Lecture 6 – 1st law for closed systems

Purdue ME 200, Thermodynamics I

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Outline

1st law for closed systems

Internal energy

Heat transfer

Examples

1st law for mechanical systems

- two lectures ago, we saw that for mechanical systems,

$$\Delta \mathrm{KE} + \Delta \mathrm{PE} = -W$$

- KE is system's kinetic energy
- PE is system's gravitational potential energy
- W is work done by system on surroundings
  ($W < 0$ if surroundings do work on system)

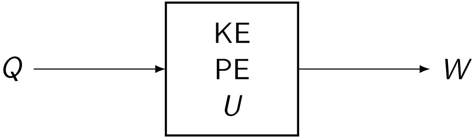
⋆ for any property x, Δx always means $x_{\mathrm{final}} - x_{\mathrm{initial}}$

1st law for general, closed systems

- for general, closed systems, the 1st law is

$$\Delta \mathrm{KE} + \Delta \mathrm{PE} + \Delta U = Q - W$$

- U is system's **internal energy**, an extensive property
- Q is energy transferred to system via **heat transfer**



Sign conventions for work and heat transfer

- $W > 0$ if system does work on surroundings
- $W < 0$ if surroundings do work on system
- $W = 0$ if no work is done
- $Q > 0$ if heat transfers from surroundings to system
- $Q < 0$ if heat transfers from system to surroundings
- $Q = 0$ if no heat transfers (process is **adiabatic**)

Differential statement of 1st law for closed systems

- 1st law for closed systems can be written as

$$\Delta E = Q - W$$

- $E = \mathrm{KE} + \mathrm{PE} + U$ is **total energy**, an extensive property (any function only of properties defines another property)
- differential statement of 1st law for closed systems is

$$\mathrm{d}E = \delta Q - \delta W$$

- E is a property, so has an exact differential (d)
- Q and W are not properties, so have inexact differentials (δ)

Rate statement of 1st law for closed systems

- suppose work and heat transfer happen over finite duration Δt
- divide 1st law by Δt:

$$\frac{\Delta E}{\Delta t} = \frac{Q}{\Delta t} - \frac{W}{\Delta t}$$

- for small Δt, we get

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \dot{Q} - \dot{W}$$

- $\dot{Q}$ is rate of heat transfer into system
- $\dot{W}$ is power (rate of work) exerted by system on surroundings
- in **steady state**, $\mathrm{d}E/\mathrm{d}t = 0$, so $\dot{Q} = \dot{W}$

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What is internal energy?

- KE and PE associated with microscopic motion and forces
- what microscopic stuff? molecules, atoms and particles
- what motion? translation, rotation and vibration
- what forces?
    - ◇ electromagnetic: molecule $\leftrightarrow$ molecule, electron $\leftrightarrow$ nucleus
    - ◇ strong nuclear: (proton or neutron) $\leftrightarrow$ (proton or neutron)
    - ◇ weak nuclear: subatomic particle $\leftrightarrow$ subatomic particle

An energy taxonomy

U includes all energy other than system's

- macroscopic KE associated with center-of-mass motion
- gravitational PE associated with center-of-mass elevation

	macroscopic	microscopic
due to motion	KE	U
due to force	PE	U

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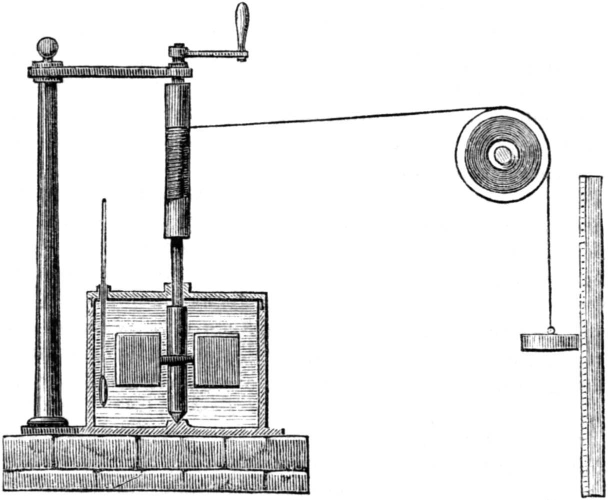
What is heat?

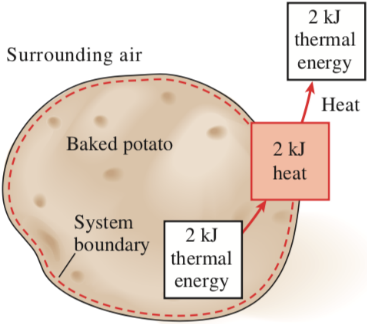
- everyone used to think heat was a substance, called ‘caloric’
- they thought that
  - caloric flowed from hot bodies to cold ones
  - like mass and energy, caloric could not be created or destroyed
- in the 1840s, James Joule proved this ‘caloric theory’ wrong
- his most famous experiment:
  - a falling block drives a paddle wheel
  - the paddle wheel stirs water in an insulated barrel
  - no ‘caloric’ is transferred, but the water temperature rises



Harper's New Monthly Magazine No. 231, August, 1869.

What is heat? (continued)

- we now know that heat is not a substance or a property (differential heat transfer is inexact: δQ, not ‘d’)
- in thermo, we only work with **heat transfer**: energy transfer
  - ◇ due to anything other than work or mass transfer
  - ◇ (alternatively) due only to temperature differences



Cengel and Boles, *Thermodynamics: An Engineering Approach* (2019)

Modes of heat transfer

- conduction
  - ⋄ nearby particles jostling each other
  - ⋄ $\dot{Q}$ is proportional to $T_h - T_c$
- radiation
  - ⋄ exchange of photons
  - ⋄ $\dot{Q}$ is proportional to $T_h^4 - T_c^4$
- convection
  - ⋄ conduction and radiation between a solid and an adjacent fluid
  - ⋄ $\dot{Q}$ is proportional to $T_h - T_c$

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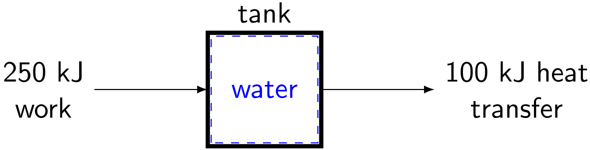
Example 1

A tank contains water, initially with 700 kJ of internal energy. A paddlewheel does 250 kJ of work stirring the water. Heat transfer through the tank walls transfers 100 kJ to the surroundings. What is the final internal energy of the water?

Example 1 solution

- **assumptions:** closed, stationary system
- **basic equation:** $\Delta\text{KE} + \Delta\text{PE} + \Delta U = Q - W$
- **system diagram:**



- **solution:**

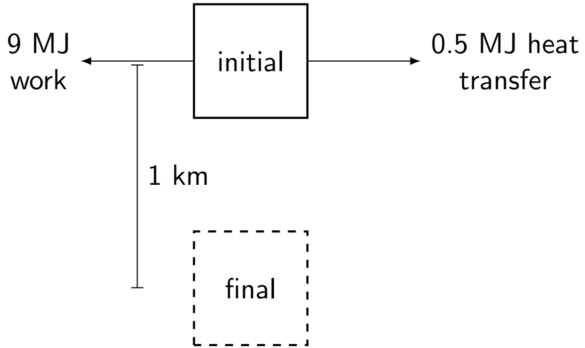
$$\begin{aligned}\cancel{\Delta\text{KE}} + \cancel{\Delta\text{PE}} + \Delta U &= Q - W \\ U_2 &= U_1 + Q - W \\ &= 700\text{kJ} + (-100\text{kJ}) - (-250\text{kJ}) \\ &= 850\text{kJ}\end{aligned}$$

Example 2

A meteor of mass 7,000 kg falls 1 km, accelerates from 100 m/s to 150 m/s, does 9 MJ of work on the surroundings, and transfers 500 kJ to the surroundings via heat transfer. How much does its specific internal energy change?

Example 2 solution

- **assumptions:**
    - ◇ closed system
    - ◇ constant acceleration of gravity, $g = 9.81$ m/s^2
- **basic equation:** $\Delta\text{KE} + \Delta\text{PE} + \Delta U = Q - W$
- **system diagram:**



Example 2 solution (continued)

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\begin{aligned}
\Delta \mathrm{KE} &= \frac{1}{2} m \Delta(\dot{r}^2) \\
&= \frac{1}{2}(7000\mathrm{kg})[(150\mathrm{m/s})^2 - (100\mathrm{m/s})^2] \\
&= 43.8\mathrm{MJ} \\
\Delta \mathrm{PE} &= mg\Delta z \\
&= (7000\mathrm{kg})(9.81\mathrm{m/s}^2)(-1\mathrm{km}) \\
&= -68.7\mathrm{MJ} \\
\Delta U &= Q - W - \Delta \mathrm{KE} - \Delta \mathrm{PE} \\
&= -0.5\mathrm{MJ} - 9\mathrm{MJ} - 43.8\mathrm{MJ} - (-68.7\mathrm{MJ}) \\
&= 15.4\mathrm{MJ} \\
\Delta u &= \frac{\Delta U}{m} = \frac{15400\mathrm{kJ}}{7000\mathrm{kg}} = 2.2\mathrm{kJ/kg}
\end{aligned}
$$