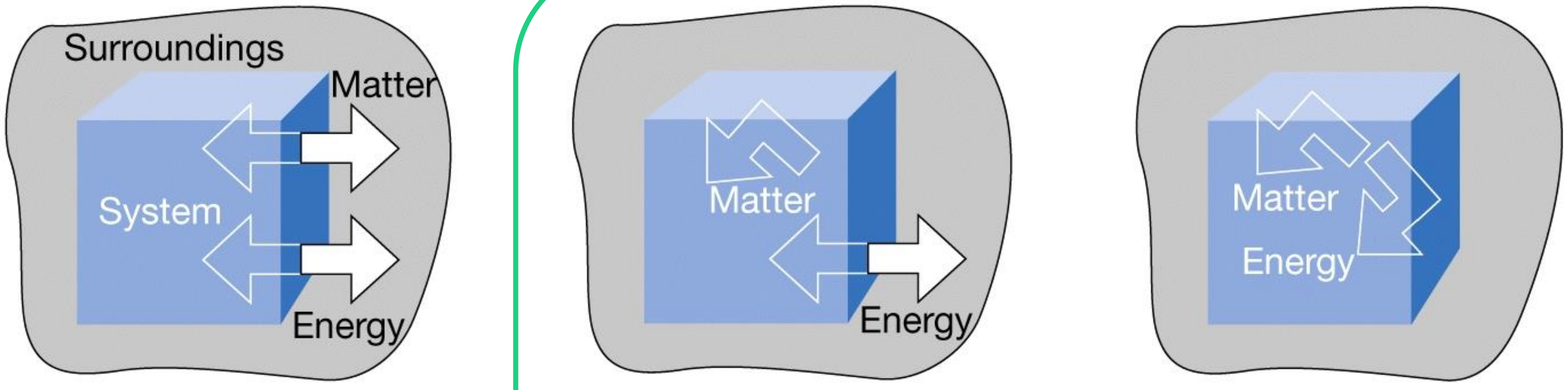
DTU

47201 Engineering thermodynamics

Lecture 2a: First law for closed systems (Ch 4.1-4.12)

Closed systems



(a) Open (b) Closed (c) Isolated

Control volume **Control mass**

- No transfer of mass to and from the system
- There can be heat and work interaction with the surroundings

Forms of energy

Gravitational potential energy

Energy stored in a body raised in a gravitational field

$$\mathrm{PE} = mgz$$
$$\Delta\mathrm{PE} = \Delta mgz$$

Kinetic energy

The energy stored in or possessed by an object due to motion

$$\mathrm{KE} = E_k = \frac{1}{2} m\mathbf{V}^2$$

Internal energy

The total microscopic energy of all atoms and molecules in a system

$$U = U(T, P, \ldots)$$

Specific energy of a system

Specific energies

For each of the total energies above, there is a corresponding specific energy (energy per amount of substance)

$$pe = g\,z \qquad ke = \frac{1}{2}v^2 \qquad u = \frac{U}{m}$$

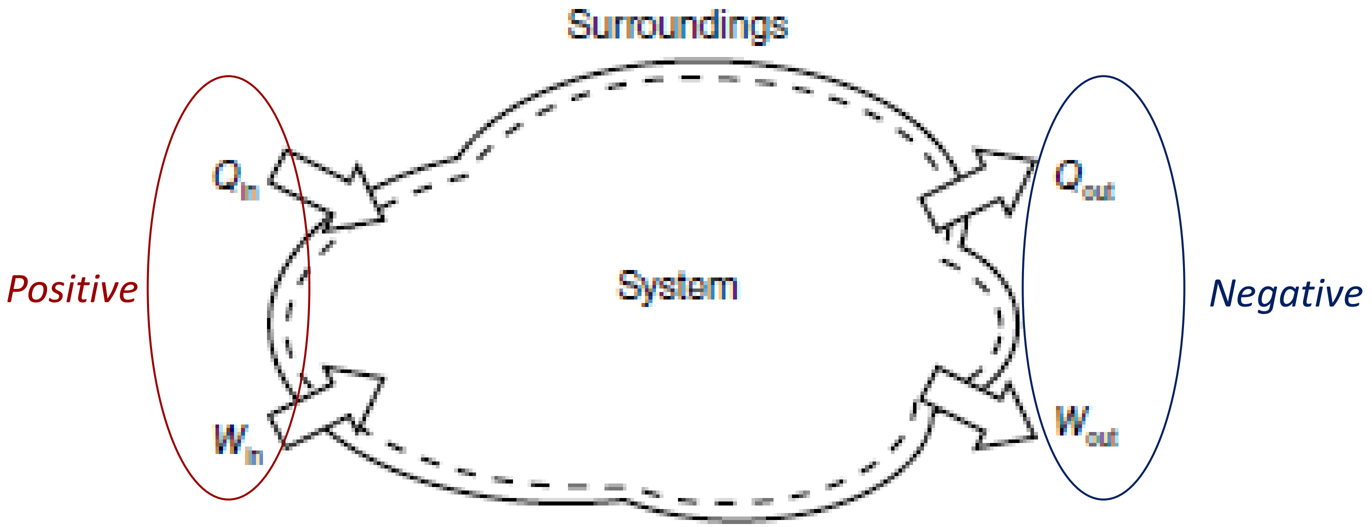
The total specific energy of a system is the sum of all energy forms

$$\mathrm{e} = gz + \frac{1}{2}v^2 + u$$

Transfer of Energy to/from a system

Transfer of energy – either via work (W) or heat (Q)

By definition: Energy from a system to surroundings = negative



The sign is (just) an indication of the direction of energy transfer.

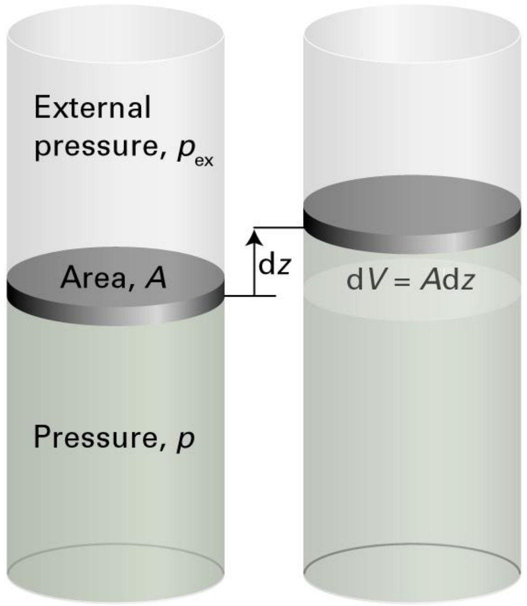
Heat

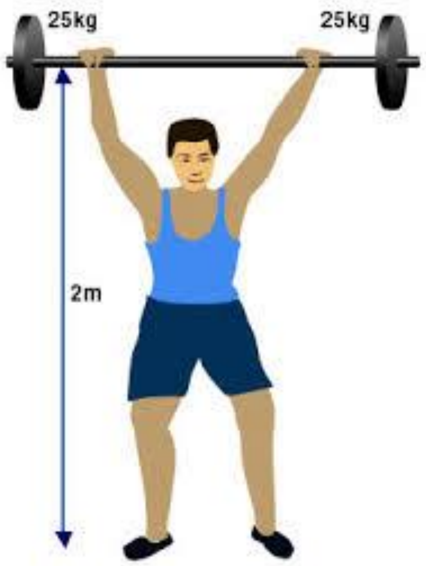
Heat is transferred to a system by a temperature difference and typically through some medium, such as the system walls

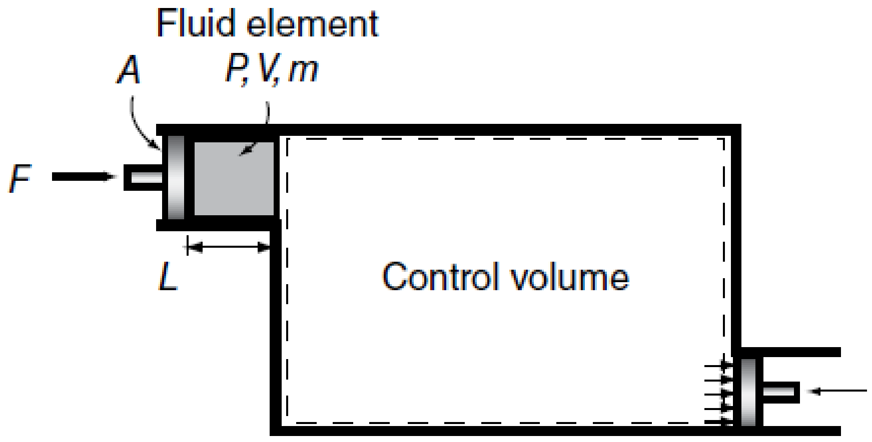
- The heat can change the conditions in the system and/or the internal energy depending on the system
- *Q* is the heat in Joules and the heat transfer rate is

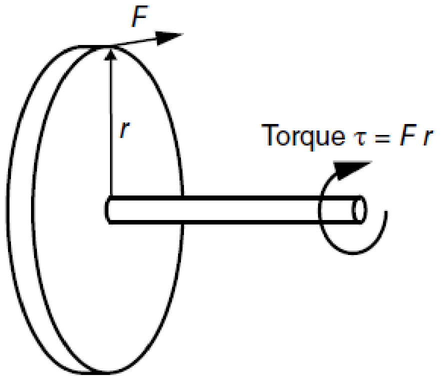
$$\dot{Q} = \frac{\delta Q}{dt}$$

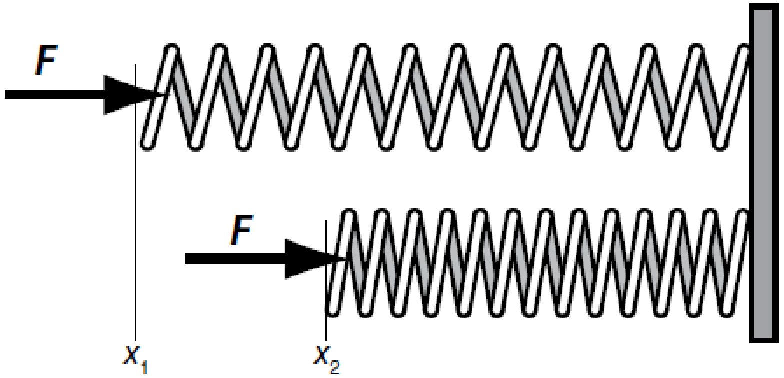
Types of work

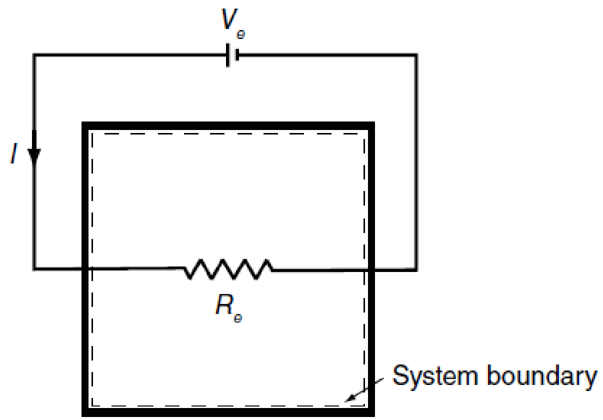












Calculating work interactions

Open or closed systems can have a work interaction with the environment in the following ways

- Boundary work from a changing volume $W_{vol} = \int_{V_1}^{V_2} PdV$ (Eq. 4.21)

- Flow work $W_{flow} = PV$ (Eq. 4.34)

- Shaft work $\dot{W}_{shaft} = 2\,\pi\,\omega\,\tau$ (Eq. 4.38)

in rev/s

- Spring work $W_{spring} = \int_{x_1}^{x_2} k\;xdx$ (Eq. 4.40)

- Mechanical work $W_{mech} = \int_{x_1}^{x_2} F\;dx$

- Electrical work $\dot{W}_{elec} = VI$ (Eq. 4.41)

Boundary, or expansion, work

Movement of the system boundary against an outside force (external pressure P_{ex})

Volume increases $\Rightarrow$ *Expansion*

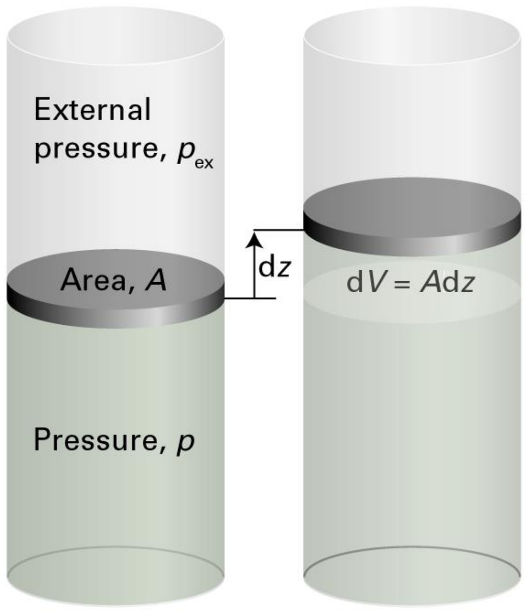
The system does work on the surroundings and the internal energy U of the system is reduced ($\Delta U < 0$ if q=0)

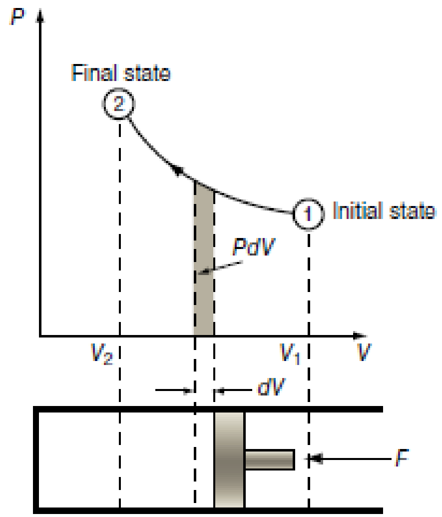
Volume decreases $\Rightarrow$ *Compression*

The surroundings does work on the system and the internal energy U of the system increases ($\Delta U > 0$ if q=0)

The system is often assumed in mechanical equilibrium with the surroundings, making the process reversible (P_{ex} = pressure P in system at all points during the process)

Be sure the process is assumed reversible before using $P = P_{ex}$





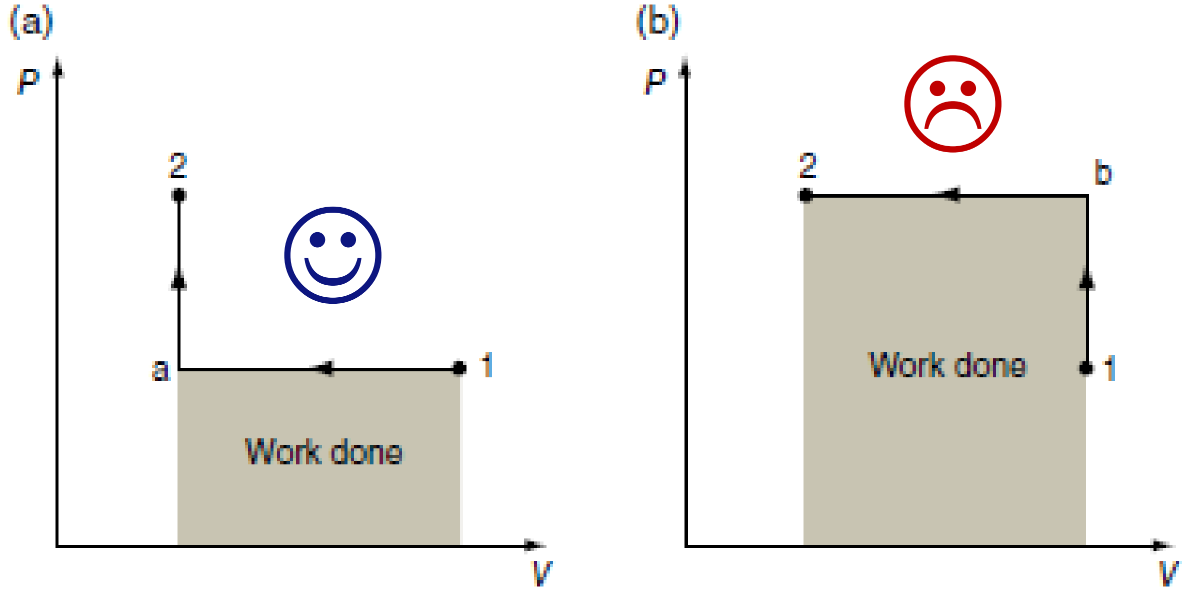
Boundary work: Path

$$\boxed{W_{boundary} = -\int_{V_1}^{V_2} P_{ex}\,dV}$$

General expression of boundary work

Here we see the consequence of **work** being a **path function** (= dependent on the path from state 1 to state 2).

What is the “lesson-learned” in an industrial perspective?

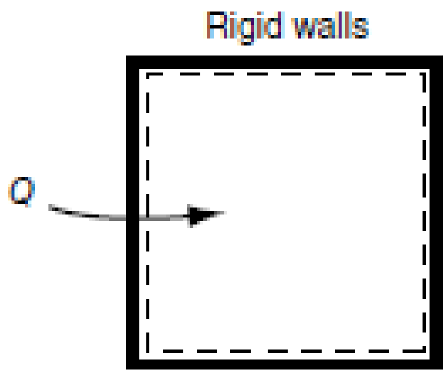


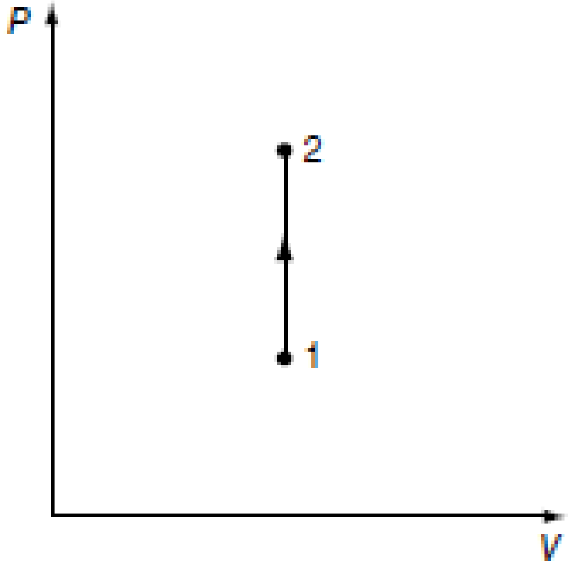
Boundary work: Isochoric

At **constant volume (isochoric)** work is calculated as:

$$\boxed{W = -\int_{V_1}^{V_2} P_{ex}\,dV = -P_{ex} \cdot 0 = 0}$$

Therefore – No boundary work done for a system where volume remains constant!

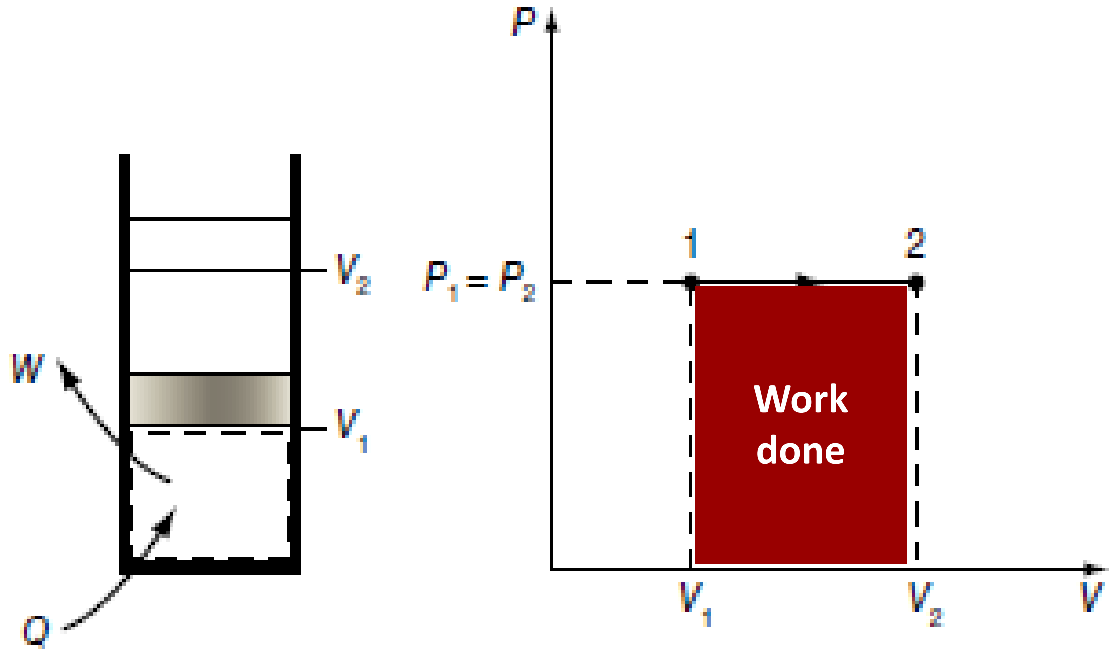




Boundary work: Isobaric

At **constant (external) pressure (isobaric)** work is calculated as:

$$W = -\int_{V_1}^{V_2} P dV = -P_1 \int_{V_1}^{V_2} dV = P_{1(}V_1 - V_{2)} = P_1 \Delta V$$



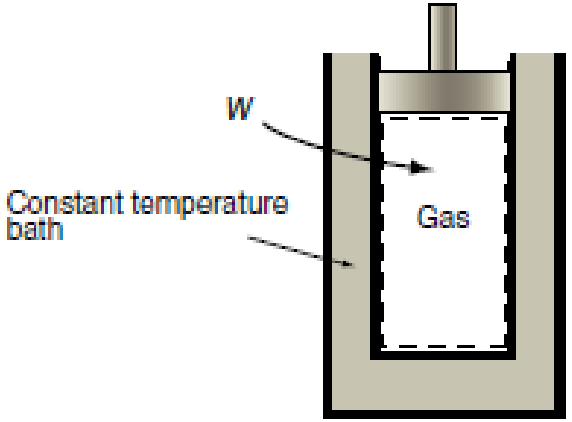
The system is in mechanical equilibrium with the surroundings so P_{ex} = P

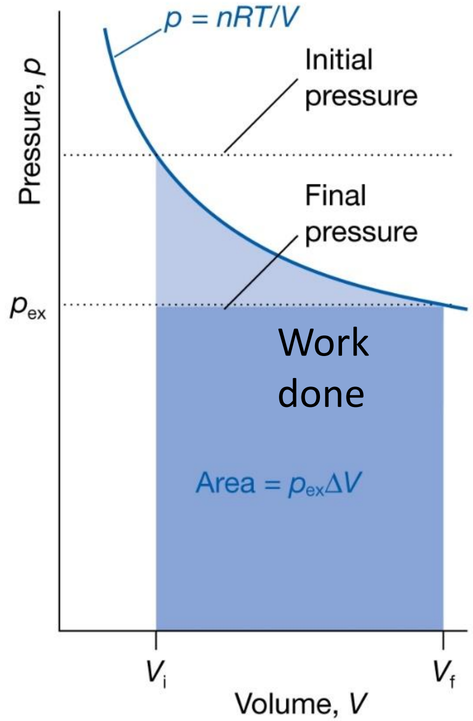
Boundary work, isothermal (reversible)

At **constant temperature (isothermal)** for ideal gas work is found as:

$$\boxed{W = -\int_{V_1}^{V_2} PdV = -\int_{V_1}^{V_2} \left(\frac{mRT}{V}\right) dV = (mRT)\ln\left(\frac{V_1}{V_2}\right)\left(= (nR_uT)\ln\left(\frac{V_1}{V_2}\right)\right)}$$

If ideal gas then: $P = mR_uT/V$





The 1st Law of Thermodynamics

***The change in energy of a closed system equals the net energy transferred to it in the form of work and heat*. Stated mathematically,**

$$\boldsymbol{Q} + \boldsymbol{W} = \Delta \boldsymbol{E}$$

$$\boldsymbol{\Delta E} = \boldsymbol{\Delta PE} + \boldsymbol{\Delta KE} + \boldsymbol{\Delta U}$$

- This is one of the most important concepts of this course. It simply states that energy cannot be created or destroyed. Therefore we will do an energy balance in almost all exercises

- This also shows that work and heat can be converted to internal energy in a material

Systems with multiple heat and work inputs

For systems with multiple work and heat inputs, we can simply add up each energy interaction, keeping in mind the sign of each input

$$\boldsymbol{Q_{net} = \sum Q_i}$$

$$\boldsymbol{W_{net} = \sum W_i}$$

Methodology for solving thermodynamics problems

1. Carefully review the problem statement and what is known.

2. Choose the system.

3. Apply a mass balance on the chosen system (for a closed system the mass is always balanced).

4. Apply an energy balance on the chosen system

Example energy conversion

An egg is thrown downward from a window 20 m high at a velocity of 20 m/s. What is the change in specific internal energy when it hits the ground (height of 0 m)?

$$\boldsymbol{Q} + \boldsymbol{W} = \Delta \boldsymbol{E}$$

Assume

- air resistance is negligible
- The egg doesn't bounce and all kinetic energy is converted

$$\mathit{\Delta} E = \mathit{\Delta} PE + \mathit{\Delta} KE + \mathit{\Delta} U = 0$$

Divide by mass and substitute energy equations

$$g\,\Delta z + \frac{1}{2}\Delta v^2 + \mathit{\Delta} u = 0$$

Example energy conversion contd

$$\Delta E = \Delta PE + \Delta KE + \Delta U = 0$$

Divide by mass and substitute energy equations

$$g\,z + \frac{1}{2}\Delta v^2 + \Delta u = 0$$

Plug in the given values and solve for Δu

$$9.8\,\frac{m}{s^2}(0 - 20\,m) + \frac{1}{2}\left[0 - \left(20\frac{m}{s}\right)^2\right] + \Delta u = 0$$

$$\Delta u = 396\,\frac{\mathrm{J}}{\mathrm{kg}}$$

Different energy types

Kinetic and potential energy can be converted back and forth, and they can both be converted directly to heat, but it doesn't go back the other was as effectively.

- *Heat has a lower thermodynamic value than other types of energy*

- *Electricity, kinetic energy, potential energy, and mechanical energy (such as a shaft providing a torque) are all pure work, but heat is lower grade.*

- Heat can be converted to kinetic energy - https://www.youtube.com/watch?v=9EA3wa7w5CQ

- It can also be converted into mechanical work or electricity

- However, the efficiency is less than 100%

Specific Heats – Constant volume

What if we have a material in rigid contain (= constant volume)?

Then $W = 0$ and $\delta q = du$

We define the specific heat for **constant volume** systems as the change in internal energy with changing temperature:

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

For **ideal** (mono atomic) **gasses** the **internal energy** *U* **depends only on *T*** (not *P*)

$$c_v(T) \equiv \left(\frac{\partial u}{\partial T}\right)_v \Rightarrow c_v(T) = \frac{du}{dT} \Rightarrow du = c_v(T)dT$$

Meaning we can integrate:

$$\Delta u = u_2 - u_1 = \int_{T_1}^{T_2} c_v(T)\,dT$$

Internal energy as a function of temperature: C_V

$$C_V = \left(\frac{\partial U}{\partial T}\right)_V$$

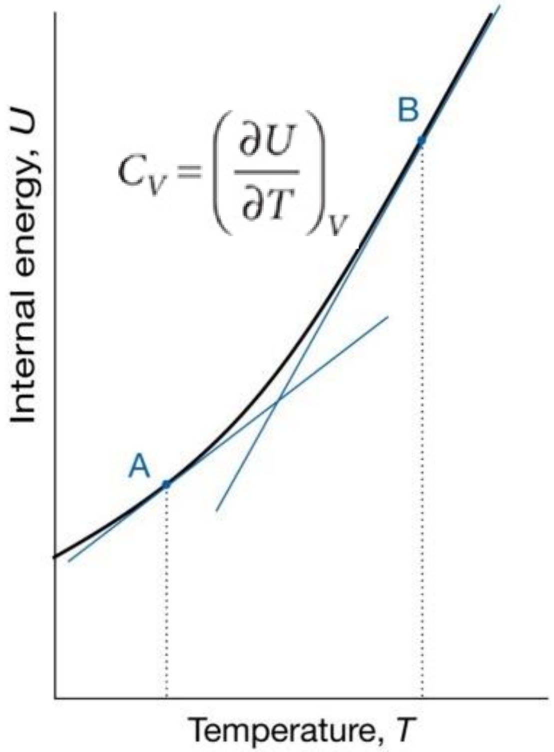
$$dU = C_V dT \quad \text{(at constant volume)}$$

C_V can often be assumed constant over small temperature ranges ΔT:

$$\Delta U = C_V \Delta T = m \cdot c_v \Delta T = q_V$$

Large (constant volume) heat capacity, C_V, = small change in temperature with heat addition.

Definition of heat capacity at constant volume



Lifting a weight with heat

We want to try converting internal energy to potential energy. To do this, we will heat up air (which we assume acts as an ideal gas) to lift a heavy piston. The piston is 100 mm in diameter and has a mass of 10 kg with an initial height of 100 mm. The atmosphere in the room has a pressure of 101.3 kPa. The initial temperature of the air is 20 C.

1) Find the pressure and mass of air inside the cylinder

2) Calculate how much the potential energy of the piston increases when 0.5 kJ of energy is added to the air in the cylinder

Assume

- air is an ideal gas
- Cylinder does not lose heat to the surroudings
- There is no friction around the piston

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

And remember that the air in the cylinder has to follow the ideal gas law

$$P\,V = m\,R\,T$$

Lifting a weight with heat 1)

- Let's draw the system

- The absolute pressure inside the cylinder must counteract the atmospheric pressure and the force of the piston mass

$$P_{cyl} = \frac{F_{pist}}{A_{pist}} + P_{atm} = \frac{10\ kg\ 9.8\frac{m}{s^2}}{\frac{\pi}{4}(0.1\ m)^2} + 101.3\ kPa\ \frac{1000\ Pa}{1\ kPa}$$

$$= 113787\ \mathrm{Pa}$$

$$m_{air} = \frac{P_1 V_1}{R\ T} = \frac{113787\ Pa\frac{\pi}{4}(0.1\ m)^2\ 0.1\ m}{0.287\frac{kJ}{kg-K}\ \frac{1000\ J}{1\ kJ}(20+273.15)K}$$

$$= 0.00106\ kg$$

Lifting a weight with heat 2)

Now let's look at the energy side. First define the system

Since there is no friction on the piston and the piston weight and atmospheric pressure are constant, the pressure in the cylinder will also be constant so $P_1 = P_2$

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

Plugging in values

$Q_{in} + P_1(V_1 - V_2) = m_{pist}\, g \left(\frac{T_2}{T_1} h_1 - h_1\right) + m_{air}\, c_v\, (T_2 - T_1)$ since the pressure is constant, $V_2 = \frac{T_2}{T_1} V_1$

Then $Q_{in} + P_1\left(V_1 - \frac{T_2}{T_1} V_1\right) = m_{pist}\, g \left(\frac{T_2}{T_1} h_1 - h_1\right) + m_{air}\, c_v\, (T_2 - T_1)$

Lifting a weight with heat 2) contd

Now we can solve for T_2

$$T_2 = \frac{Q_{in} + P_1 V_1 + m_{air}\, c_v\, T_1}{m_{pist}\, g \frac{h_1}{T_1} + m_{air}\, c_v + P_1 \frac{V_1}{T_1}}$$

$$= \frac{0.5\ kJ + 10\ kg\ 9.8 \frac{m}{s^2} 0.1\ m \frac{1\ kJ}{1000\ J} + 113787\ Pa\ * 7.854\ e^{-4}\ m^3 \frac{1\ kJ}{1000\ J} + 0.00106\ kg\ 0.742 \frac{kJ}{kg-K} 293.15\ K}{10\ kg\ 9.8 \frac{m}{s^2} \frac{0.1\ m}{293.15\ K} \frac{1\ kJ}{1000\ J} + 0.00106\ kg\ 0.742 \frac{kJ}{kg-K} + 113787\ Pa \frac{7.854\ e^{-4}\ m^3}{293.15\ K} \frac{1\ kJ}{1000\ J}} = 737.7\ K$$

And finally find the change in potential energy

$$\Delta\mathrm{PE} = m_{pist}\, g \left(\frac{T_2}{T_1} h_1 - h_1\right) = 10\ kg\ 9.8 \frac{m}{s^2} \left(\frac{737.7\ K}{293.2\ K} 0.1 m\ - 0.1\ m\right) = 14.9\ J = 0.0149\ kJ$$

Let's do the problem also in EES

What I want you to learn from the previous example

- Converting heat to work is less efficient that work to heat
  – Much of the heat goes to increasing the air's internal energy rather than raising the mass
  – But heat can still be useful for such applications

- The conversion process will depend on the conditions but also the properties of the materials that are being used

- Choosing the system can have a significant effect on how you solve the problem

- Be careful with units. Pressure in kPa will give energy in kJ and pressure in bar will give energy in $1e^2$ kJ. Kinetic energy and potential energy will be in J if you use kg, m, and m/s

Exercises part 1

- 4.4
- 4.5
- 4.7
- 4.8
- 4.10

Exercises part 1 with answers

- 4.4 15.7 kW
- 4.5 160 J
- 4.7 981 J
- 4.8 T = 450 K, V = 0.075 m^3
- 4.10 184.9 kJ