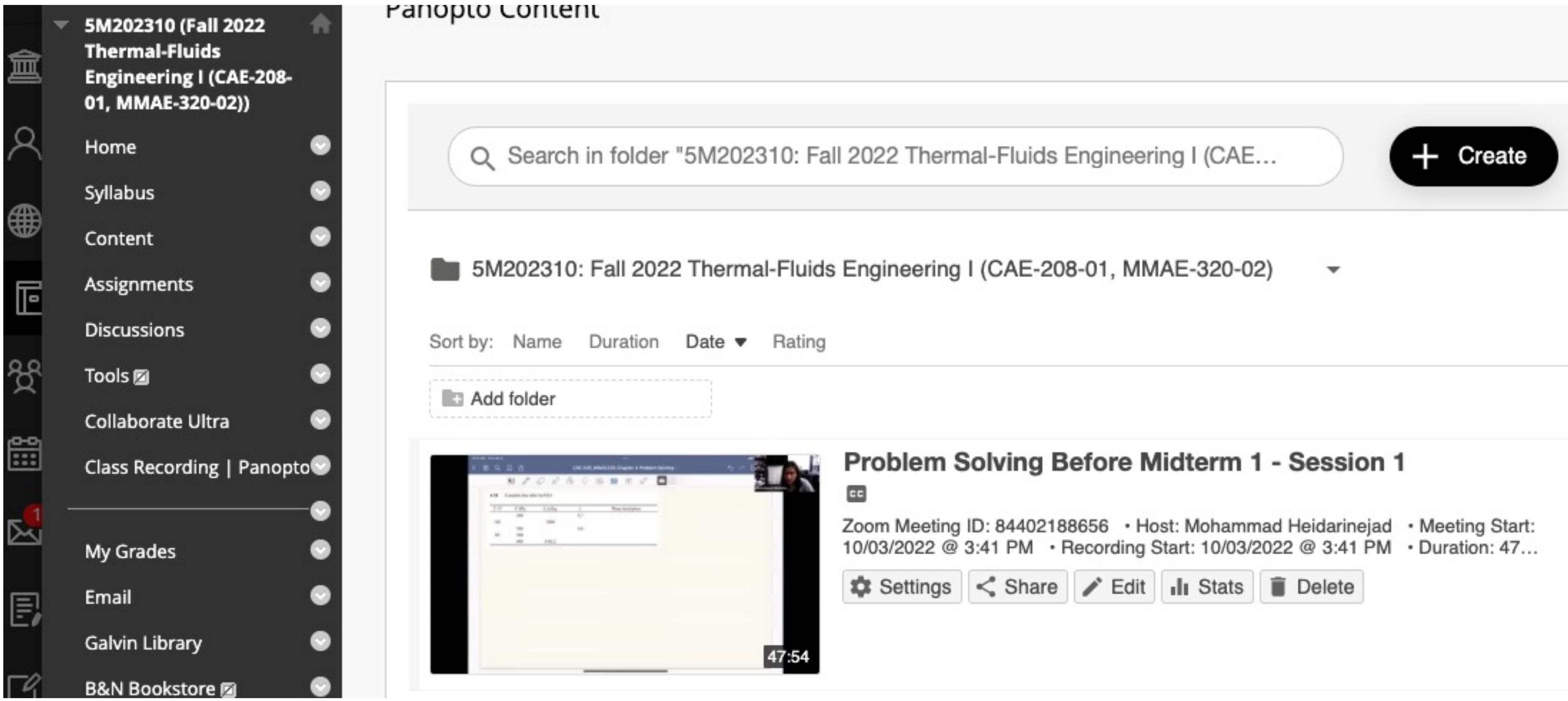
ANNOUNCEMENTS

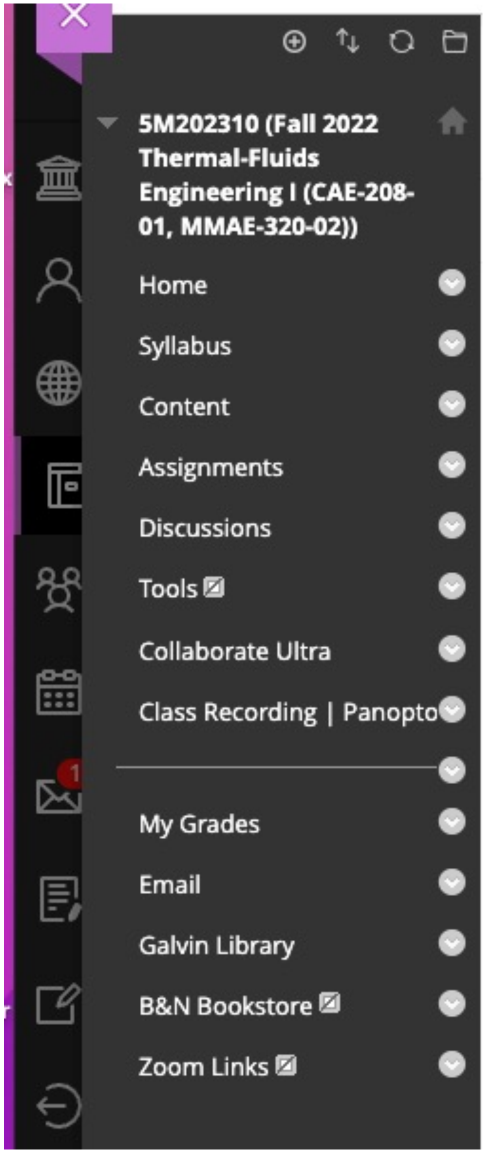
Announcements

- First problem solving session was yesterday (watch the recording and posted notes)



Announcements

- The second problem solving session is today



Announcements

- Assignment 5 is posted

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

Announcements

ASHRAE
Illinois Institute of Technology
Student Branch

IES

Sustainable Building Design & Simulation

SPEAKER
Matthew Duffy
Business Development Manager

WHEN
October 6th, 2022
12:40pm – 1:40pm

WHERE
John T. Rettaliata Engineering Center, RE 034

TALK ABOUT
- ✔ Work experiences
- ✔ IESVE (Virtual Environment Software)

For more information, feel free to contact ASHRAE official email
ashrae_iit@iit.edu

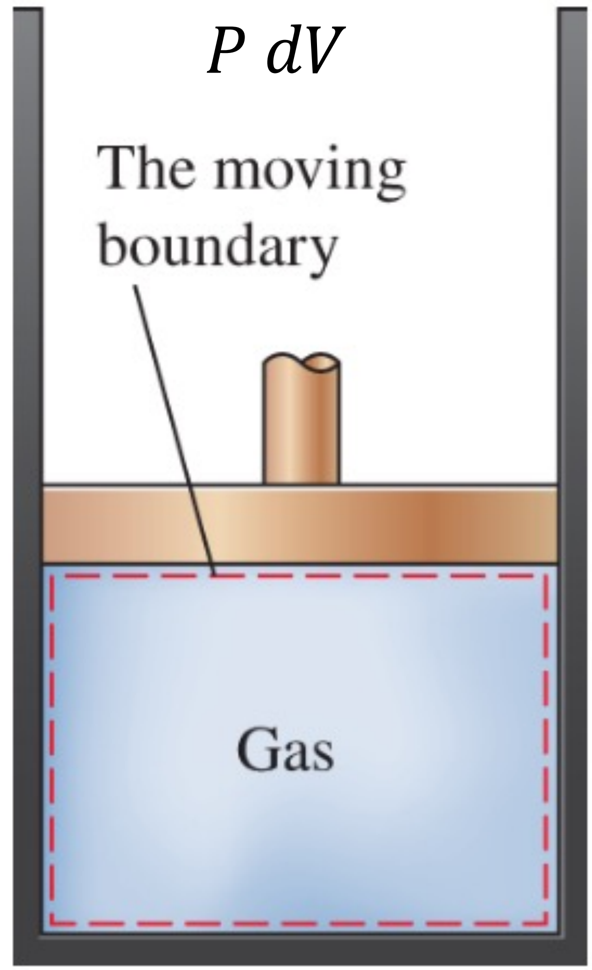
Interested in Joining

Lunch will be provided!

MOVING BOUNDARY WORK

Moving Boundary Work

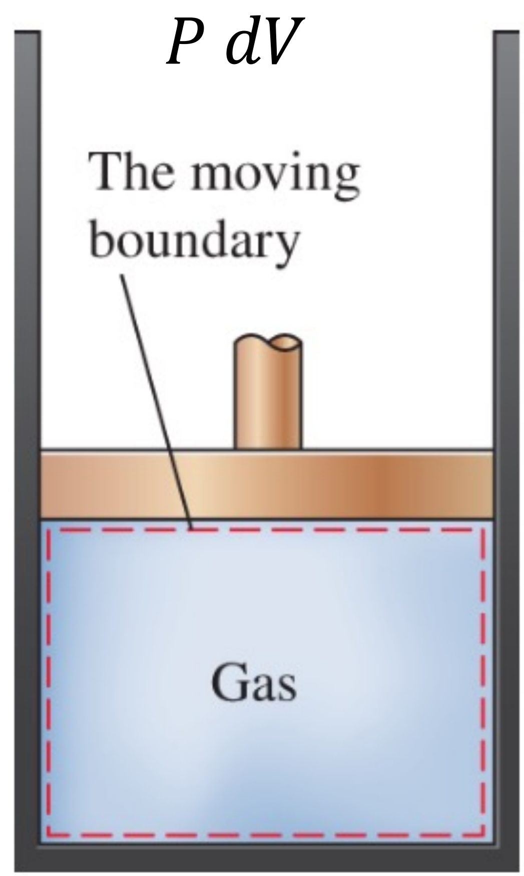
- The expansion or compression work is often called *moving boundary work* or simply *boundary work*



Think about internal combustion engines

Moving Boundary Work

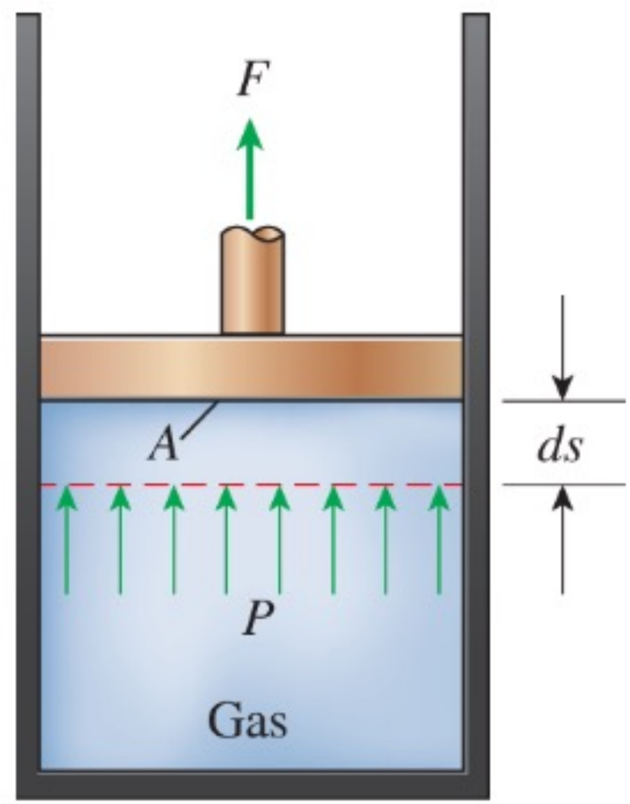
- The moving work associated with real engines or compressors cannot be determined exactly from a thermodynamic analysis alone!



Moving Boundary Work

- Consider the gas enclosed in the cylinder-piston device
- The process is quasi equilibrium (ds)

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



Moving Boundary Work

- Let’s think about dV

Moving Boundary Work

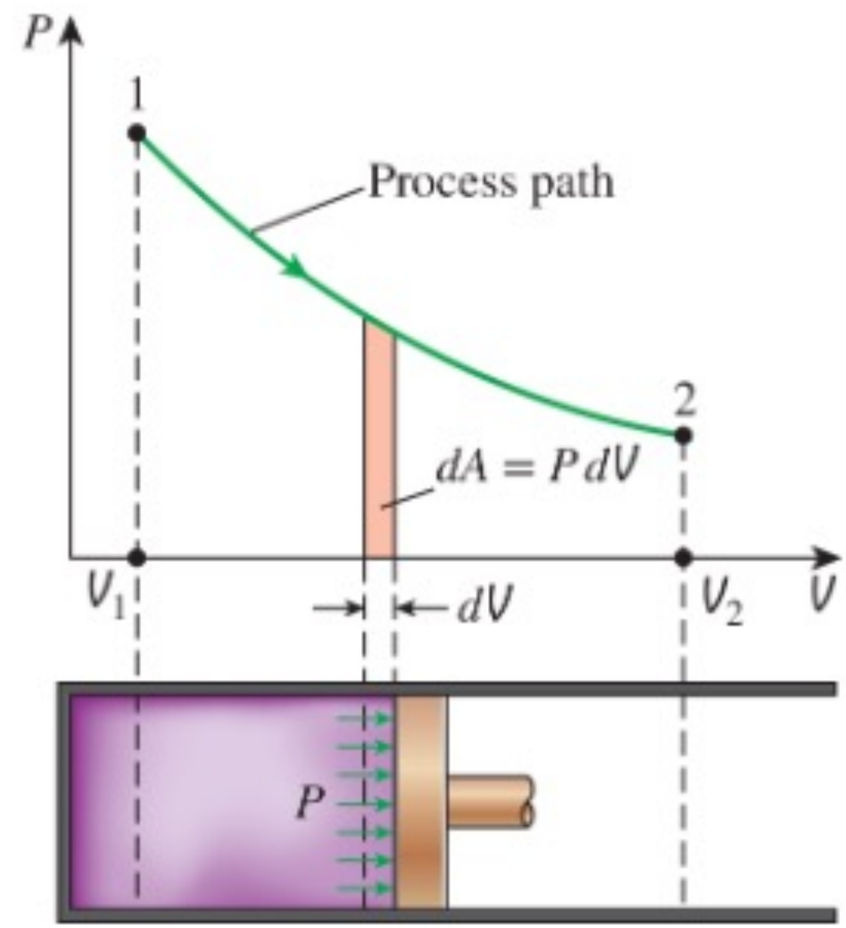
- The total boundary work done during the entire process as the piston moves is obtained by adding all the differential works from the initial state to the final state

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

Moving Boundary Work

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

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



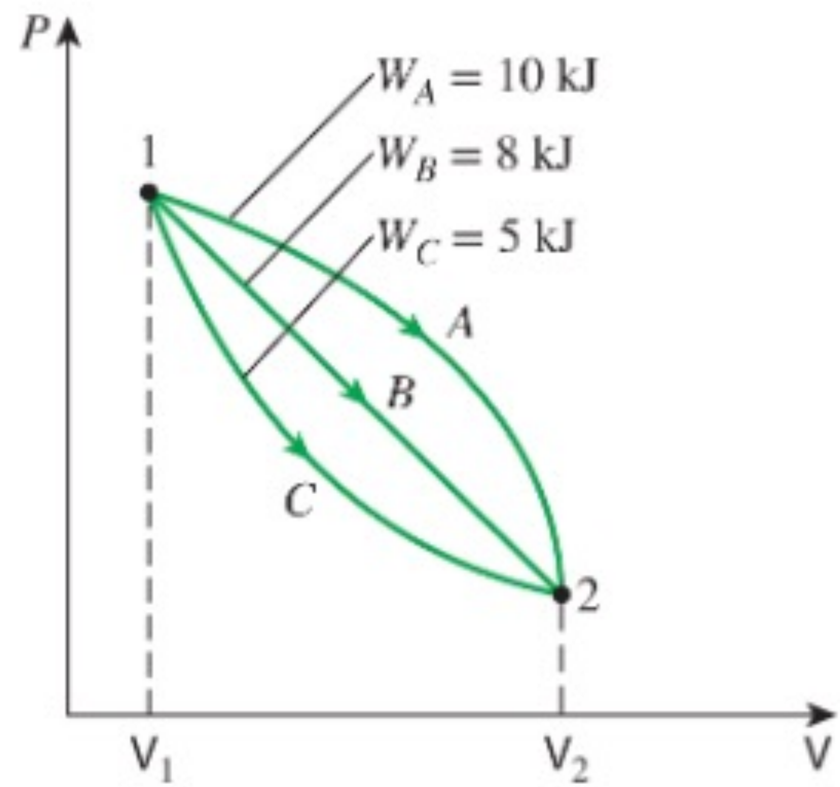
Moving Boundary Work

- Basically we can say:

The area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system (on the P-V diagram, in presents the boundary work done per unit mass)

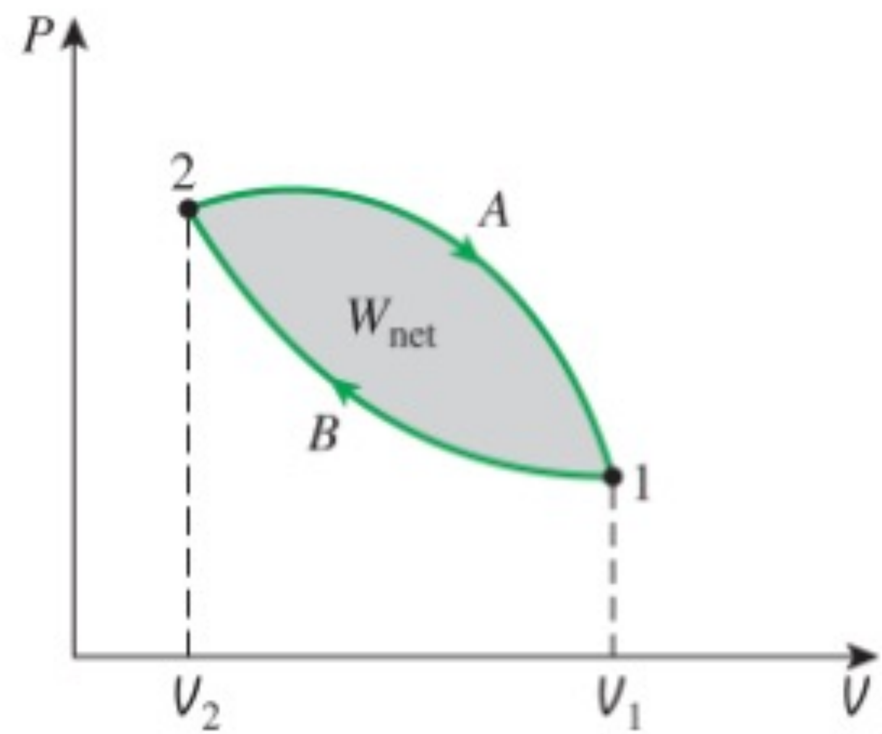
Moving Boundary Work

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



Moving Boundary Work

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



Moving Boundary Work

- We can use the equation for nonquasi-equilibrium process since properties are defined for equilibrium states only

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

Moving Boundary Work

- We can use the equation for nonquasi-equilibrium process since properties are defined for equilibrium states only

$$W_b = W_{friction} + W_{atm} + W_{crank} = \int_1^2 \left(F_{friction} + P_{atm}A + F_{crank}\right)dx$$

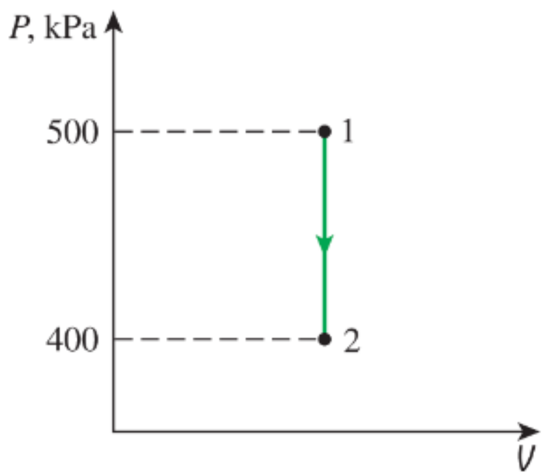
CLASS ACTIVITY

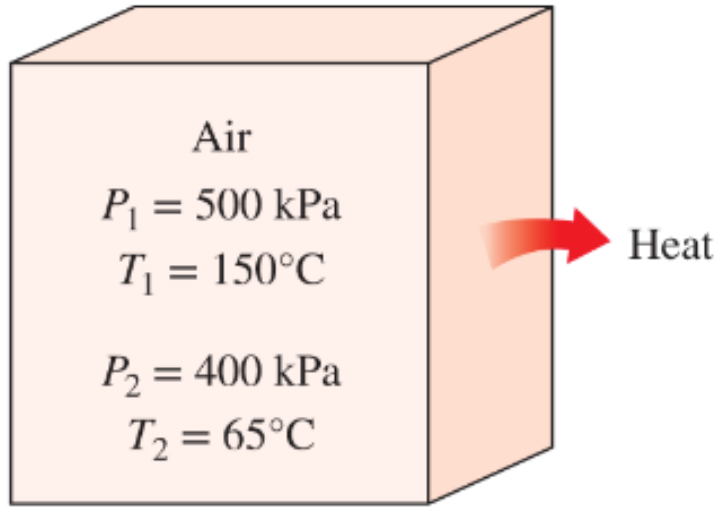
Class Activity

- A rigid tank contains air at 500 kPa and 150 °C. As a result of heat to the surroundings, the temperature and pressure inside the tank drop to 65 °C and 400 kPa, respectively. Determine the boundary work done during this process

Class Activity

- Solution





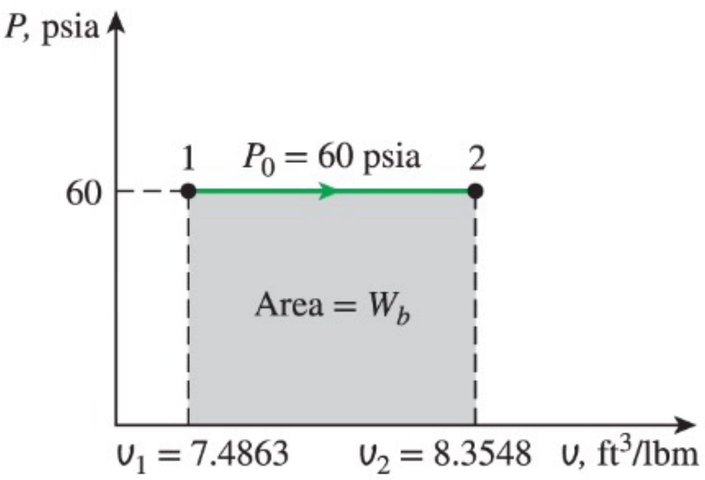
CLASS ACTIVITY

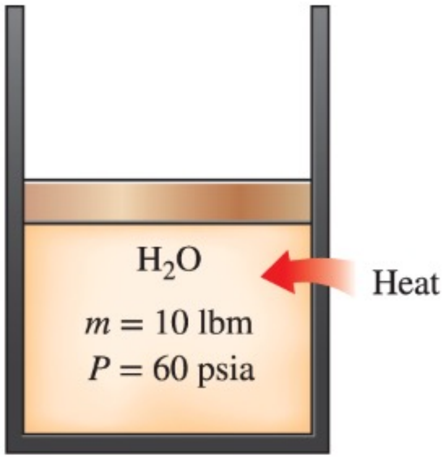
Class Activity

- A frictionless piston-cylinder device contains 10 lbm of steam at 60 psia and 320 °F. Heat is now transferred to the steam until the temperature reaches 400 °F. If the piston is not attached to a shaft and its mass is constant, determine work done by the steam during this process.

Class Activity

- Solution:





$$W_b = \int_1^2 P dV = P_0 \int_1^2 dV = P_0(V_2 - V_1)$$

$$W_b = mP_0(v_2 - v_1)$$

Class Activity

- Solution:

$$\begin{cases} P_1 = 60\ psia \\ T_1 = 320\ °F \end{cases} \qquad v_1 = 7.4863\ \frac{ft^3}{lbm}$$

$$\begin{cases} P_2 = 60\ psia \\ T_2 = 400\ °F \end{cases} \qquad v_2 = 8.3548\ \frac{ft^3}{lbm}$$

$$W_b = mP_0(v_2 - v_1)$$

$$= (10\ lbm)(8.3548 - 7.4863)\left(\frac{ft^3}{lbm}\right)\left(\frac{1Btu}{5.404\ psia - ft^3}\right) = 96.4\ Btu$$

Class Activity

Conversion Factors

Dimension	Metric	English
Acceleration	$1\ m/s^2 = 100\ cm/s^2$	$1\ m/s^2 = 3.2808\ ft/s^2$ $1\ ft/s^2 = 0.3048\ m/s^2$
Area	$1\ m^2 = 104\ cm^2 = 10^6\ mm^2 = 10^{-6}\ km^2$	$1\ m^2 = 1550\ in.^2 = 10.764\ ft^2$ $1\ ft^2 = 144\ in.^2 = 0.0929034\ m^2$
Density	$1\ g/cm^3 = 1\ kg/L = 1000\ kg/m^3$	$1\ g/cm^3 = 62.428\ lbm/ft^3 = 0.036127\ lbm/in.^3$ $1\ lbm/in.^3 = 1728\ lbm/ft^3$ $1\ kg/m^3 = 0.062428\ lbm/ft^3$
Energy, Heat, Work, Internal Energy, Enthalpy	$1\ kJ = 1000\ J = 1000\ N{\cdot}m = 1\ kPa{\cdot}m^3$ $1\ kJ/kg = 1000\ m^2/s^2$ $1\ kWh = 3600\ kJ$ $1\ Wh = 3600\ J$ $1\ cal = 4.1868\ J$ $1\ Cal = 4.1868\ kJ$	$1\ kJ = 0.94782\ Btu$ $1\ Btu = 1.055056\ kJ$ $= 5.40395\ psia{\cdot}ft^3$ $= 778.169\ lbf{\cdot}ft$ $1\ Btu/lbm = 25.037\ ft^2/s^2$ $= 2.326\ kJ/kg$ $1\ kJ/kg = 0.430\ Btu/lbm$ $1\ kWh = 3412.14\ Btu$ $1\ therm = 10^5\ Btu = 1.055 \times 10^5\ kJ$ (natural gas)

https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118848944.app8

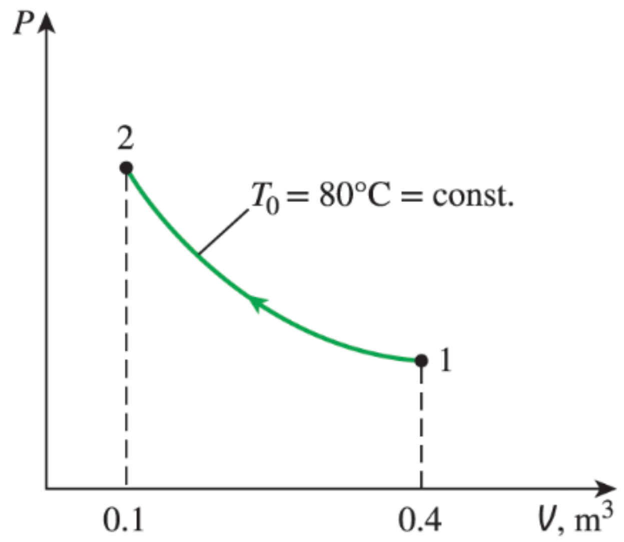
CLASS ACTIVITY

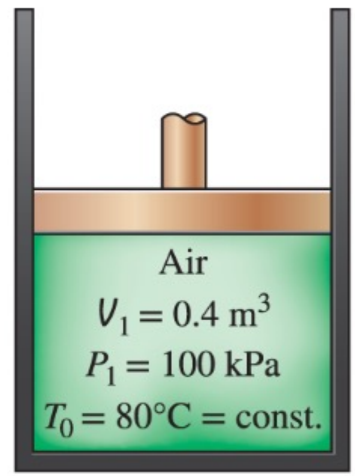
Class Activity

- 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:



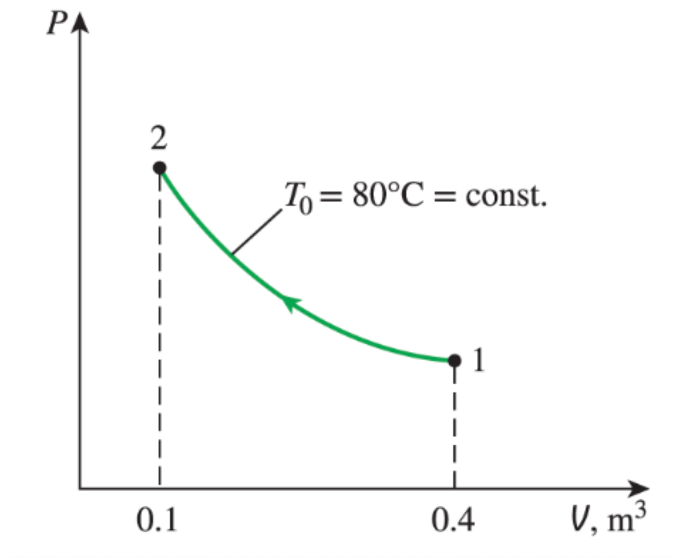


$$PV = mRT_0 \;\; \rightarrow \;\; P = \frac{C}{V}$$

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

Class Activity

- Solution:

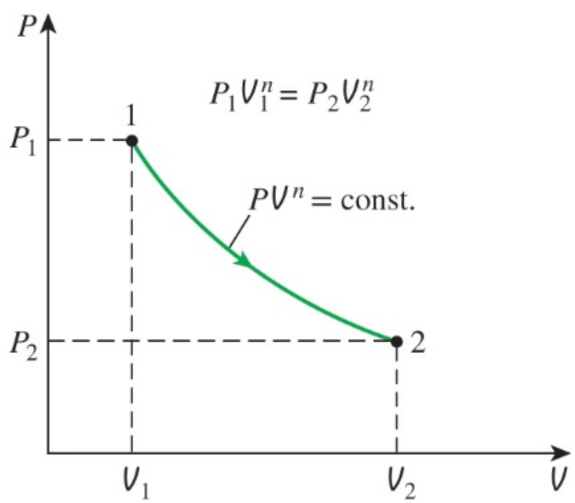


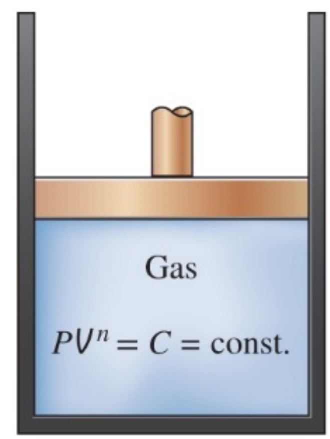
$$W_b = C \times Ln(V)\Big|_{V_1}^{V_2} = C[Ln(V_2) - Ln(V_1)] = P_1V_1 \times Ln(\frac{V_2}{V_1})$$

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

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

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

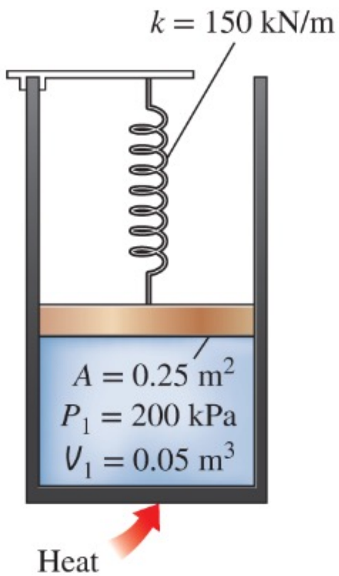
CLASS ACTIVITY

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

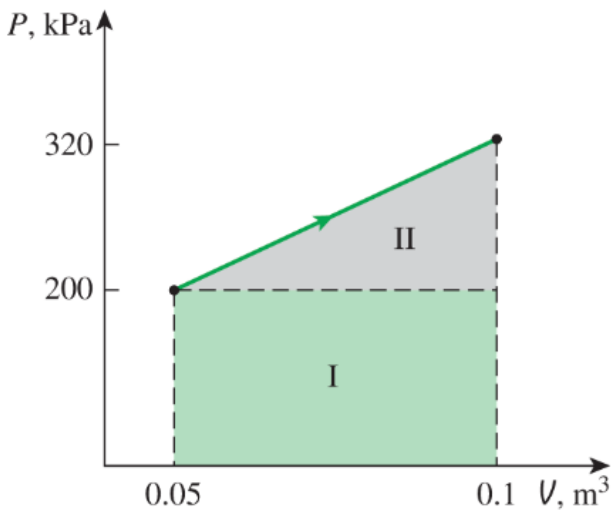


$$V_2 = 2V_1 = 2(0.05\ m^3) = 0.1\ m^3$$

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

Class Activity

- Solution



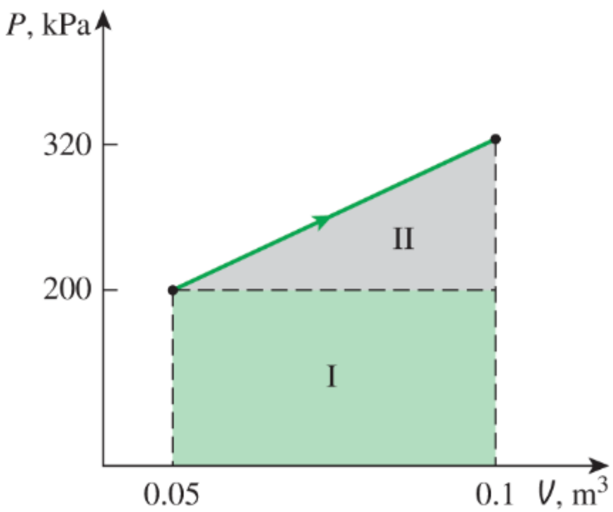
$$F = kx = \left(150\,\frac{kN}{m}\right)(0.2\,m) = 30\,kN$$

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

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

Class Activity

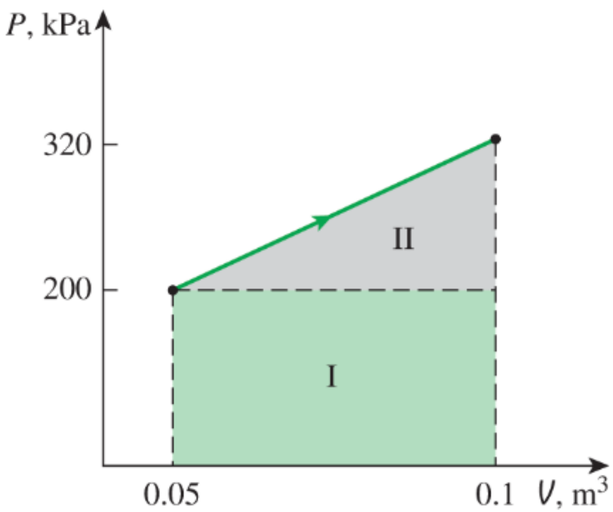
- Solution (b)



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

Class Activity

- Solution (c)



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

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

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:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}$$

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:

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

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

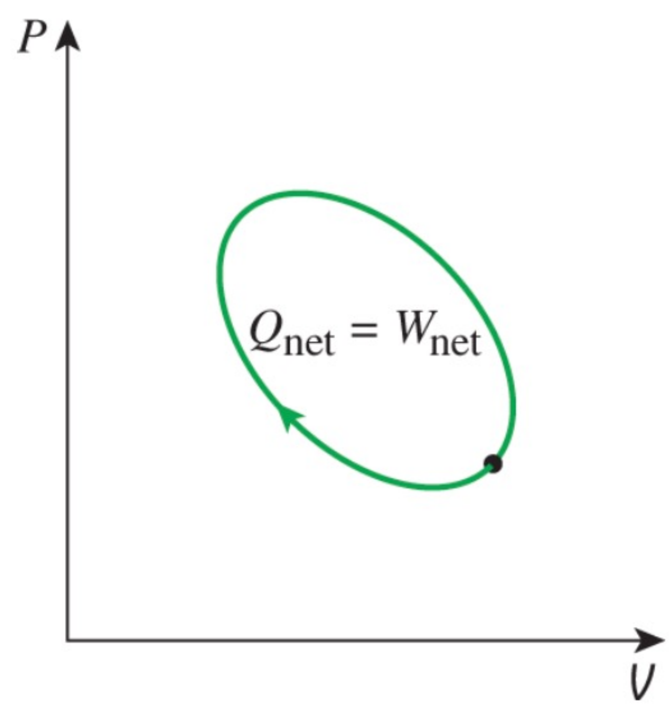
$$E = \left(\frac{dE}{dt}\right)\Delta t$$

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: