Lecture 4

Topic 2
First law of thermodynamics

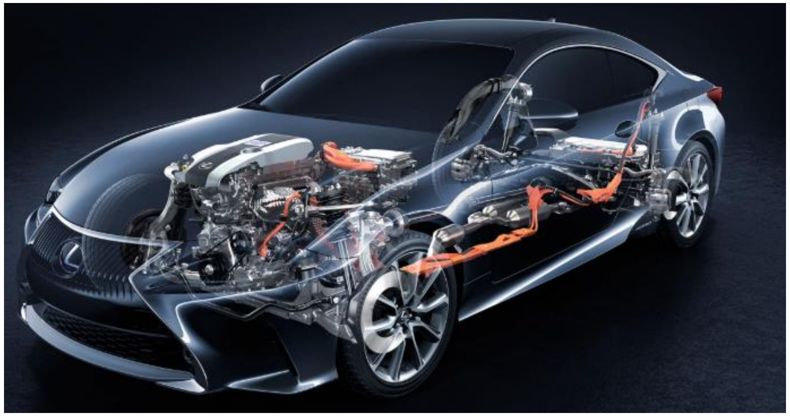
2.1 Introduction to 1st law of thermodynamics

2.2 Energy transfer by heat and work

Reading: Ch 3.1-3.6 Borgnakke & Sonntag Ed. 8
Ch 2 Cengel & Boles Ed. 5

2.1 Energy

- Relate the change of state of a system to the amount of energy transferred during a given process.
  - Relevant energy forms: work & heat



Chemical/electrical energy → shaft work → kinetic energy

Chemical energy → heat

2.1 Introduction to the First Law

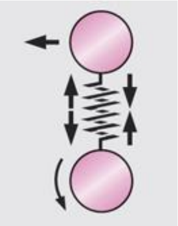
1st law of thermodynamics

- Conservation of energy principle - energy can be neither created nor destroyed; it can only change forms

- Total energy of system

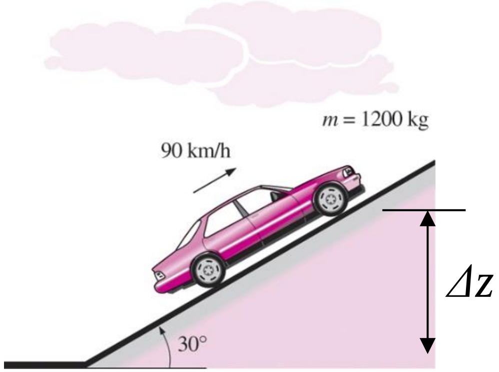
$$E_{system} = Internal\ Energy + Kinetic\ Energy + Potential\ Energy$$

- Internal Energy (U): energy contained within molecules of system
  - Translational, rotational, vibrational motion
  - Intermolecular forces



- Kinetic Energy (KE): energy related with motion of system

$$KE = \int_{\vec{V}=0}^{\vec{V}} m\vec{V}d\vec{V} = \frac{m\vec{V}^2}{2}$$



- Potential Energy (PE): energy related to system elevation

$$PE = \int_{z=0}^{z} mg\ dz = mgz$$

2.1 Introduction to the First Law

- Conservation of energy principle (1st law of thermodynamics):

$$\begin{pmatrix} \textit{Change in Total} \\ \textit{Energy of the System} \end{pmatrix} = \begin{pmatrix} \textit{Total Energy} \\ \textit{Entering the System} \end{pmatrix} - \begin{pmatrix} \textit{Total Energy} \\ \textit{Leaving the System} \end{pmatrix}$$

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

- ΔE_{system}: change in internal energy, kinetic energy and potential energy of the system
  - $\Delta E_{system} = \Delta U + \Delta KE + \Delta PE$
  - $\Delta E_{system} = m\Delta u + \frac{1}{2} m\Delta\vec{V}^2 + mg\Delta z \quad (kJ)$

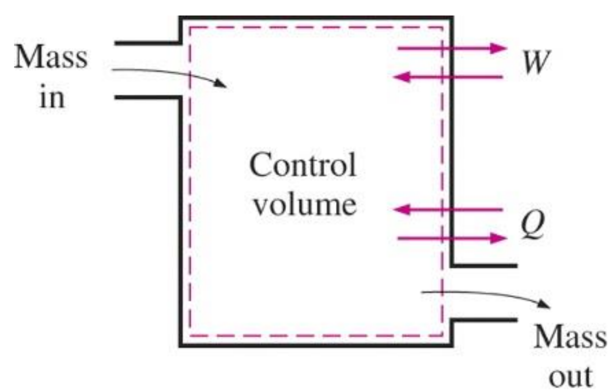
Stationary Systems

$z_1 = z_2 \rightarrow \Delta\mathrm{PE} = 0$

$V_1 = V_2 \rightarrow \Delta\mathrm{KE} = 0$

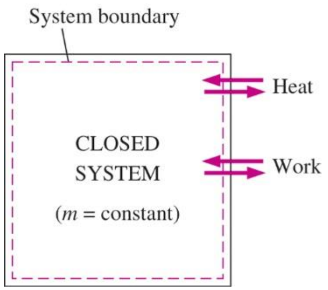
$\Delta E = \Delta U$

- E_{in} & E_{out}: energy crossing system boundaries
  - Work
  - Heat
  - Mass

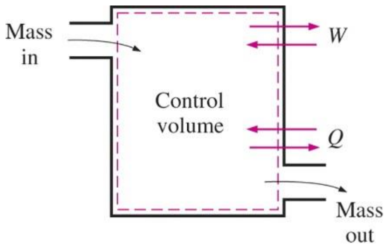


2.1 Introduction to the First Law

Different forms of energy balance



- **General:** $$\underbrace{\Delta E_{system}}_{Change\ in\ U,KE,PE} = \underbrace{E_{in} - E_{out}}_{\substack{Net\ energy\ transfer\\ by\ heat,work,mass}} \quad (kJ)$$



- **Rate form:** $$\underbrace{\Delta \dot{E}_{system}}_{\substack{Rate\ change\ in\\ U,KE,PE}} = \underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{Rate\ of\ net\ energy\ transfer\\ by\ heat,work,mass}} \quad (kW)$$

- Rate form: energy per unit time (kW)

$$\Delta \dot{E} = \frac{\Delta E}{\Delta t} \qquad \Delta \dot{Q} = \frac{\Delta Q}{\Delta t} \qquad \Delta \dot{W} = \frac{\Delta W}{\Delta t}$$

- Energy balance per unit mass
  - $\Delta e_{system} = \Delta u + \frac{1}{2}\Delta \vec{V}^2 + g\Delta z \quad (kJ/kg)$
  - $e_{in} - e_{out} = q_{net} - w_{net} \quad (kJ/kg)$

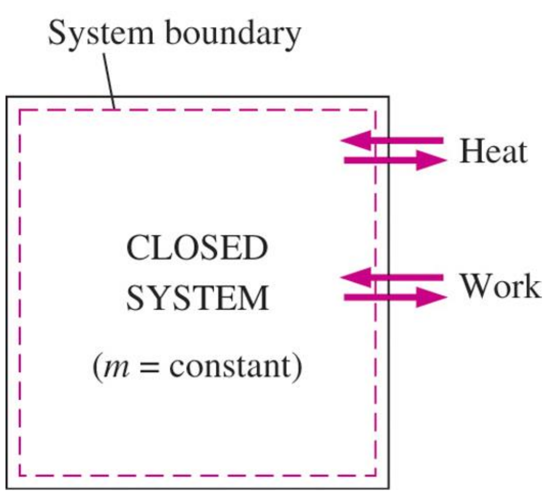
2.1 Introduction to the First Law

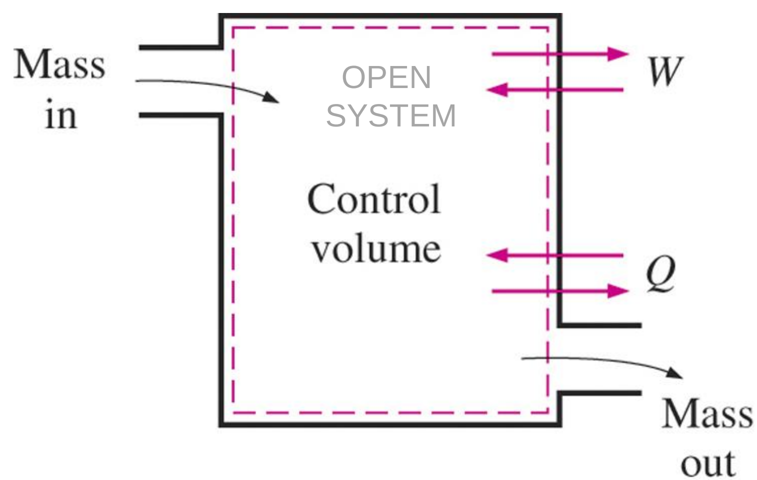
The energy balance for a general system is

$$\boxed{\Delta E_{system} = \Delta U + \Delta KE + \Delta PE = \underbrace{(Q_{in} - Q_{out})}_{Q_{net}} + \underbrace{(W_{in} - W_{out})}_{-W_{net}} + \left(E_{mass,in} - E_{mass,out}\right)}$$

Types of systems

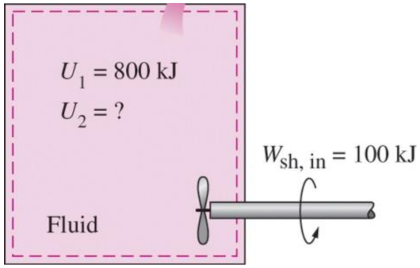
- **<u>Closed system</u>**: work and heat are only forms of energy that cross the system boundary (no mass transfer!)
- **<u>Open system</u>**: mass, work and heat can cross the system boundary (lecture 7)



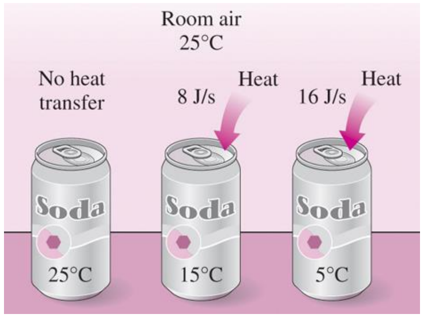


2.2 Energy transfer by work, heat, and mass

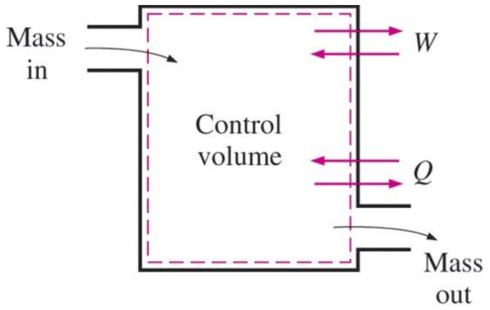
1. **Work, W:** Energy associated with forces exerted on the system by the surroundings. Work <u>performed on a system</u> causes the system's energy to <u>increase</u>. Work <u>performed by a system</u> causes the system's energy to <u>decrease</u>.



2. **Heat, Q:** Energy associated with a temperature difference between the system and surroundings. Heat transfer <u>to the system</u> causes the system's energy to <u>increase</u>. Heat transfer <u>from a system</u> causes the system's energy to <u>decrease</u>.



3. **Mass flow:** Energy associated with mass entering/leaving the system. Mass <u>entering</u> the system <u>increases</u> its energy. Mass <u>leaving</u> the system <u>decreases</u> its energy.



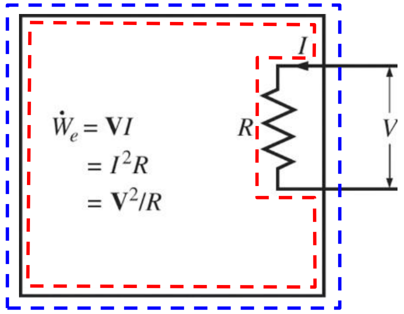
2.2.1 Energy transfer by work

Forms of Work

Electrical Work: electrons crossing the system boundary (e.g. electrical heater inside the system (blue)).

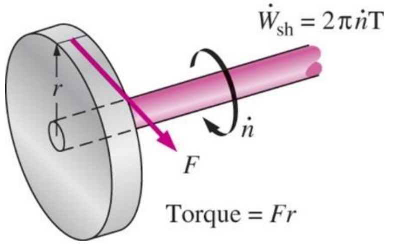
- Note: if heater is outside the boundary (red), energy is transferred as heat.

$$W_e = \int_1^2 V\,I\,dt \qquad \text{(kJ)}$$



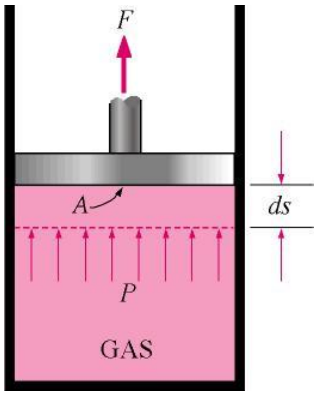
Mechanical Work: energy from a force, F, acting through a displacement, s. Common types: shaft work, spring work, or work done to move an object

$$\delta W = F \cdot ds = F ds\, cos\theta$$



Boundary work: special type of "force acting through displacement" work. Work due to moving boundaries of the system.

- Commonly seen in piston/cylinder devices.



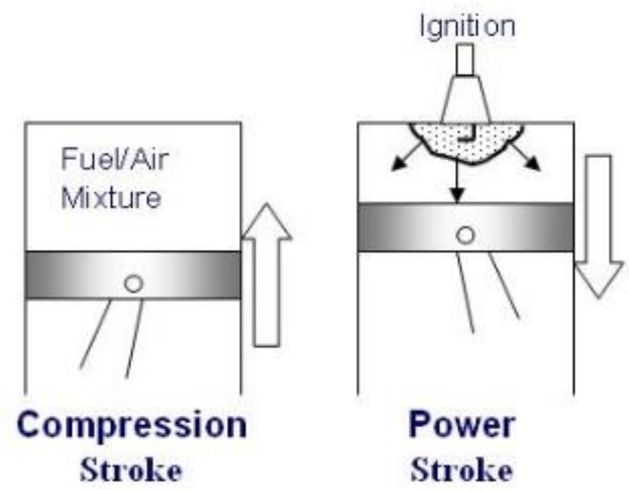
2.2.1 Energy transfer by work

Net Work Done By A Closed System

$$W_{net} = \left(\sum W_{out} - \sum W_{in}\right)_{Elec.+Mech.} + W_{boundary}$$

<u>Example 2-1</u>

A piston engine requires 500 kJ of work into the system to compress air/fuel. The fuel ignites (giving heat), increasing pressure & temperature of the system. This forces the piston downward giving 1000 kJ of work out of the system to power the car. What is the net work out of the system?



2.2.2 Moving Boundary Work

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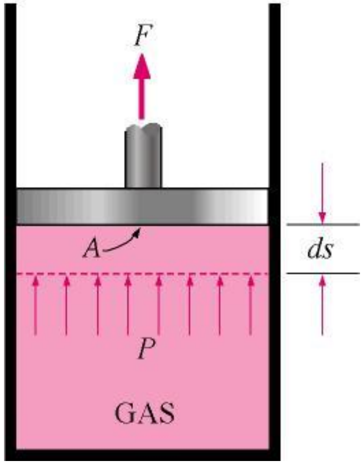
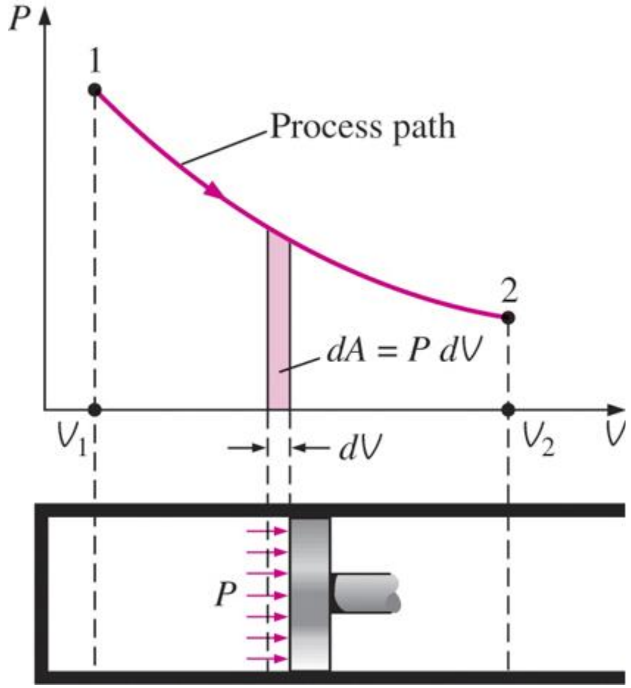
- Boundary work: force acting on system boundary, which moves boundary
  - Force can be external (acting on system) or internal (acting by the system; e.g. pressure)

- $W_b = \int_1^2 \delta W_b = \int_1^2 F ds = \int_1^2 PA ds$
- $W_b = \int_1^2 P dV$



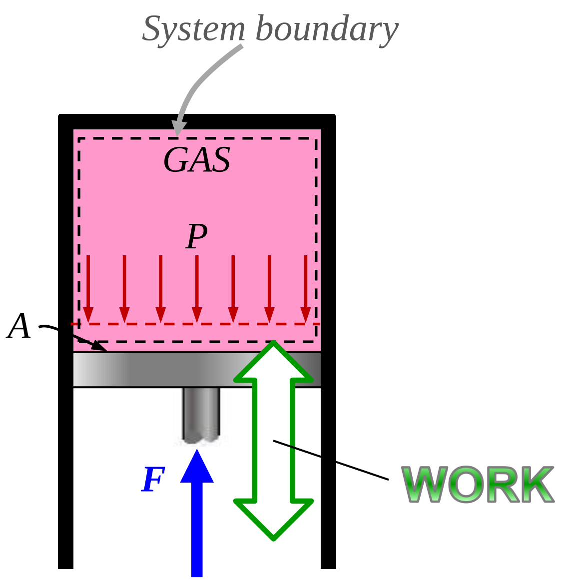


- The area under the process path on P-V diagram represents the boundary work. P is the absolute pressure.

2.2.2 Moving Boundary Work

- Sign convention of boundary work

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



- If $PA > F$ piston will move outwards
  - Gas will expand; volume increase (+ dV)
  - $W_b = \int_1^2 P dV$ is out of the system (positive value)

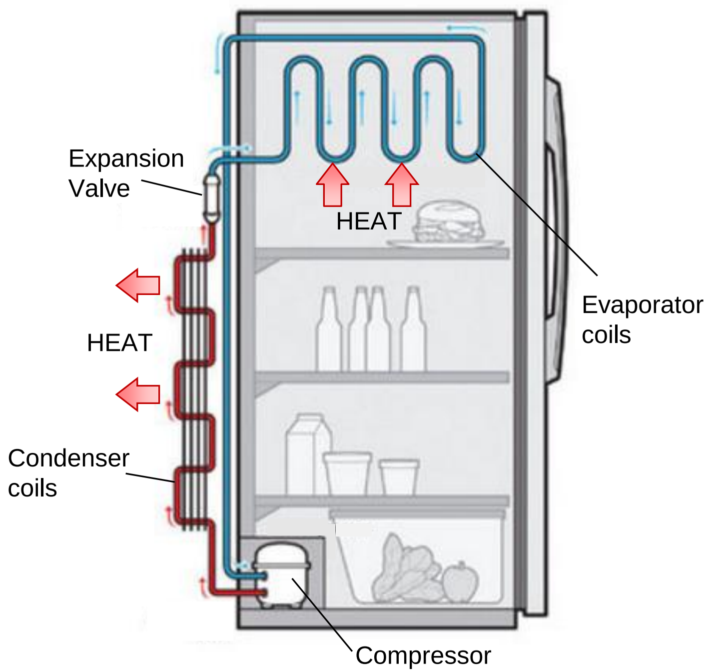
- If $PA < F$ piston will move inwards
  - Gas will compress; volume decrease (- dV)
  - $W_b = \int_1^2 P dV$ is into the system (negative value)

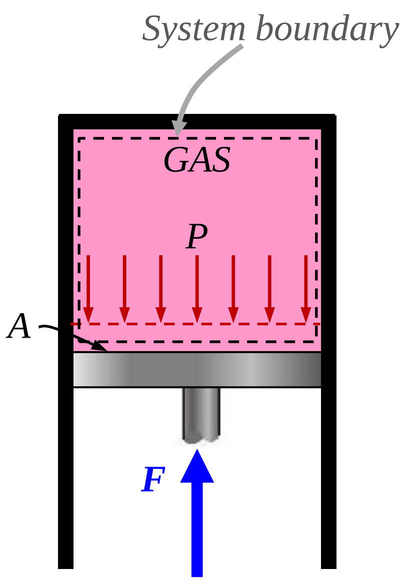
- Is work in or out?
  - Always draw a diagram of the system
  - Work will point in the same direction as the larger force (PA or F)

2.2.2 Moving Boundary Work

- Piston/cylinder devices are common devices we will study in Thermodynamics
  - Example: vapor compression refrigeration

https://m.youtube.com/watch?v=kFQu9uoZWKg





2.2.2 Moving Boundary Work

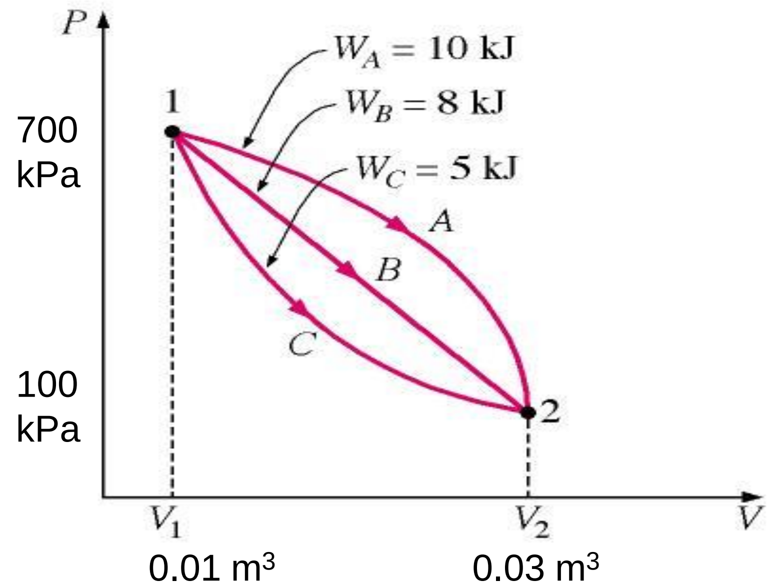
- Boundary work is process dependent

$$\delta W_b = PdV$$

- Boundary work is a <u>path function</u> → the magnitude depends on the path followed
    - $\int_1^2 \delta W_b = W_{21} \qquad (not\ \Delta W)$

- Work is not a property of the system
    - i.e. not $W_2 - W_1$
- Work is determined by adding differential amounts of work (δW) along the process path (i.e. integration)
- The P-V relationship must be known

$$P = f(V)$$



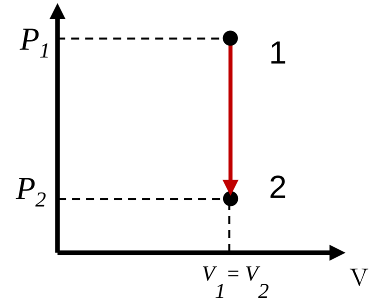
2.2.2 Moving Boundary Work

Common boundary work processes:

a) Constant volume

If the volume is held constant, $dV = 0$, and the boundary work equation becomes

$$W_b = \int_1^2 P\,dV = 0$$

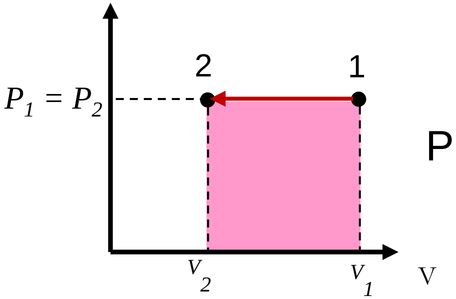


P-V diagram for V = constant

b) Constant pressure

If the pressure is held constant, the boundary work equation becomes

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



P-V diagram for P = constant

2.2.2 Moving Boundary Work

Common boundary work processes:

c) Constant temperature, ideal gas
Ideal gas equation of state provides the pressure-volume relation

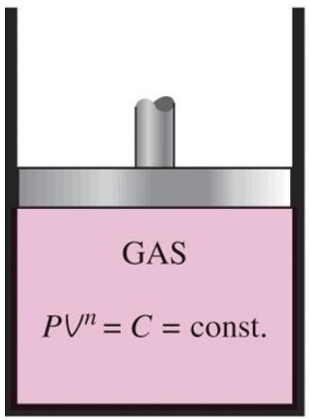
- $PV = mRT$
- $P = \frac{mRT}{V}$
- $W_b = \int_1^2 PdV = \int_1^2 \frac{mRT}{V} dV$
- $W_b = mRT \int_1^2 \frac{1}{V} dV$
- $\boxed{W_b = mRT \ln\left(\frac{V_2}{V_1}\right)}$

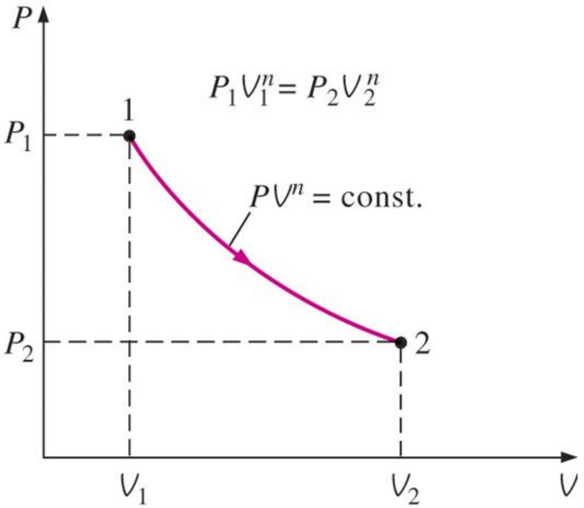
2.2.2 Moving Boundary Work

Common boundary work processes:

d) The polytropic process:

$$\boxed{PV^n = \text{constant}}$$





The exponent (n) values are determined from the process.

Process	**Exponent (n)**
Constant pressure	0
Constant volume	∞
Isothermal & ideal gas	1
Adiabatic & ideal gas	$k = C_P/C_V$

k : ratio of the specific heats C_P and C_V.
(lecture 6)

2.2.2 Moving Boundary Work

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Common boundary work processes:

d) The polytropic process: ... continued

- Boundary work is determined by substituting the pressure-volume relation into the boundary work equation.

$$PV^n = constant \rightarrow P_1V_1{}^n = P_2V_2{}^n$$

$$W_b = \int_1^2 PdV = \int_1^2 \frac{Const}{V^n} dV$$

$$= \frac{P_2V_2 - P_1V_1}{1-n}, \ \mathrm{n} \neq 1$$

$$= PV \ln\left(\frac{V_2}{V_1}\right), \ \mathrm{n} = 1$$

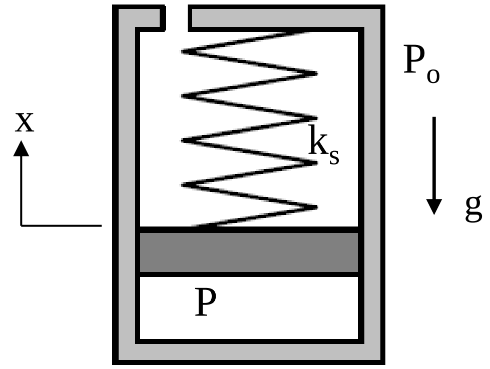
For an ideal gas (n = 1): result is equivalent to the isothermal process.

2.2.2 Moving Boundary Work

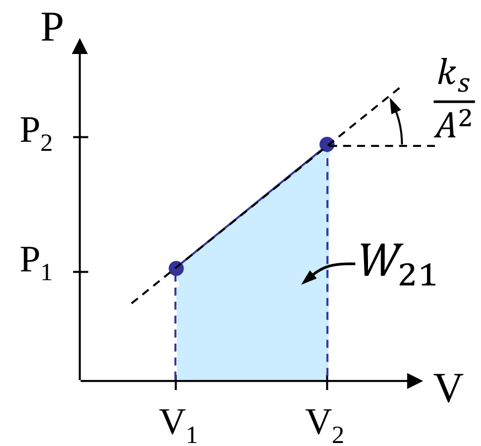
Common boundary work processes:

e) Other P-v relationships

Piston loaded with linear spring



- $F_{spring} = k_s x$; k_s is the spring constant (N/m)
- $W_{spring} = \int F_{spring} dx = \int k_s x dx = \frac{1}{2} k_s x^2$
- $F = P * A = k_s x; \quad V = A * x$
- $P = \frac{k_s}{A^2} V$ → linear relationship between P and V
  - $Slope = k_s / A^2$
- $W_{boundary} = \int_1^2 PdV = area\ under\ P - V\ curve$
- $W_{boundary} = \frac{1}{2}(P_1 + P_2) * (V_2 - V_1)$
- Note that the spring work may not equal the work done by/on the system

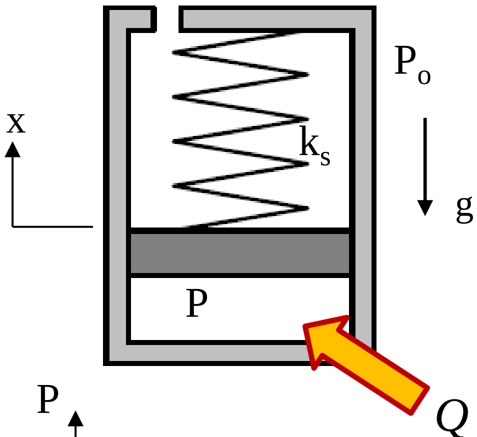


2.2.2 Moving Boundary Work

Example 2.2

A cylinder equipped with an linear spring is filled with air with 200 kPa and volume 0.2m^3. Initially the spring is in contact with the piston, but does not exert any forces. Heat is added to the system until the air reaches a pressure of 800 kPa and volume of 0.5 m^3.

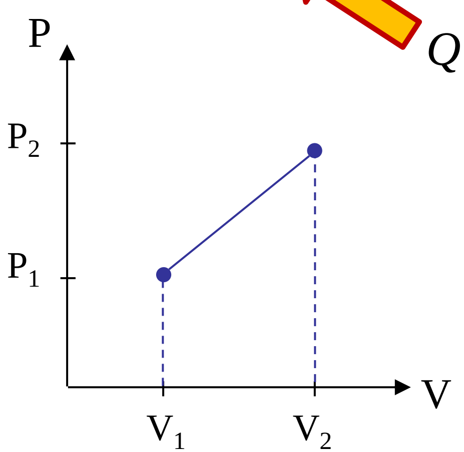
What is the final work done by the system? What is the work done by the spring?



Solution:

$$W_{system} = \int_1^2 PdV = area\ under\ P - V\ curve$$

$$W_{system} = \frac{1}{2}(P_1 + P_2) * (V_2 - V_1) = 150kJ$$



If there were no spring, pressure would be constant at 200 kPa as the piston rises (i.e. force of piston is constant; *mg*).

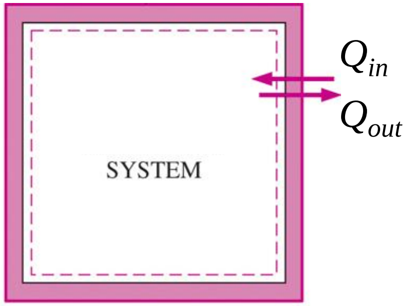
$$W_{no\ spring} = \int_1^2 PdV = P(V_2 - V_1) = 60\text{kJ}$$

$$W_{spring} = W_{system} - W_{no\ spring} = 90kJ$$

2.2.3 Energy transfer by heat

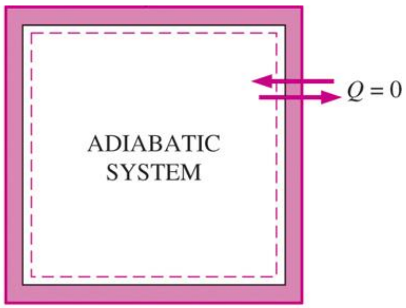
- Heat: energy from a temperature difference between the system and the surroundings
- The net heat transferred to a system:

$$Q_{net} = \sum Q_{in} - \sum Q_{out}$$



- Q_{in} and Q_{out} are magnitudes of heat transfer values

- Adiabatic system is a system with NO heat transfer: $Q = 0$



<u>Three modes of heat transfer</u>

- Conduction
- Convection
- Radiation

2.2.3.1 Modes of Heat Transfer

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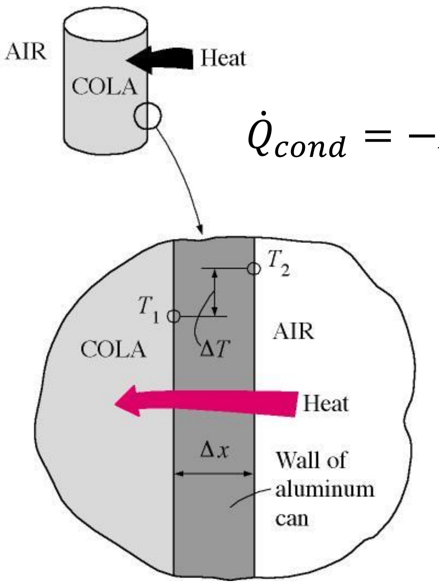
Conduction

Heat transfer between stationary molecules of a substance.

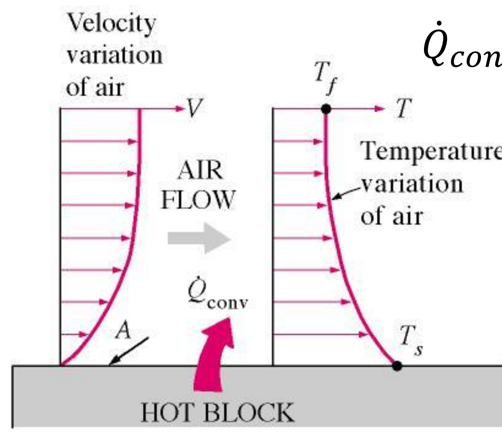
$$\dot{Q}_{cond} = -Ak_t \frac{dT}{dx}$$



Convection

Heat transfer between a solid surface and adjacent fluid in motion.

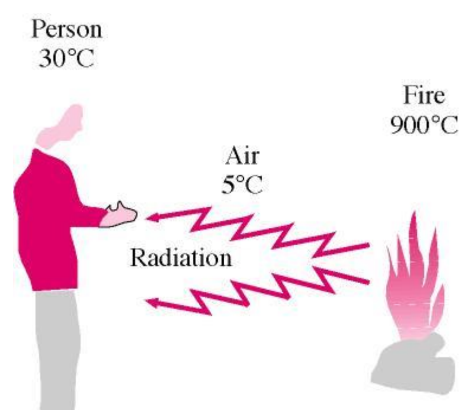
$$\dot{Q}_{conv} = hA(T_s - T_f)$$



Radiation

Heat transfer from the surface of one body to another by electromagnetic radiation.

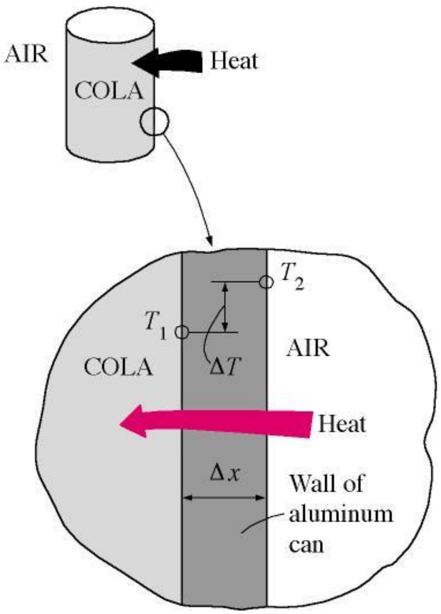
$$\dot{Q}_{rad} = \epsilon\sigma A(T_s^4 - T_{surr}^4)$$



2.2.3.1 Conduction

Conduction – heat exchange between stationary molecules of a substance.

- Fourier's law of heat conduction: $\dot{Q}_{cond} = -Ak_t \dfrac{dT}{dx}$



$\dot{Q}_{cond}$ = heat flow per unit time (W; 1W=1J/s), i.e. dQ/dt
k_t = thermal conductivity (W/m·K)
A = area normal to heat flow (m^2)
$\frac{dT}{dx}$ = temperature gradient in the direction of heat flow (°C/m)

Exercise 2-1
A flat wall is composed of 20 cm of brick having a thermal conductivity k_t = 0.72 W/m·K. The right face temperature of the brick is 900°C, and the left face temperature of the brick is 20°C. Determine the rate of heat conduction through the wall per unit area of wall.

[ans: 3168 W/m^2]

2.2.3.2 Convection

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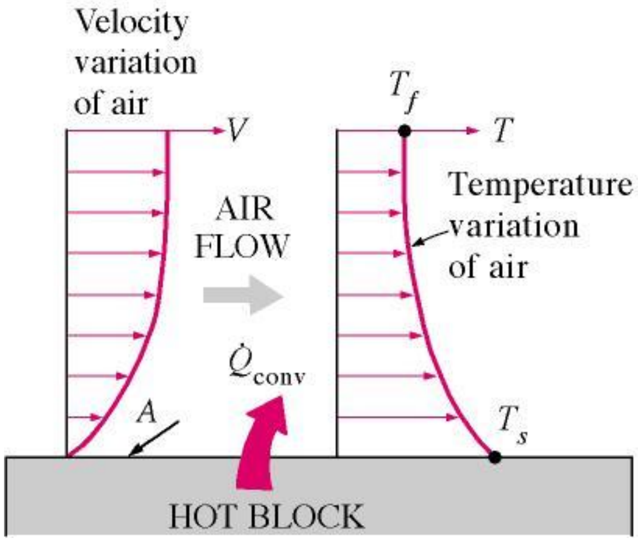
Convection – heat transfer between a solid surface and the adjacent liquid or gas that is in motion.

The rate of heat transfer by convection ($\dot{Q}_{conv}$) is determined from Newton's law of cooling:

$$\dot{Q}_{conv} = hA\left(T_s - T_f\right)$$



Heat is first transferred to the air layer adjacent to the surface by conduction. This energy is then carried away from the surface by convection.

$\dot{Q}_{conv}$	= heat transfer rate (W)
A	= heat transfer area (m^2)
h	= convective heat transfer coefficient ($W/m^2 \cdot K$)
T_s	= surface temperature (K)
T_f	= bulk fluid temperature (K)

2.2.3.2 Convection

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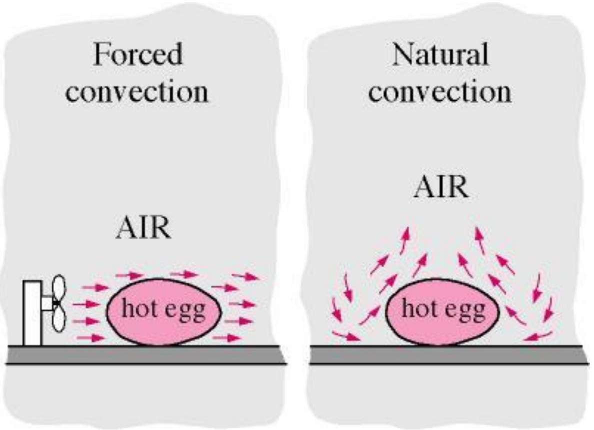
$$\dot{Q}_{conv} = hA\left(T_s - T_f\right)$$



The convective heat transfer coefficient (h) is an experimentally determined parameter. It depends upon the surface geometry, fluid properties, nature of flow, and the bulk fluid velocity.

Note: in the absence of fluid motion the heat is transferred conducted by natural convection.

Ranges of the convective heat transfer coefficient are:

	h **W/m^2·K**
free convection of gases	2-25
free convection of liquids	50-100
forced convection of gases	25-250
forced convection of liquids	50-20,000
convection in boiling and condensation	2500-100,000

2.2.3.3 Radiation

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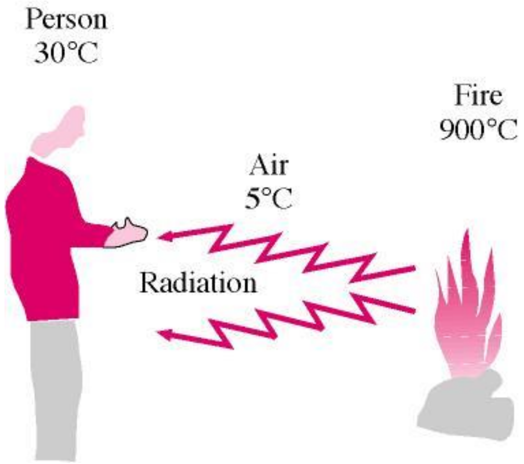
Radiation – heat transfer from the surface of one body to the another surface by electromagnetic radiation.

$$\dot{Q}_{rad} = \epsilon\sigma A(T_s^4 - T_{surr}^4)$$



$\dot{Q}_{rad}$	= heat transfer per unit time (W)
A	= surface area for heat transfer (m^2)
σ	= Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2K^4 and 0.1713×10^{-8} $BTU/h\ ft^2\ R^4$
ε	= emissivity
T_s	= absolute temperature of surface (K)
T_{surr}	= absolute temperature of surroundings (K)

2.2 Energy transfer by work & heat

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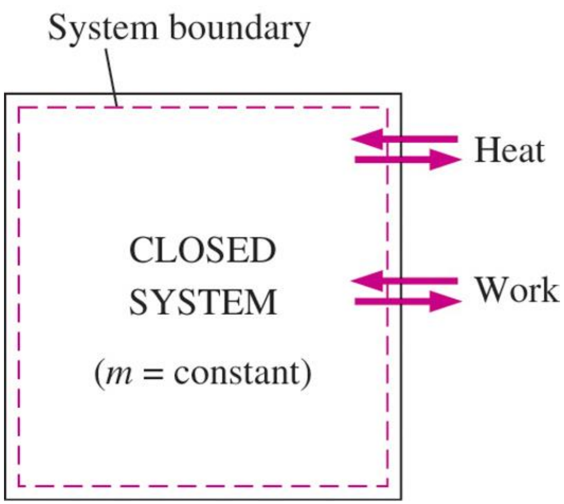
Similarities between work & heat



1. They are both boundary phenomena.

2. Both are path functions. Their magnitudes depend on the path followed during a process as well as the end states.