KU LEUVEN

B-KUL-Z55337
Applied Thermodynamics

Sylvain Quoilin

Adapted from: Y.A. Cengel, M. A. Boles, Thermodynamics – An Engineering Approach (5th Edition)

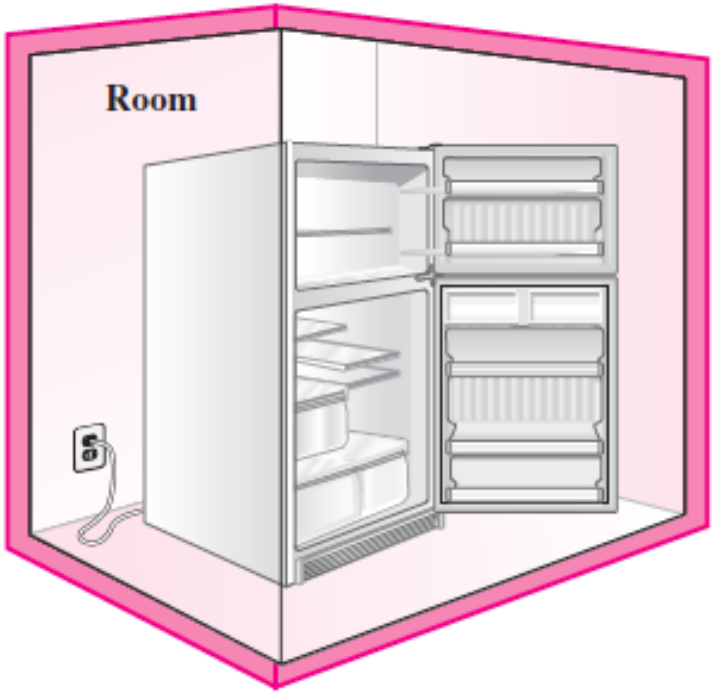
Chapter 2

Energy, energy transfer, and general energy analysis

KU LEUVEN

Energy

- 1st law: Energy cannot be created or destroyed, it can only be converted



How does the temperature of the room vary is the door of the fridge is left open?

KU LEUVEN

Energy

- Energy can take different forms: thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, nuclear
- Their sum is the Total Energy E (J) of the system
- The specific total energy is e = E/m (J/kg)
- The total energy depends on a reference point (for which E=0)

=> What we consider is the variation of energy. Thermodynamics does not have an absolute value of the total energy

KU LEUVEN

Energy

- Microscopic forms of energy:
  - Kinetic energy of the molecules (translational, rotational, …) = **sensible energy** (function of temperature)
  - Binding force between the molecules = **latent energy**
  - Atomic bonds in a molecule = **chemical energy**
  - Strong bonds within the nucleus of the atoms = **nuclear energy**
- **Internal energy** U of a system = sum of the microscopic forms of energy

$$e = u + \frac{V^2}{2} + gz$$

KU LEUVEN

Energy

- Macroscopic forms of energy
  - Kinetic energy
  - Potential energy
- Mechanical energy can be defined as the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.
- Mechanical energy of a flow is given by::

$$e_{mec} = P.v + \frac{V^2}{2} + gz$$

- The mechanical power of the flow is given by:

$$\dot{E}_{mec} = \dot{m}\,.\,e_{mec} = \dot{m}\,.\left(P.v + \frac{V^2}{2} + gz\right)$$

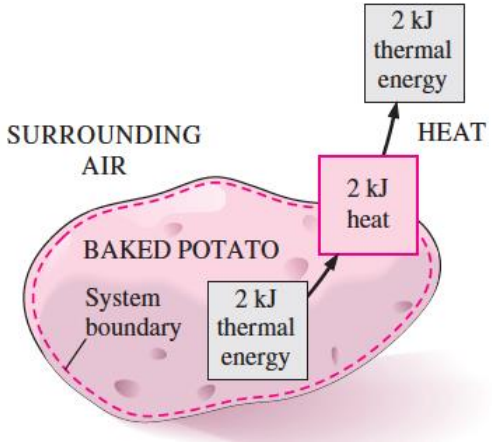
KU LEUVEN

Energy transfer by heat

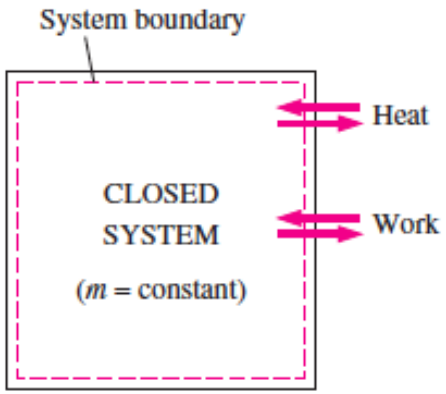
Energy can cross the boundary of a closed system in two distinct forms:

heat and work

- Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.
- A system does not have a « heat content » but its boundaries can be crossed by a heat flow



Internal energy is turned into heat when it crosses the boundary

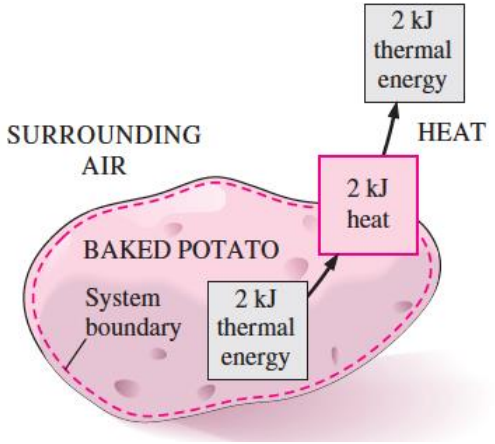


KU LEUVEN

Energy transfer by heat

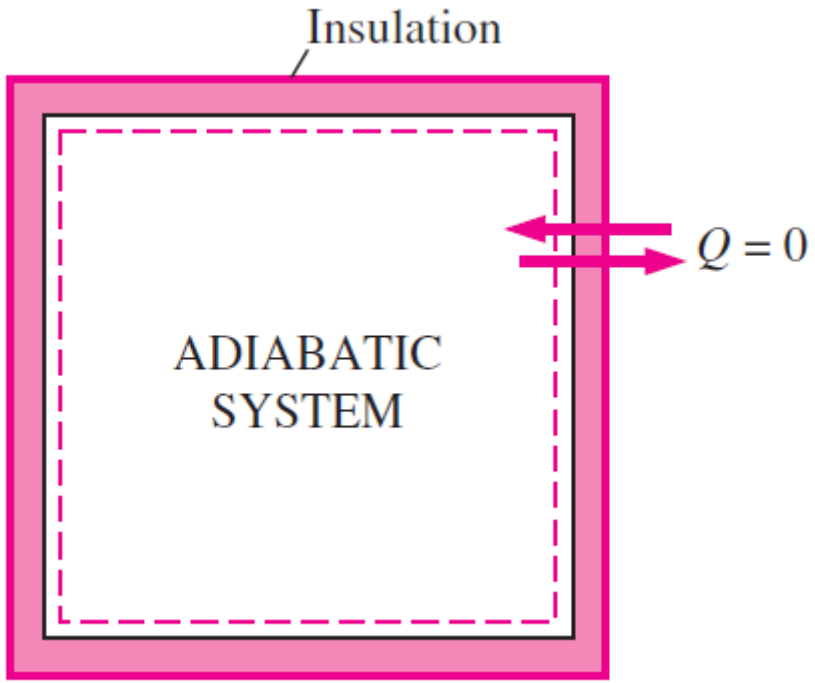
- Heat transfer modes: conduction, convection, radiation.
- If Q is the amount of heat exchanged between the system and its surrounding (J)
- The **rate of heat transfer (or heat flow)** is the amount of heat by unit of time (J/s) or (W)

$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt$$



Energy transfer by heat

- A process during which there is no heat transfer is called an **adiabatic process**



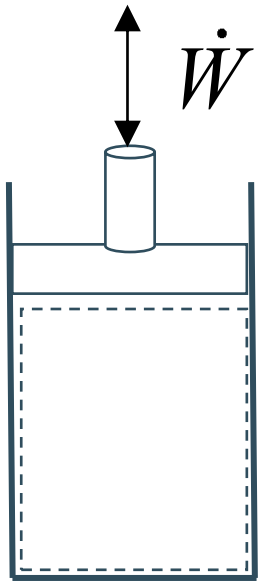
- Examples?

Energy transfer by work

Energy can cross the boundary of a closed system in two distinct forms:

heat and work

- Work W is the energy transfer associated with a force acting through a distance
- There is often an exchange of work with a system for when there is a displacement of its boundary
- Power is defined as the work per unit of time



KU LEUVEN

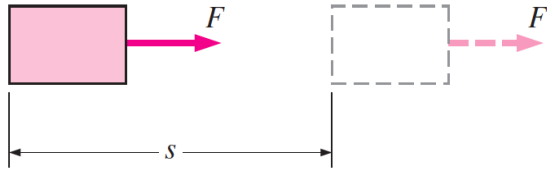
Heat and work

- Heat and work are energy transfer mechanisms between a system and its surroundings, and there are many similarities between them:
  - Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are boundary phenomena.
  - Systems possess energy, but not heat or work.
  - Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.

Mechanical forms of work

- **The mechanical work** *W* by a force *F* on a body displaced by a distance *s* is given by:

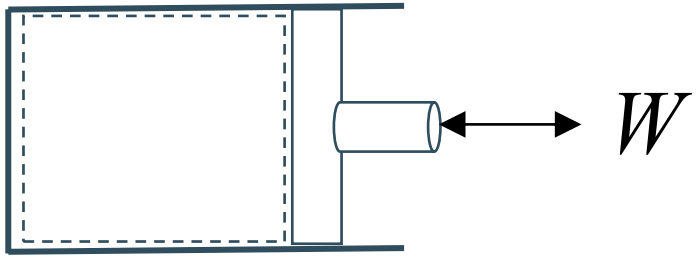
$$W = Fs \text{ (kJ)}$$



- If the force is not constant:

$$W = \int_1^2 F\, ds \text{ (kJ)}$$

- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a force acting on the boundary,
  - the boundary must move.

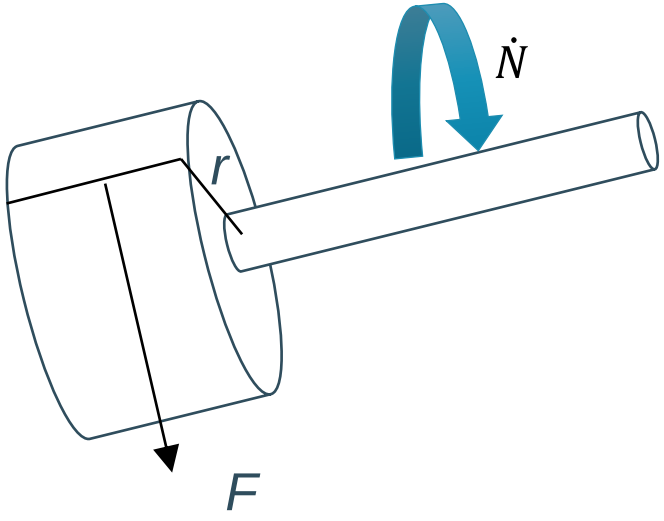


Example of the expansion of gas within a cylinder-piston in a vacuum surroundings: There is no force (no pressure outside => no work!

KU LEUVEN

Mechanical forms of work

- **Shaft work** W_{sh} is very common in engineering practice.
  - The force (spinning the shaft) is the torque divided by the moment arm:
    $$F = \frac{T}{r}$$
  - The displacement after N rotations is: $s = 2\pi RN$
  - The shaft work is therefore given by: $W_{sh} = 2\pi NT$
  - The shaft power is: $\dot{W}_{sh} = 2\pi\, \dot{N}T$



$$\dot{W}_{sh} = 2\pi\, \dot{N}T$$

Examples?

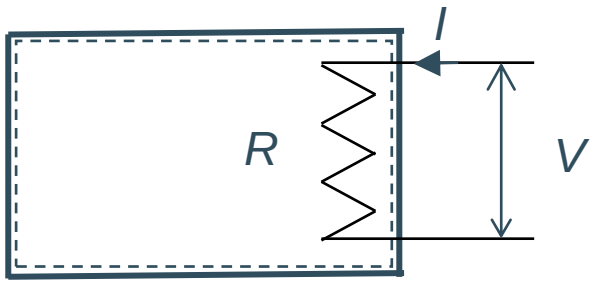
Electrical work

- The electrical current crossing a boundary does electrical work on the system.
- When N coulombs of electrical charge move through a potential difference V, the electrical work done is:

$$W = V\,N\ (\mathrm{kJ})$$

- The electrical power is then given by:

$$\dot{W}_{el} = V\,I = RI^2\ (\mathrm{W})$$



Examples?

KU LEUVEN

The first law of thermodynamics

- Goal: find the relation between the different forms of energy (Q, W, E) during a transformation

- The First Law of Thermodynamics, also known as the conservation of energy principle is expressed as:

energy can be neither created nor destroyed during a process; it can only change forms

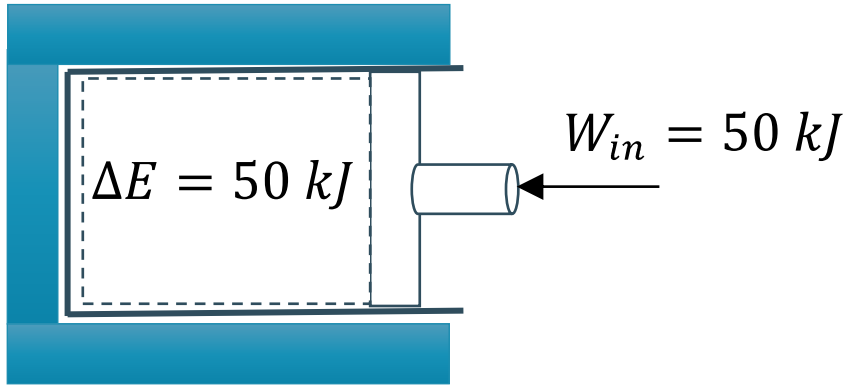
= Energy is conserved

KU LEUVEN

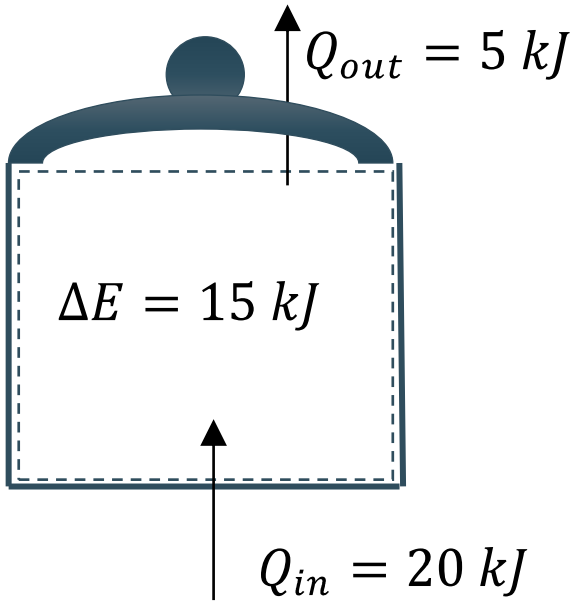
The first law of thermodynamics

A few examples:

Adiabatic cylinder-piston:



Cooking Pot



KU LEUVEN

The first law of thermodynamics

- **Energy balance**:

the conservation of energy principle can be expressed as follows:

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 that process.

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

- Energy is a property, and the value of a property does not change unless the state of the system changes.

KU LEUVEN

The first law of thermodynamics

- **Energy Change of a System**

The change in the total energy of a system during a process is the sum of the changes in its internal, kinetic, and potential energies:

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

With

$$\Delta U = m(u_2 - u_1)$$
$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$
$$\Delta PE = mg(z_2 - z_1)$$

NB:

- The values u_1 et u_2 can be obtained using thermodynamic tables.
- If the kinetic and potential energy do not vary (stationary system):

$$\Delta E = \Delta U$$

KU LEUVEN

The first law of thermodynamics

- **Mechanisms of Energy Transfer** to or from a system:

1) Heat transfer *Q*. It can be heat gain or a heat loss.
2) Work transfer *W:* Mechanical (e.g. displacement of the boundary, spiniing shaft), or electrical.
3) Mass transfer *m*. The mass going in or out of a system carries energy

The energy balance is written:

$$E_{in} - E_{out} = \underbrace{(Q_{in} - Q_{out})}_{\text{= 0 if adiabatic}} + \underbrace{(W_{in} - W_{out})}_{\text{= 0 if no work transfer}} + \underbrace{\left(E_{mass,in} - E_{mass,out}\right)}_{\text{= 0 if closed system}} = \Delta E_{system}$$

KU LEUVEN

The first law of thermodynamics

The energy balance can also be written in its temporal form. It becomes a power balance:

$$\dot{E}_{in} - \dot{E}_{out} = \underbrace{\left(\dot{Q}_{in} - \dot{Q}_{out}\right)}_{\text{= 0 if adiabatic}} + \underbrace{\left(\dot{W}_{in} - \dot{W}_{out}\right)}_{\text{= 0 if no work transfer}} + \underbrace{\left(\dot{E}_{mass,in} - \dot{E}_{mass,out}\right)}_{\text{= 0 if closed system}} = \frac{dE_{system}}{dt}$$

KU LEUVEN

Energy conversion efficiencies

- Efficiency indicates the quality of the energy conversion or transer.
- The performance (or efficiency) is defined by:

$$\textbf{Performance} = \frac{\textbf{Desired output}}{\textbf{Required input}}$$

The manufacturer indicates the the efficiency of the electrical water heater is 90% What does that mean?

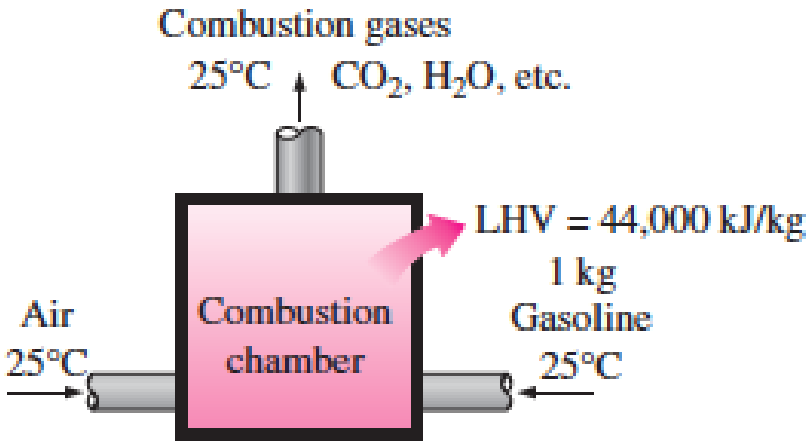
=> 90% of the electrical energy is converted into heat for sanitary hot water

KU LEUVEN

Energy conversion efficiencies

- The combustion efficiency is expressed by:

$$\eta_{combustion} = \frac{\dot{Q}}{\dot{m}_{fuel}.HV_{fuel}}$$



⇒ An efficiency of 100% indicates a complete combustion and the combustion products (the flue gases) are cooled to the room temperature.

- ✧ HV (« Heating Value ») or LHV (« Lower Heating value »): chemical energy contained in the fuel

Energy conversion efficiencies

- The mechanical efficiency can be expressed by:

$$\eta_{mech} = \frac{Mechanical\ energy\ output}{Mechanical\ energy\ input} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

- Efficiency of an electric motor:

$$\eta_{motor} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elec,in}}$$

- Efficiency of an alternator:

$$\eta_{motor} = \frac{\dot{W}_{elec,out}}{\dot{W}_{shaft,in}}$$

- Efficiency of an internal combustion engine:

$$\eta_{MCI} = \frac{\dot{W}_{shaft,out}}{\dot{m}_{fuel}.HV_{fuel}}$$

KU LEUVEN

Exercises in EES

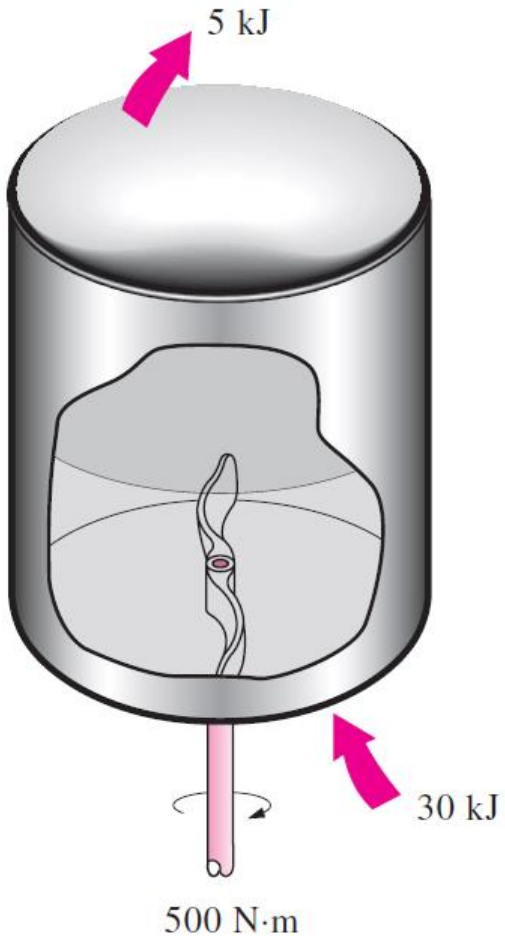
2–28E Determine the torque applied to the shaft of a car that transmits 450 hp and rotates at a rate of 3000 rpm.

NB: 1hp = 0.7457 kW

KU LEUVEN

Exercises in EES

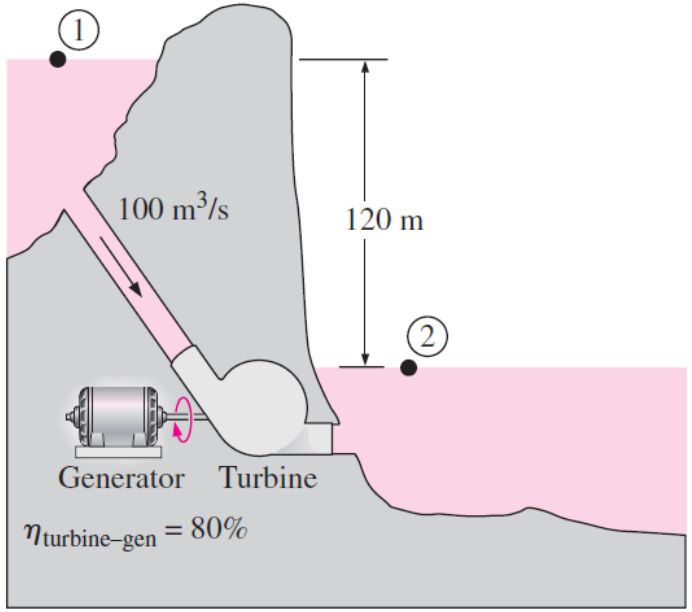
2–37 Water is being heated in a closed pan on top of a range while being stirred by a paddle wheel. During the process, 30 kJ of heat is transferred to the water, and 5 kJ of heat is lost to the surrounding air. The paddle-wheel work amounts to 500 N · m. Determine the final energy of the system if its initial energy is 10 kJ. *Answer:* 35.5 kJ



KU LEUVEN

Exercises in EES

2–123 In a hydroelectric power plant, 100 m^3/s of water flows from an elevation of 120 m to a turbine, where electric power is generated. The overall efficiency of the turbine–generator is 80 percent. Disregarding frictional losses in piping, estimate the electric power output of this plant. *Answer:* 94.2 MW



KU LEUVEN