CAE 208 Thermal-Fluids Engineering I
MMAE 320: Thermodynamics

Fall 2022

September 13, 2022

Energy, energy transfer, and energy analysis (III)

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ANNOUNCEMENTS

Announcement

- Assignment 1 is graded (solution is also provided)
- Do not forget about assignment 2 submission tonight
- Assignment 3 is posted (more time for this submission)
- No class on Thursday (Instead problem-solving videos are uploaded on Blackboard)
- And we have our first quiz today!

RECAP

Recap

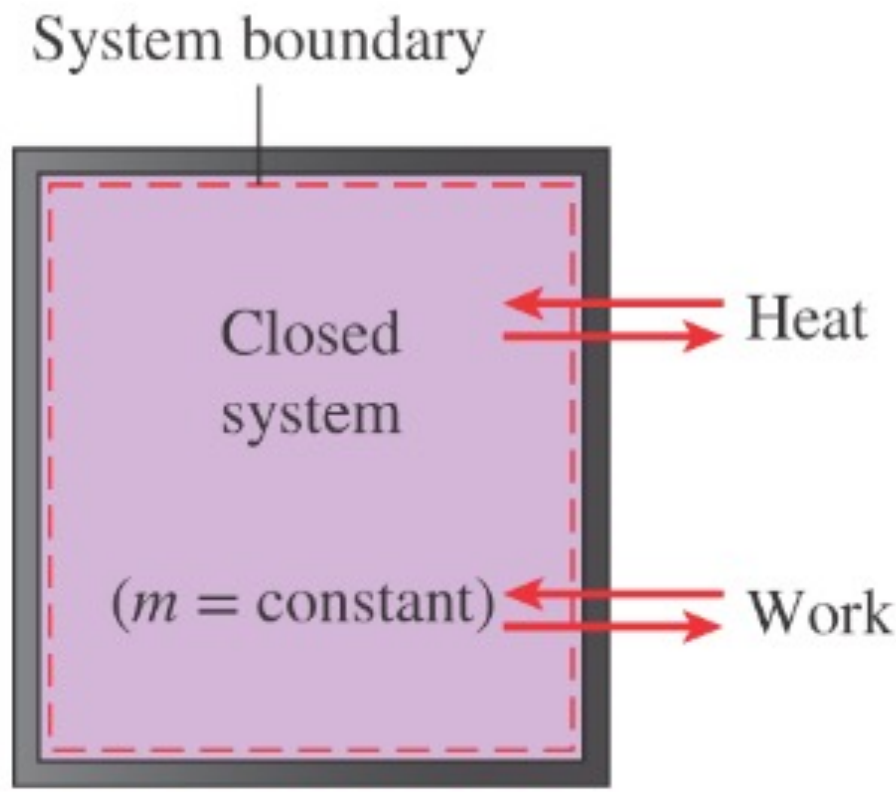
- Total energy of a system in the absence of magnetic, electric, and surface tension effects is

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \quad (kJ)$$

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (kJ/kg)$$

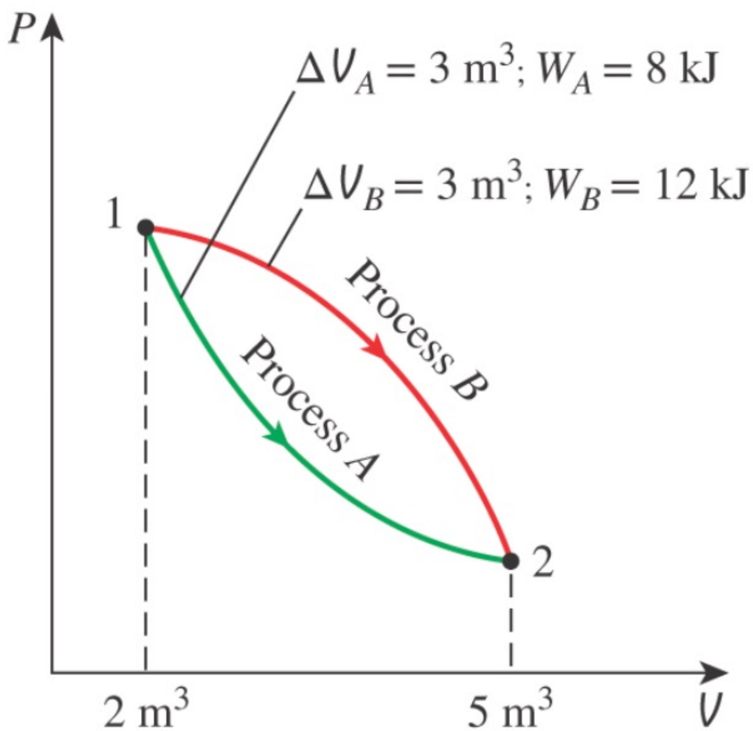
Recap

- Energy can cross the boundary of a closed system in two distinct forms:
  - ❑ Heat
  - ❑ Work



Recap

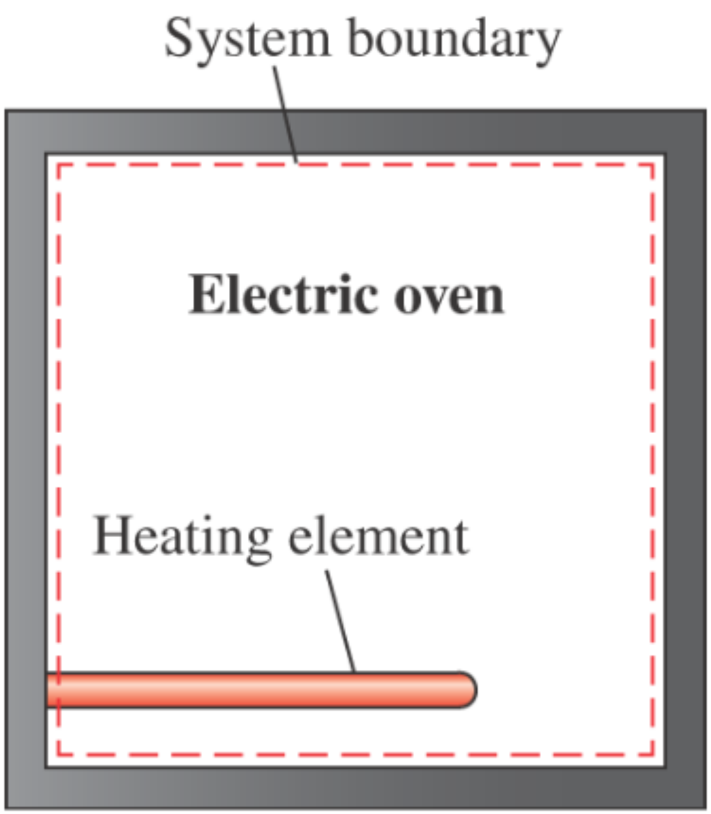
- Total work is obtained by following the process path and adding differential amounts of work (δW) done along the way
- The integral of δW is not $W_2 - W_1$ (Work is not a property!)
- Systems do not posses work at a state



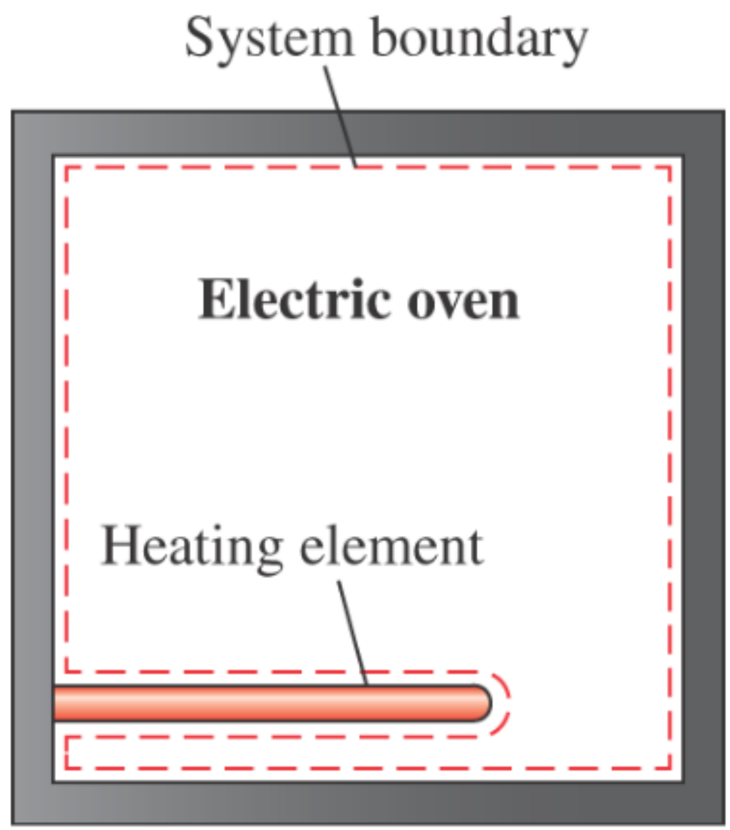
$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

$$\int_1^2 \delta W = W_{12}\ (not\ \Delta W)$$

Recap



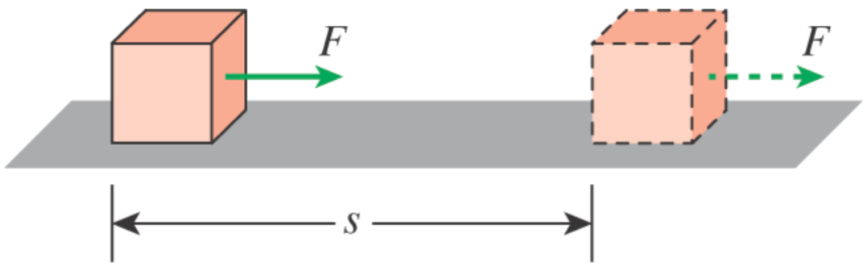
System boundary
Electric oven
Heating element



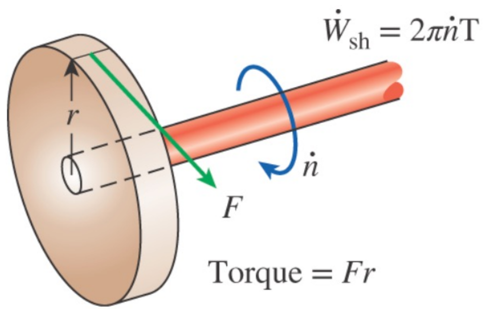
System boundary
Electric oven
Heating element

Recap

- Work

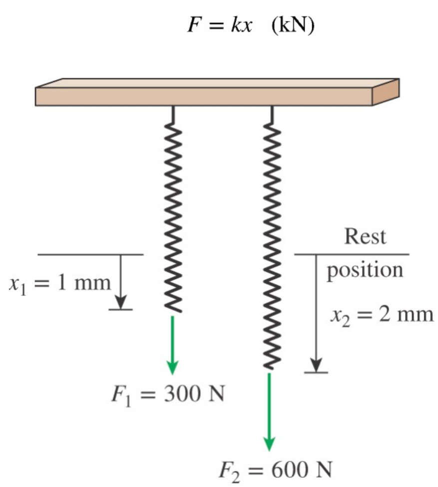


$$W = Fs \qquad (kJ)$$



$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi r)n = 2\pi nT$$

$$\dot{W}_{sh} = Fs = 2\pi\dot{n}T$$



$$W_{spring} = \frac{1}{2}k(x_2^2 - x_1^2)$$

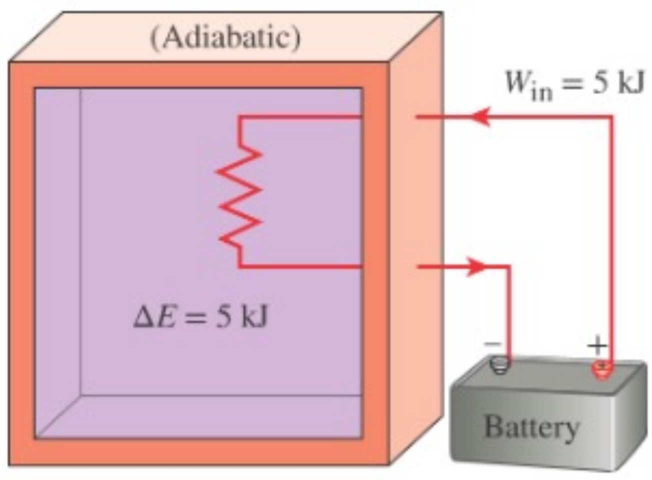
Recap

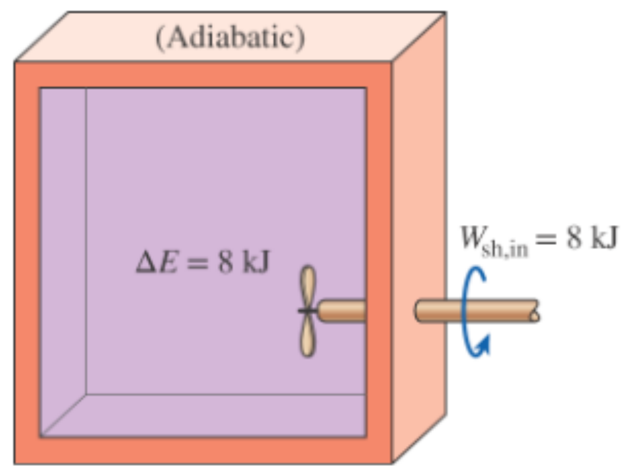
- Consider a system undergoing a series of adiabatic processes from a specified state 1 to another specified state 2.

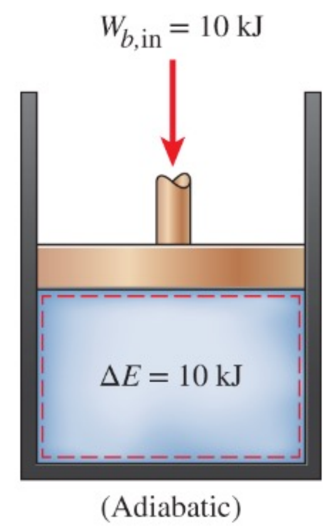
For all adiabatic processes between two specified states of a closed system the net work done is the same regardless of the nature of the closed system and the details of the process

Recap

- Example processes that involve work but no heat transfer interactions:







QUIZ

THE FIRST LAW OF THERMODYNAMICS

The First Law of Thermodynamics

- 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

The First Law of Thermodynamics

- 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

The First Law of Thermodynamics

- Energy change of a system ΔE_{system}

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

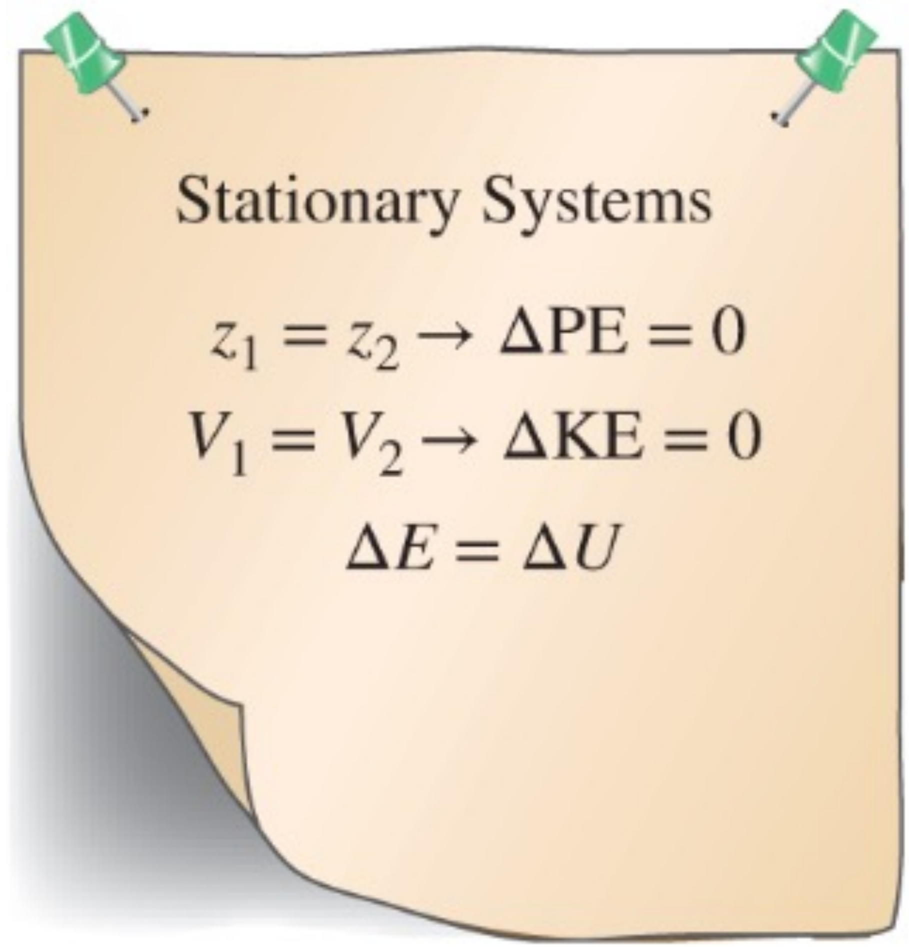
$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$

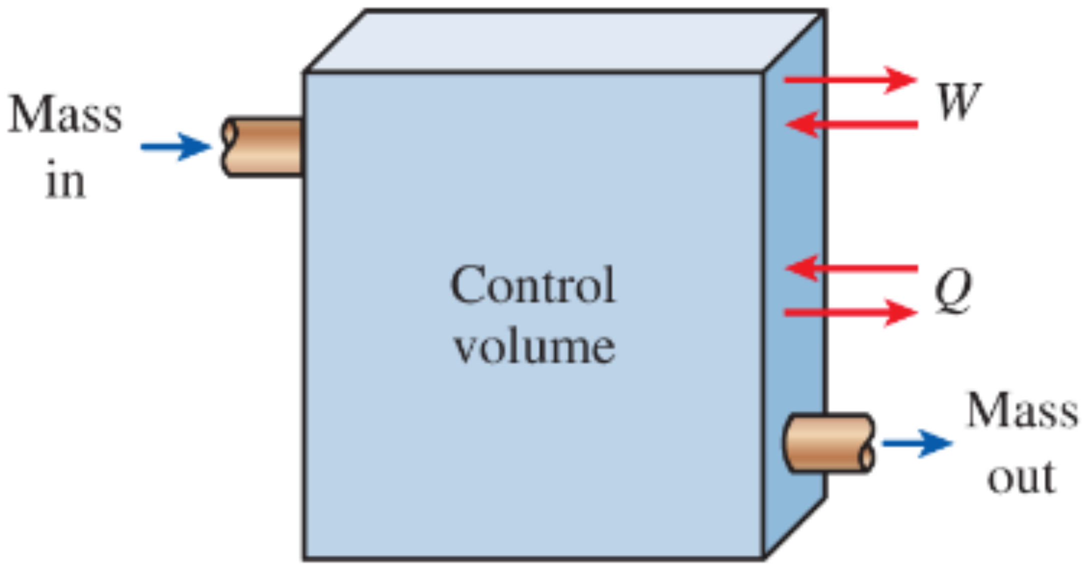
The First Law of Thermodynamics

- Most systems encountered in practice are stationary:



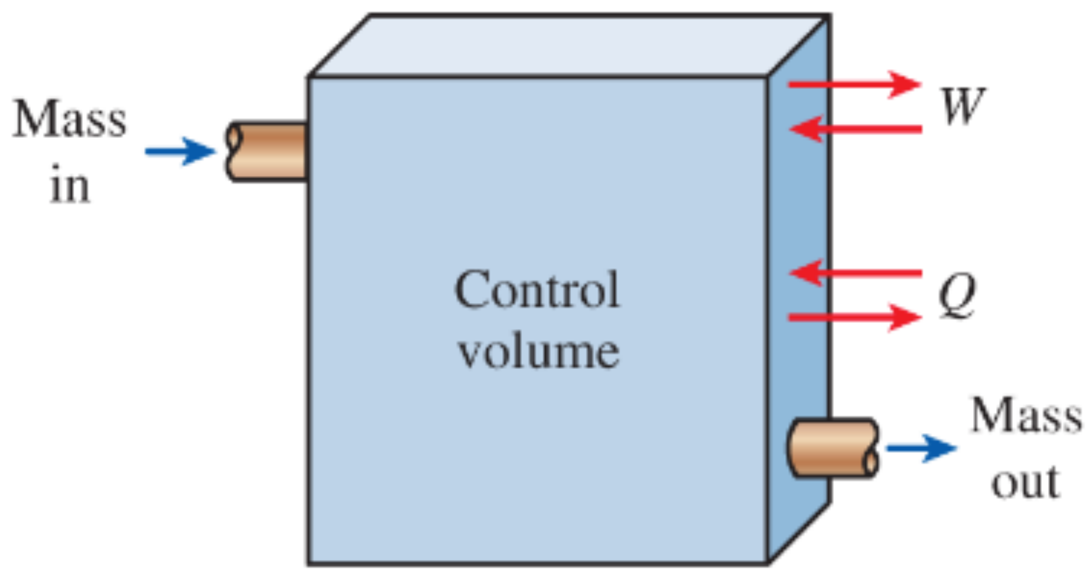
The First Law of Thermodynamics

- Mechanisms of energy transfer, E_{in} and E_{out}:
  - ❑ Energy can be transferred to or from in three forms: heat, work, and mass flow



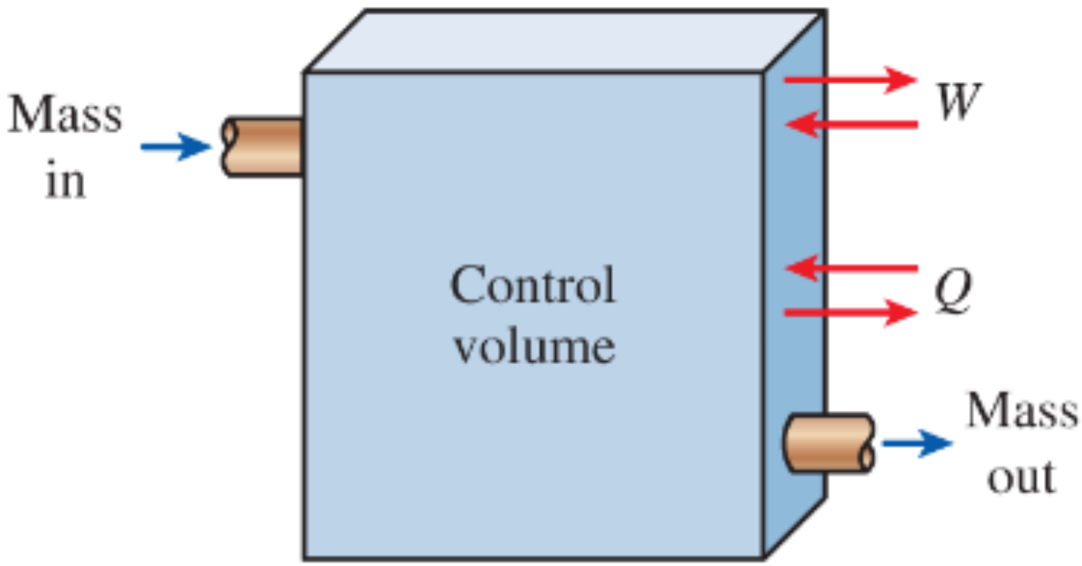
The First Law of Thermodynamics

- Mechanisms of energy transfer, E_{in} and E_{out}:
  - ❑ Each energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process



The First Law of Thermodynamics

- Mechanisms of energy transfer, E_{in} and E_{out}:
  - ❑ The only two forms of energy interactions associated with a fixed mass or closed system are heat transfer and work



The First Law of Thermodynamics

- Heat Transfer (Q):
  - Heat transfer to a system (heat gain) increases the energy of the molecules and thus the energy of the system
  - Heat transfer from a system (heat loss) decreases the energy since the energy transferred out as heat comes from the energy of the molecules of the system

The First Law of Thermodynamics

- Work (W):
  - ❑ An energy interaction that is not caused by a temperature different between a system and its surroundings (e.g., a rising piston, a rotating shaft, an electrical wire)
  - ❑ Work transfer to a system (i.e., work done on a system) increases the energy of the system
  - ❑ Work transfer from a system (i.e., work done by the system) decreases the energy of the system since the energy transferred out as work comes from the energy contained in the system
    - e.g., car engines, hydraulic, steam/gas turbines produce work
    - e.g., compressors, pumps, mixers consume work

The First Law of Thermodynamics

- Mass flow (m)
  - Mass flow in and out of the system serves as an additional mechanism of energy transfer
  - When mass enters a system, the energy of the system increases because mass carries energy with it (in fact, mass is energy)
  - When some mass leaves the system, the energy contained within the system decreases because the departing mass takes out some energy with it
  - When hot water is taken out a water heater and is replaced by the same amount of cold water, the energy content of the hot-water tank (the control volume) decreases as a result of this mass interaction

The First Law of Thermodynamics

- We can sum the heat, work, and mass, and the heat transfer:

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + \left(E_{mass,in} - E_{mass,out}\right) = \Delta E_{system}$$

Net energy transfer by heat, work, and mass

Change in internal, kinetic, potential, …, energies

The First Law of Thermodynamics

- We can sum the heat, work, and mass, and the heat transfer:

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, …, energies}}$$

Net energy transfer by heat, work, and mass

Change in internal, kinetic, potential, …, energies

The First Law of Thermodynamics

- We can sum the heat, work, and mass, and the heat transfer in the rate form:

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

Rate of net energy transfer by heat, work, and mass

Rate of change in internal, kinetic, potential, …, energies

The First Law of Thermodynamics

- The energy balance can be expressed on a per unit mass basis as

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

The First Law of Thermodynamics

- For constant rates, we can write:

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

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

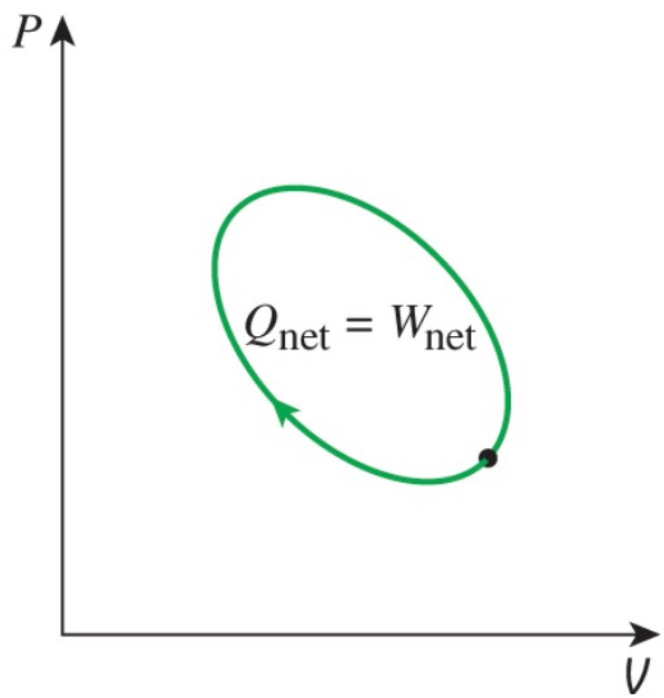
$$E = \left(\frac{dE}{dt}\right)\Delta t$$

The First Law of Thermodynamics

- For a closed system undergoing a cycle, the initial and final states are identical:

$$\Delta E = E_{in} - E_{out} = 0 \quad \rightarrow E_{in} = E_{out}$$

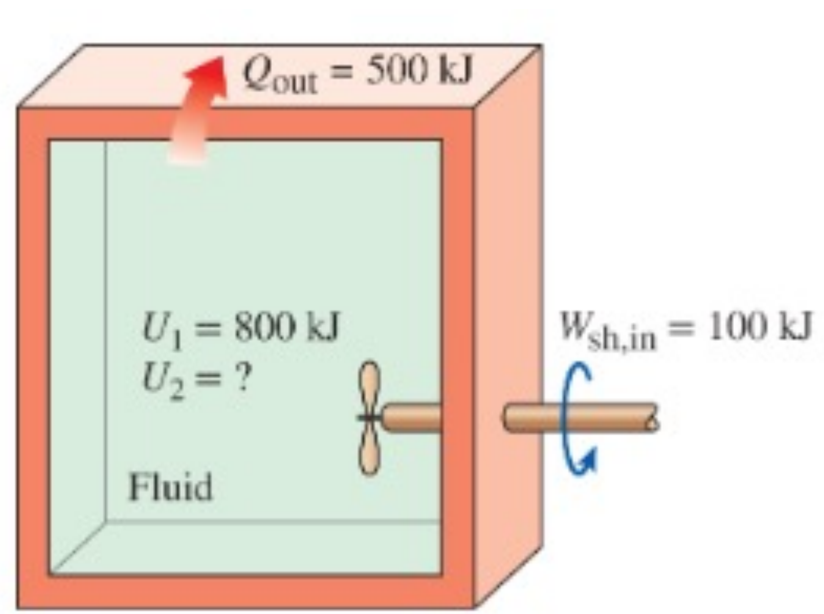
$$W_{net,out} = Q_{net,in} \quad \rightarrow \dot{W}_{net,out} = \dot{Q}_{net,in}$$



CLASS ACTIVITY

Class Activity

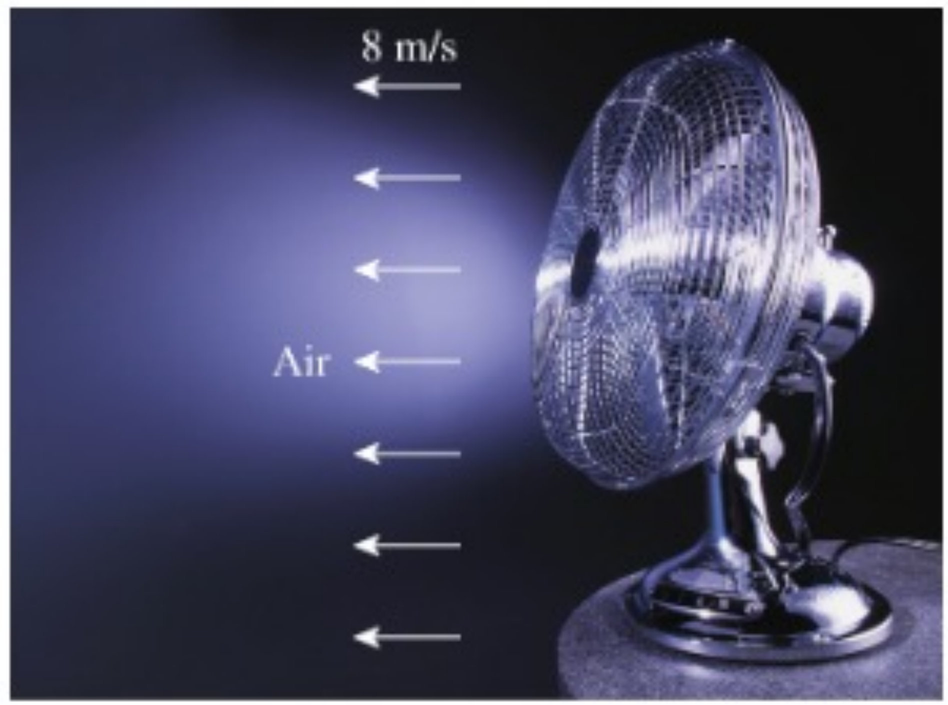
- A rigid tank contains a hot flid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel



CLASS ACTIVITY

Class Activity

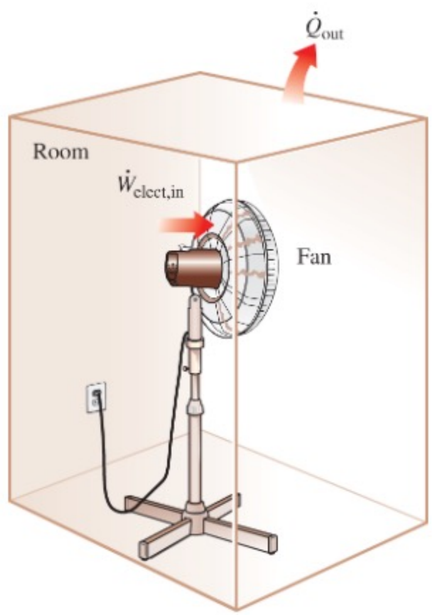
- A fan that consumes 20 W of electric power when operating is claimed to discharge air from a ventilated room at a rate of 1 kg/s at a discharge velocity of 8 m/s. Determine if this claim is reasonable



CLASS ACTIVITY

Class Activity

- A room is initially at the outdoor temperature of 25 °C. Now a large fan that consumes 200 W of electricity when running is turned on The heat transfer rate between the room and the outdoor air is given $\dot{Q} = UA(T_i - T_o)$ where U = 6 W/m2C is the overall heat transfer coefficient. A = 30 m2 is the exposed surface area of the room, Ti and To are the indoor and outdoor air temperatures, respectively. Determine the nd oor air temperature when steady operating are established



ENERGY CONVERSION EFFICIENCIES

Energy Conversion Efficiencies

- Efficiency, in general, can be expressed in terms of the desired output and the required input as:

$$Efficiency = \frac{Desired\ output}{Required\ input}$$

Energy Conversion Efficiencies

- Heating value (HV) of the fuel is equal to the amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature

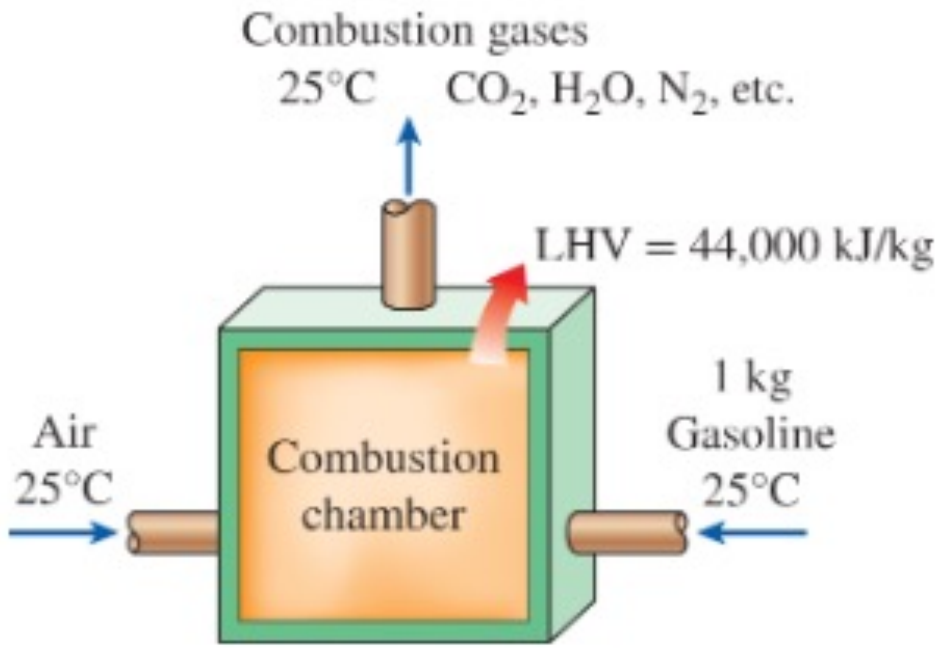
$$\eta_{comb,equip} = \frac{Q_{useful}}{HV}$$

$$= \frac{Useful\ heat\ delivered\ by\ the\ combustion\ equipment}{Heating\ value\ of\ the\ fuel\ burned}$$

$$(e.g., \eta_{heater}, \eta_{furnace}, \eta_{boiler})$$

Energy Conversion Efficiencies

- Heating value (HV)



$$C \quad + \quad O_2 \quad \rightarrow \quad CO_2$$

$$CH_4 \quad + \quad 2O_2 \quad \rightarrow \quad CO_2 \quad + \quad 2H_2O$$

Energy Conversion Efficiencies

- LHV: When water leaves as a vapor
- HHV: When water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered

Could you provide an example when this is applicable?

Energy Conversion Efficiencies

- Combustion of methane can be written as:

$$CH_4 \quad + \quad 2O_2 + 2(3.76)N_2 \rightarrow \quad CO_2 \quad + \quad 2H_2O + 7.52\ N_2$$

Energy Conversion Efficiencies

- Combustion reaction with a hydrocarbon fuel and air is written as:

$$C_xH_y \quad + \quad v_{o_2}(O_2 \; + 3.76N_2) \; \rightarrow v_{Co_2}CO_2 \quad + \quad v_{H_2O}H_2O + v_{N_2}\, N_2$$

$$C: \qquad v_{Co_2} = x$$

$$H: \qquad 2v_{H_2O} = y$$

$$N_2: \qquad 2v_{N_2} = 3.76 \times v_{O_2}$$

$$O_2: \qquad v_{O_2} = v_{CO_2} + \frac{v_{H_2O}}{2} = x + \frac{y}{4}$$

Energy Conversion Efficiencies

- Air-fuel (AF) ratio:

$$AF_{mass} = \frac{m_{air}}{m_{fuel}}$$

$$\Phi = \frac{AF_s}{AF}$$

Energy Conversion Efficiencies

- For heating systems annual fuel utilization efficiency is defined (AFUE)

Energy Conversion Efficiencies

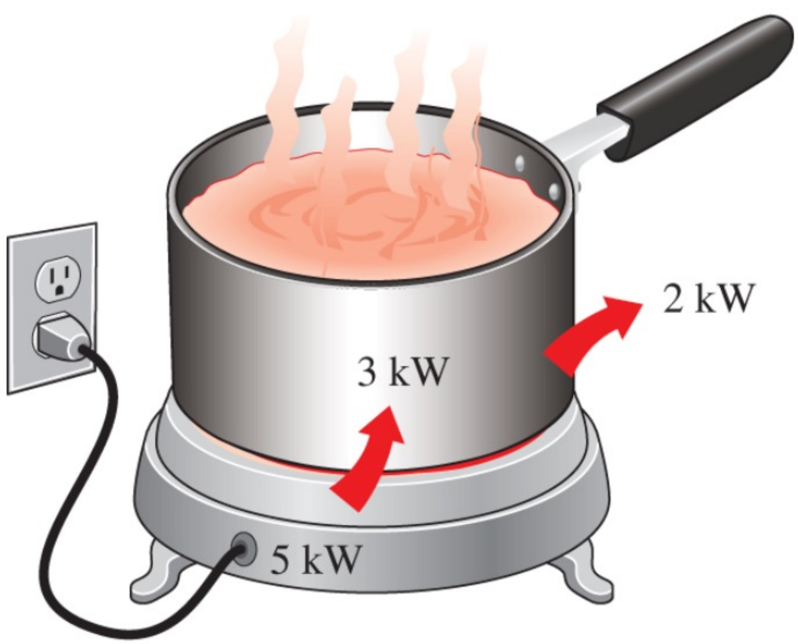
- For generator in power plants the overall efficiency is

$$\eta_{overall} = \eta_{combustion} \times \eta_{thermal} \times \eta_{generator} = \frac{\dot{W}}{HHV \times \dot{m}\_fuel}$$

Energy Conversion Efficiencies

- Efficiency of a cooking appliance

$$Efficiency = \frac{Energy\ Utilized}{Energy\ supplied\ to\ appliace}$$



Energy Conversion Efficiencies

- Summarize efficiencies:

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

Energy Conversion Efficiencies

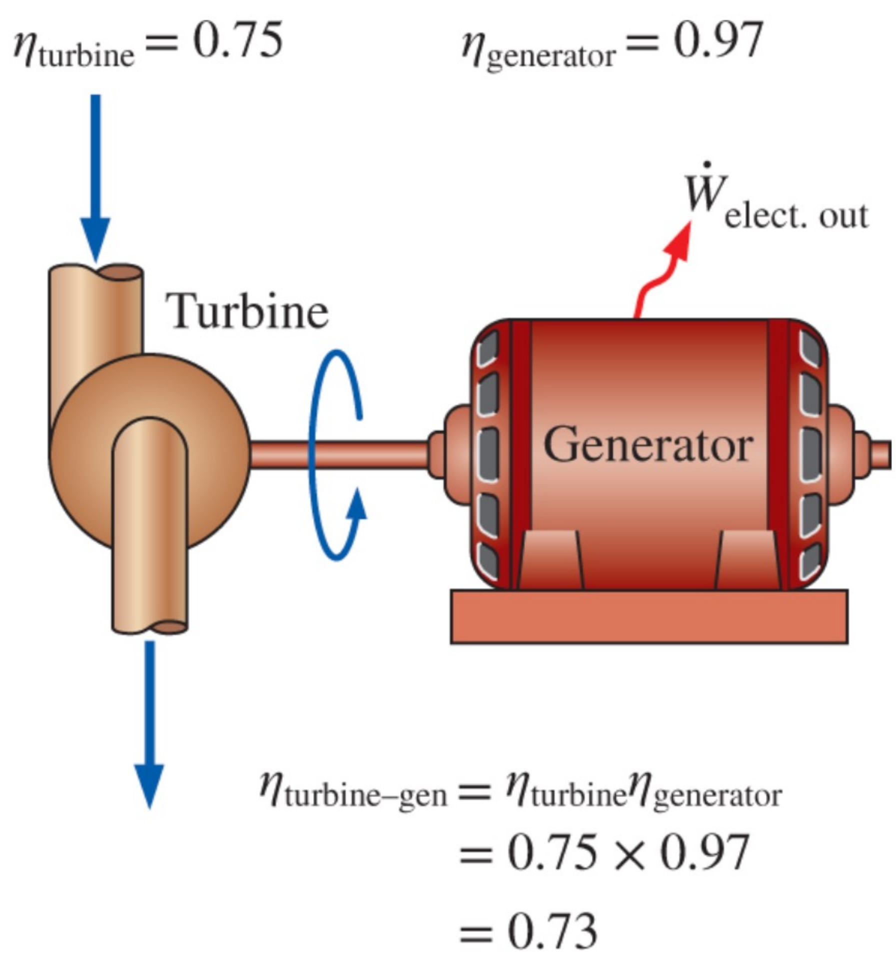
- Summarize efficiencies:

$$\eta_{pump} = \frac{mechanical\ energy\ increase\ of\ the\ fluid}{Mechanical\ energy\ input} = \frac{E_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

$$\eta_{turbine} = \frac{mechanical\ energy\ output}{Mechanical\ energy\ decrease\ of\ the\ fluid} = \frac{\dot{W}_{shaft,out}}{|\Delta\dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

Energy Conversion Efficiencies

- Summarize efficiencies:



CLASS ACTIVITY

Class Activity

- Can the combined pump–motor efficiency be greater than either the pump or the motor efficiency?

CLASS ACTIVITY

Class Activity

- The efficiency of cooking appliances affects the internal heat gain from them since an inefficient appliance consumes a greater amount of energy for the same task, and the excess energy consumed shows up as heat in the living space. The efficiency of open burners is determined to be 73 percent for electric units and 38 percent for gas units. Consider a 2-kW electric burner at location where the unit costs of electricity and natural gas are $0.09/kWh and $1.2/therm, respectively. Determine the rate of energy consumption by the burner and the unit cost of utilized energy for both electric and gas burners.