Chemical Thermodynamics

Chem 211: Lecture 3

1st Law of Thermodynamics

Ahmad Alakraa

Outline

- Equation of State
- Adiabatic Processes
- Closed Cycled Systems
- Case Study
- Heating Effect of a Fan
- Lighting of a Classroom
- Energy Conversion Efficiency
- Gas Water Heaters
- Work Output in Pumps & Turbines
- Efficiency of Cooking Appliances
- Mechanisms of Heat transfer.

1st law of Thermodynamics

Energy can be neither **created** nor **destroyed** during a process; it can only **change** forms.

- is known as the principle of energy conservation.
- Helpful for studying energy interactions & formulating relationships involved.
- Is based on **experimental** observations.

Thermodynamics provides no information about the **absolute** value of the total energy. It deals only with the change of the total energy.

1^{st} law of TD: Mathematically

In absence of external magnetic, electric, and surface tension effects (i.e., for simple compressible systems)

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

For Stationary Systems

$$\Delta KE = \Delta PE = 0$$

$$\Delta E = \Delta U$$

- Note: U involves internal microscopic KE and PE.
- ΔE & ΔU are inspired by mass transfer (m), heat transfer, (Q) and/or Work, (W)

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

$$= (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})$$

in rates

$$\dot{E}_{in} - \dot{E}_{out} = {}^{\mathrm{d}E_{system}}/_{dt} \quad (kW)$$

For constant rates,

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

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

$$\Delta E_{mass} = \left(\frac{dE_{mass}}{dt}\right)\Delta t$$

For closed systems (no mass flow), $\Delta E_{mass} = 0$

$$\Delta E_{system} = \Delta U_{system} = U_{in} - U_{out}$$
$$= (Q_{in} - Q_{out}) + (W_{in} - W_{out})$$

Simply,

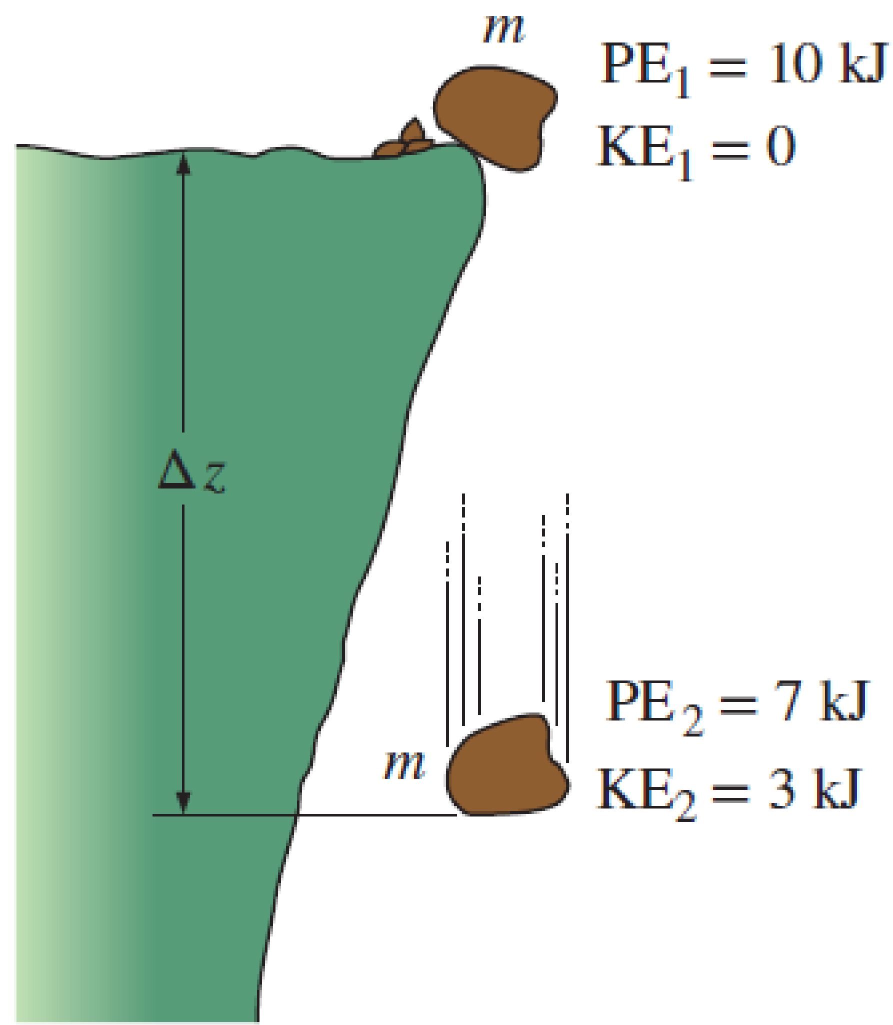
$$\Delta E_{system} = \Delta U = Q + W$$

Equation of State

- ΔU of a **closed** system equals to the energy passing via its boundary as **heat** and/or **work**.

Falling a rock from an elevation

- The decrease in **potential energy** ($mg\Delta z$) exactly equals the increase in kinetic energy [$\frac{m(V_2^2 - V_1^2)}{2}$] when the air resistance is negligible.



- This confirms the conservation of energy principle for mechanical energy (moving an object by a force).

Defining the Property E

The net **work** (**non-state** function, not **property**) is the same for all **adiabatic** (Q=0) processes of a closed system between two specified states

- The net work must depend on the end states (of course + initial state) of the system only (not the pathway), and thus it must correspond to a change in a **property** of the system which is ***E***.

1st Law states

"the *change* in the total energy during an adiabatic process must be equal to the net work done".

Adiabatic Processes

- involve **No** **heat transfer**.
- may involve several kinds of work interactions.

(Adiabatic + Closed) ≠ Adiabatic ≠ Isolated ($\Delta E=0$)

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.

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

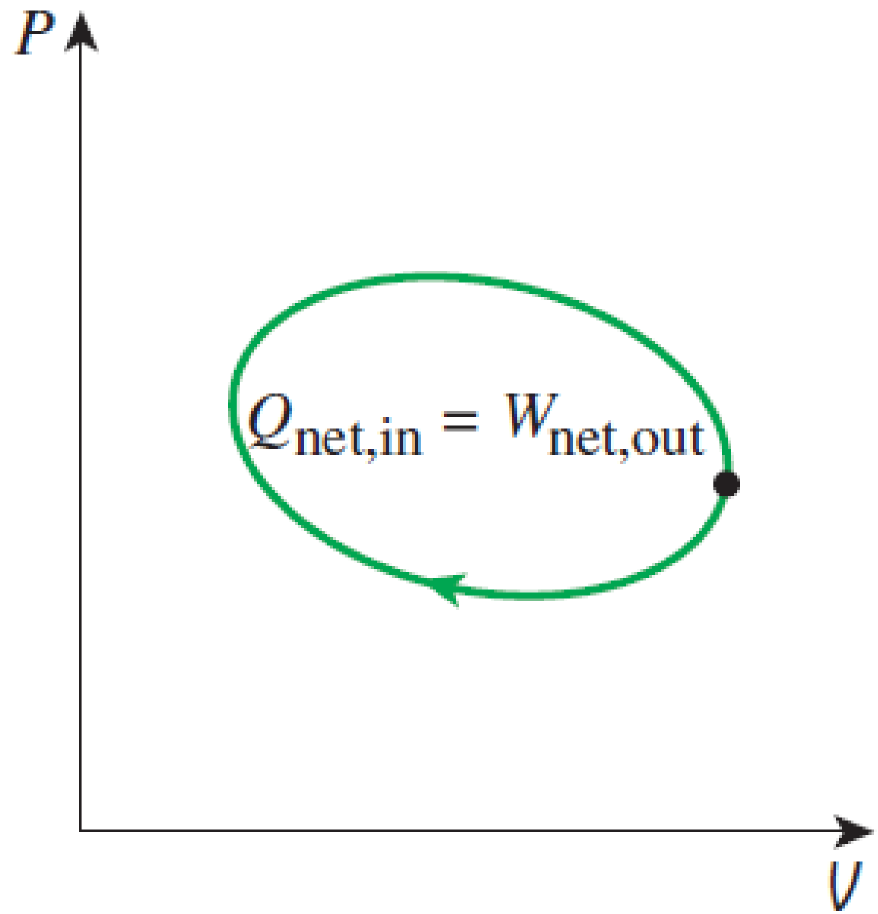
Closed Cycled Systems

$$\Delta E_{system} = \Delta U_{system} = Q + W = 0$$

- Net heat input is equal to net work output.

$$W_{net,out} = Q_{net,in}$$

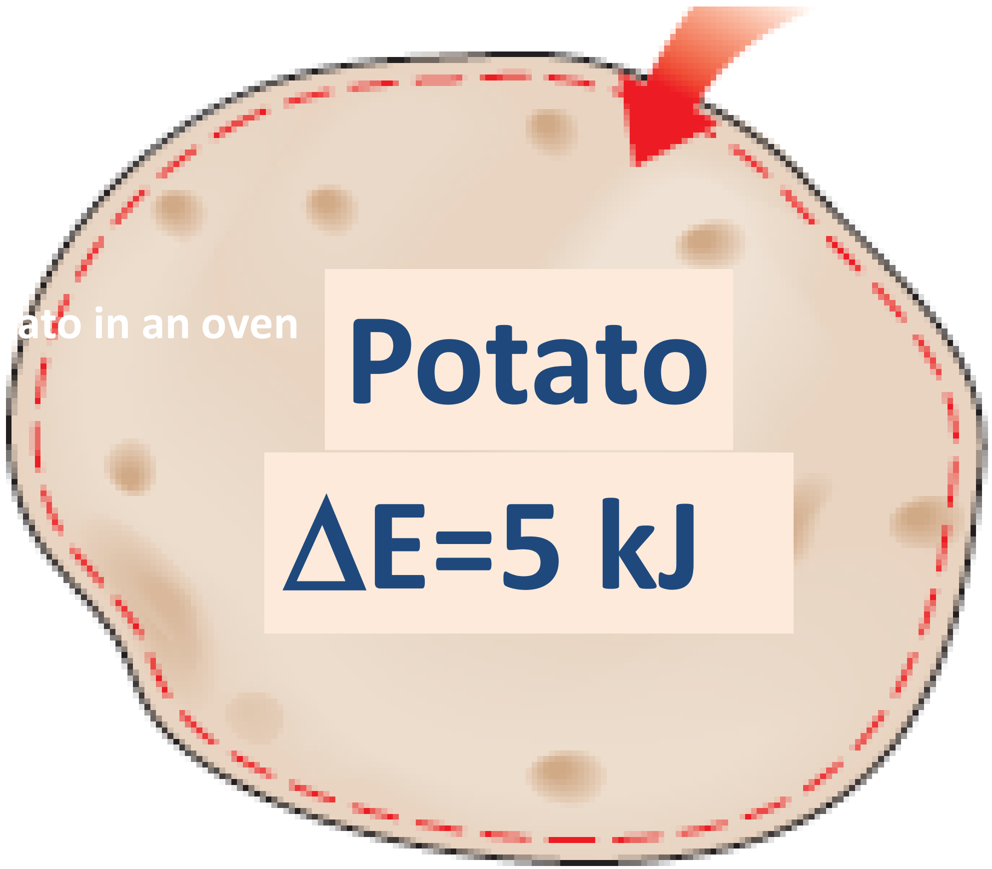
$$\dot{W}_{net,out} = \dot{Q}_{net,in}$$



Baked potato in an oven

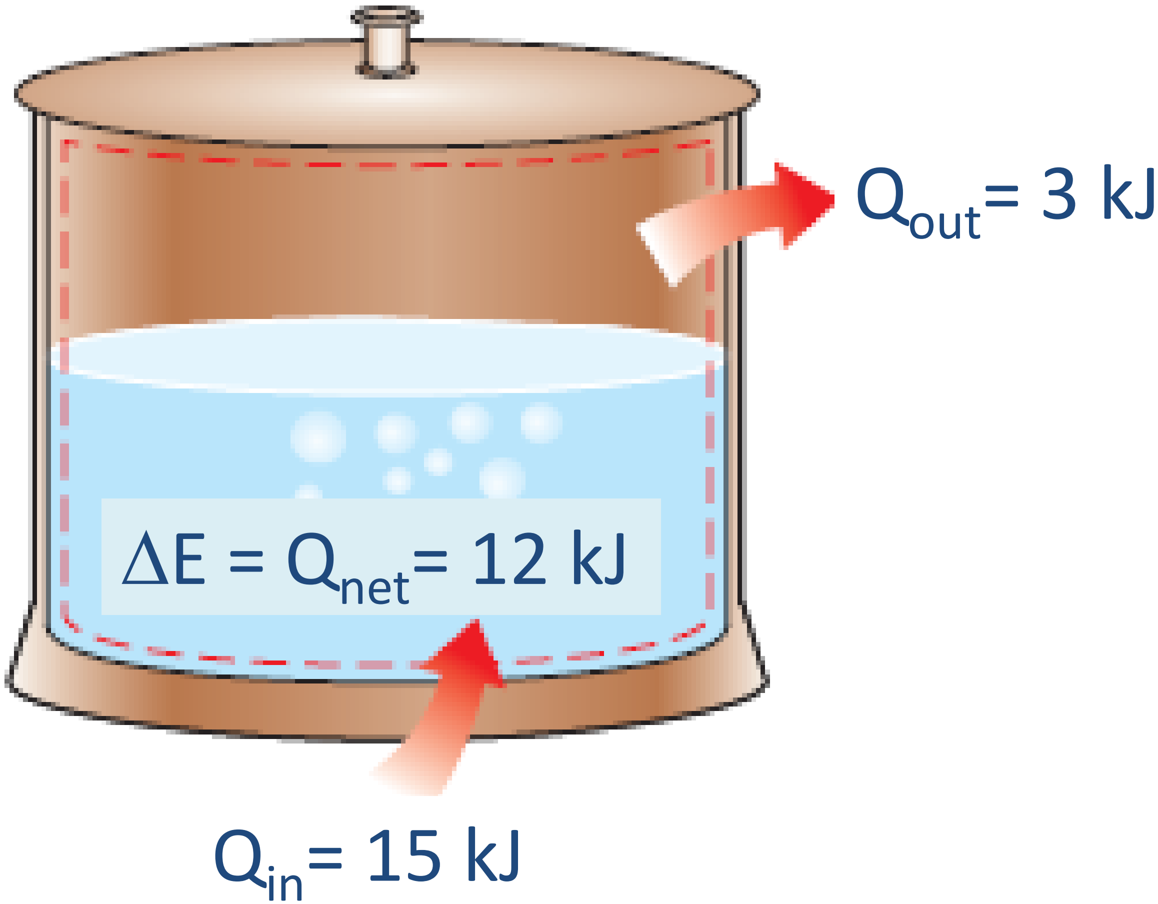
Disregarding any mass transfer (moisture loss from the potato),

Potato = sys $Q_{in} = 5$ kJ



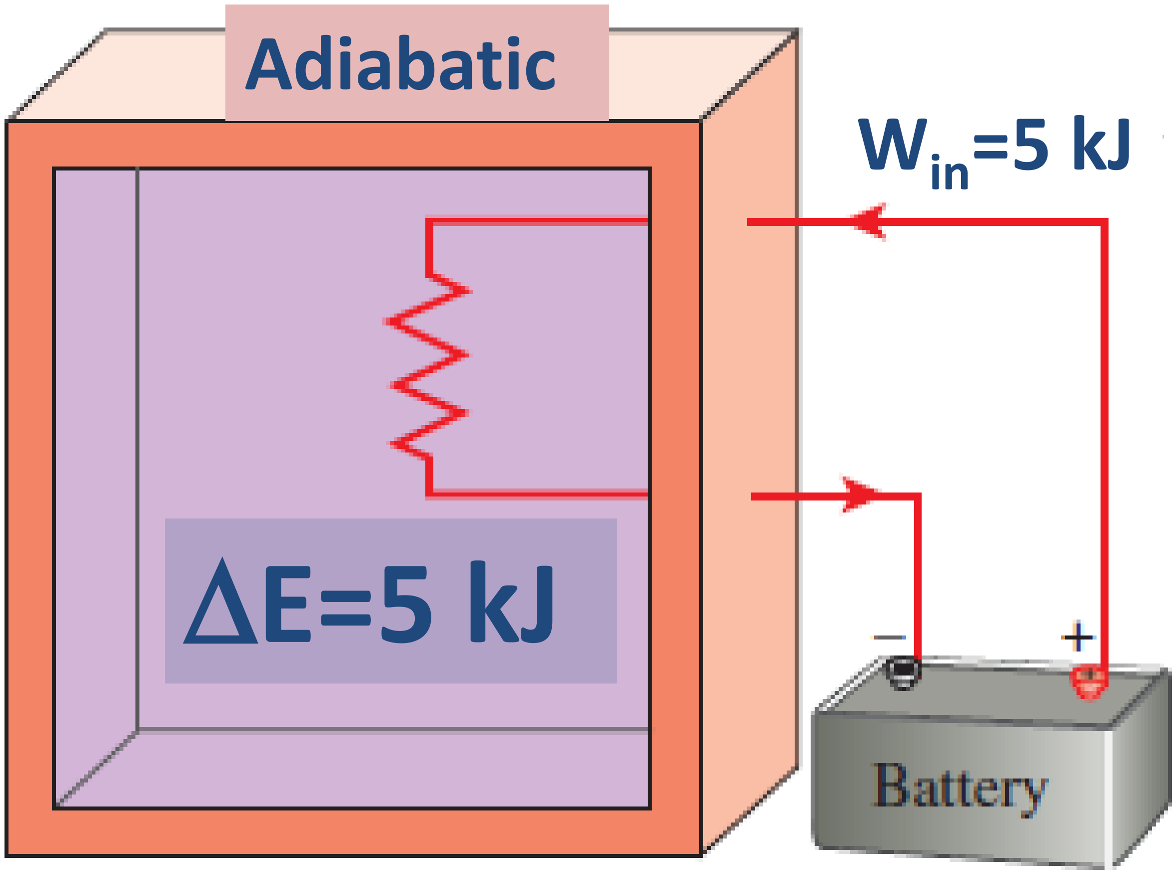
$$\Delta E_{system} = Q + W = 5 + 0 = 5\ kJ$$

Heating water in a pan



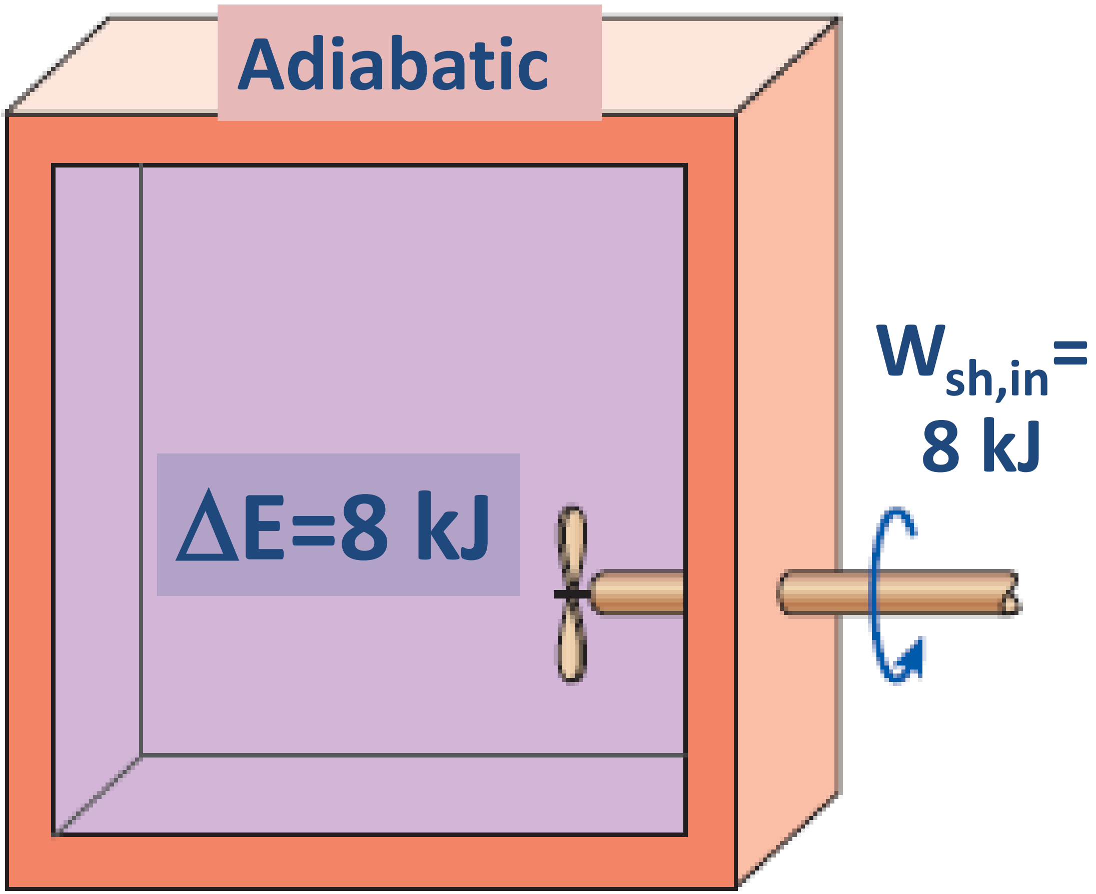
$$\Delta E_{system} = Q_{in} - Q_{out} = 15 - 3 = 12\ kJ$$

Adiabatic heating electrically



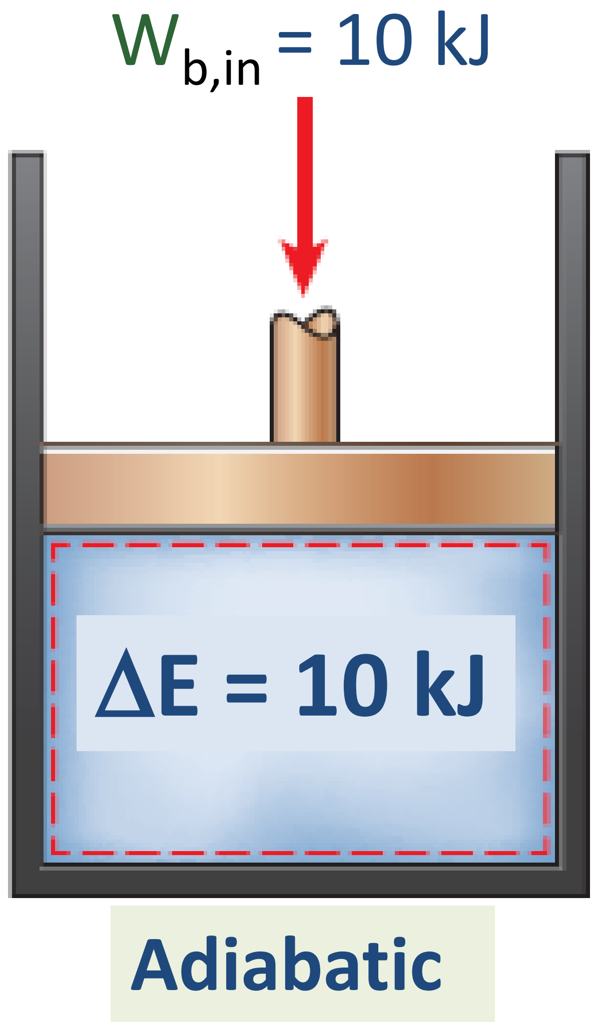
$$\Delta E_{system} = W_{electrical} = 5\ kJ$$

Adiabatic heating with a paddle wheel



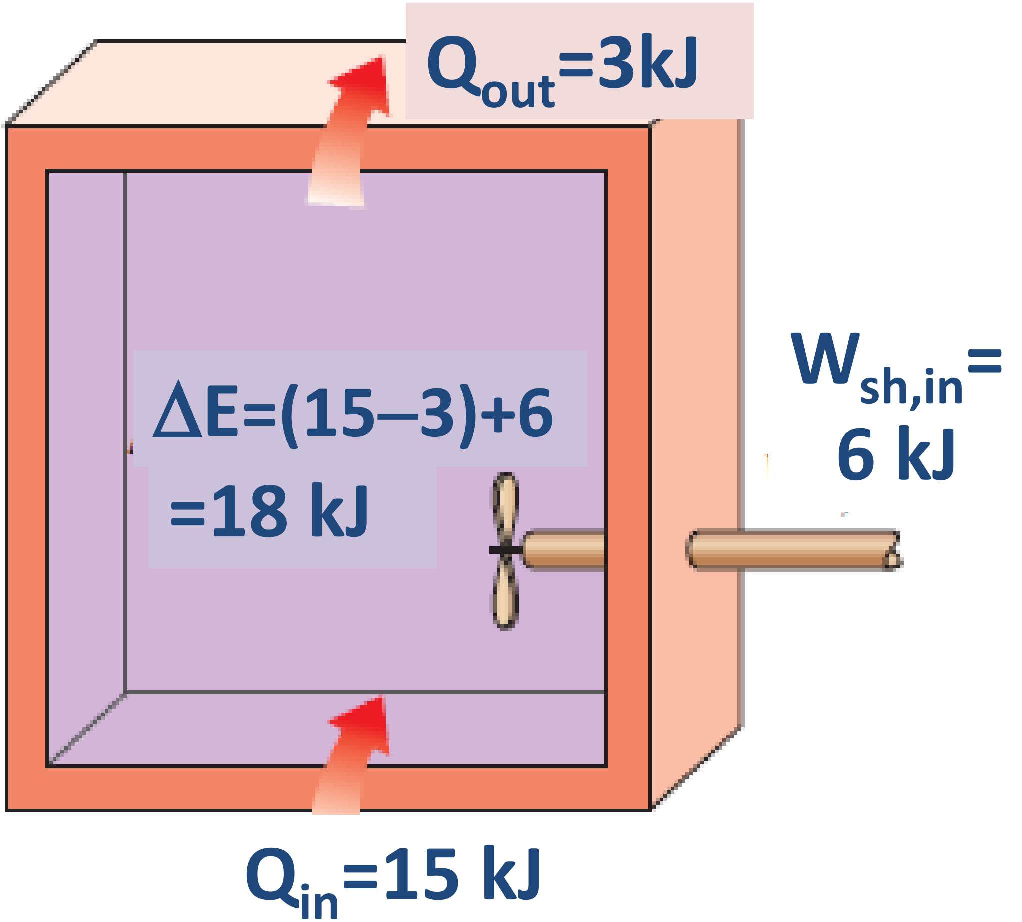
$$\Delta E_{system} = W_{shaft} = 8\ kJ$$

Adiabatic air heating upon compression



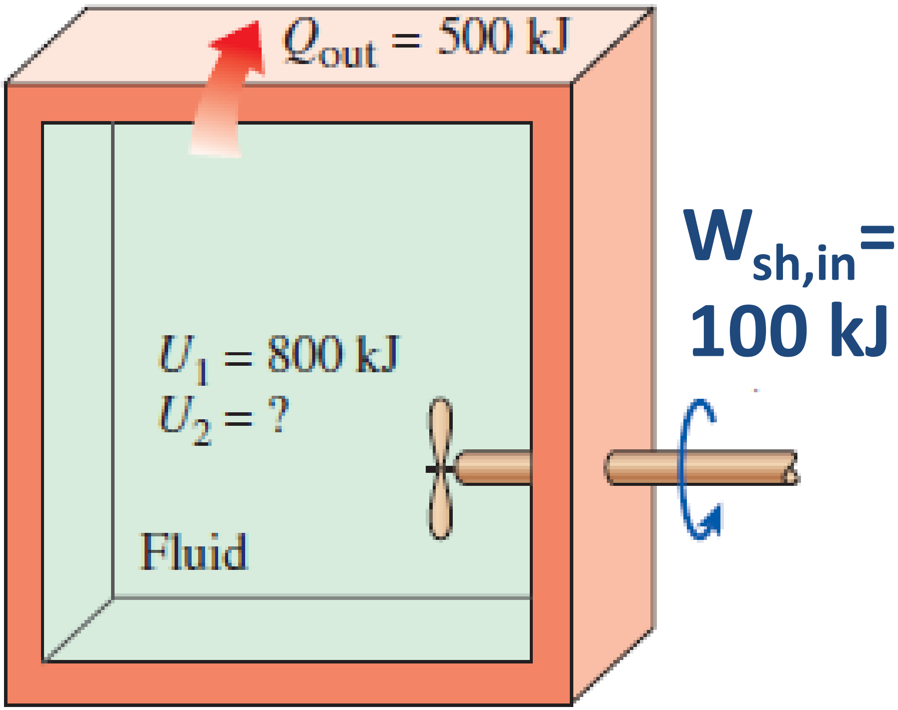
$$\Delta E_{system} = W_{b,in} = 10\ kJ$$

Heat and work interactions



$$\Delta E_{system} = \Delta U_{system} = Q_{in} - Q_{out} + W_{shaft}$$
$$= 15 - 3 + 6 = 18\ kJ$$

Cooling of a hot fluid in a tank

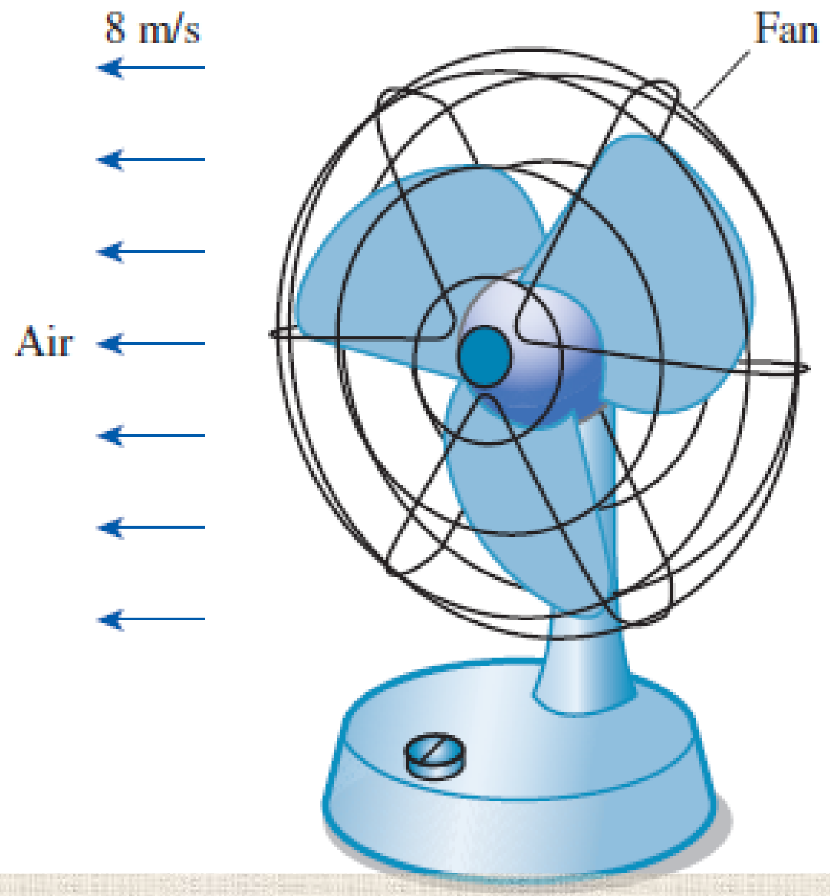


$$\Delta U_{system} = U_2 - 800 = Q + W = -500 + 100 = -400$$

$$U_2 = -400 + 800 = 400\ kJ$$

Exercise Accelerated air by a fan

- A 20 W fan is claimed to discharge air from a ventilated room at a rate of 1.0 kg/s at a discharge velocity of 8 m/s. Determine if this claim is reasonable.



Assumption

- The fan's motor converts part of the electrical power to mechanical (shaft) power, to rotate the fan blades in air.
- The blades are shaped to impart a large fraction of the mechanical power of the shaft to air by mobilizing it.

- In the limiting ideal case of **no losses** (no conversion of electrical and mechanical energy to thermal energy) in steady operation, the electric power input will be equal to the rate of increase of the kinetic energy of air.

- Hence, for a control volume that encloses the fan-motor unit, the energy balance can be written as

$$\frac{dE_{steady\ system}}{dt} = 0, \qquad \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{elect,in} = \dot{m}_{air}\frac{V_{out}^2}{2}$$

$$V_{out} = \sqrt{\frac{2\dot{W}_{elect,in}}{\dot{m}_{air}}} = \sqrt{\frac{2(20\,J/s)}{1.0\,kg/s}\left(\frac{1\,m^2/s^2}{1\,J/kg}\right)}$$

$$= 6.3\,m/s$$

- The maximum air velocity should not exceed 6.3 m/s, which is less than 8 m/s. Therefore, the claim is false.

- In reality, the air velocity will be considerably lower than 6.3 m/s because of the losses associated with the conversion of electrical energy to mechanical shaft energy, and the conversion of mechanical shaft energy to kinetic energy of air

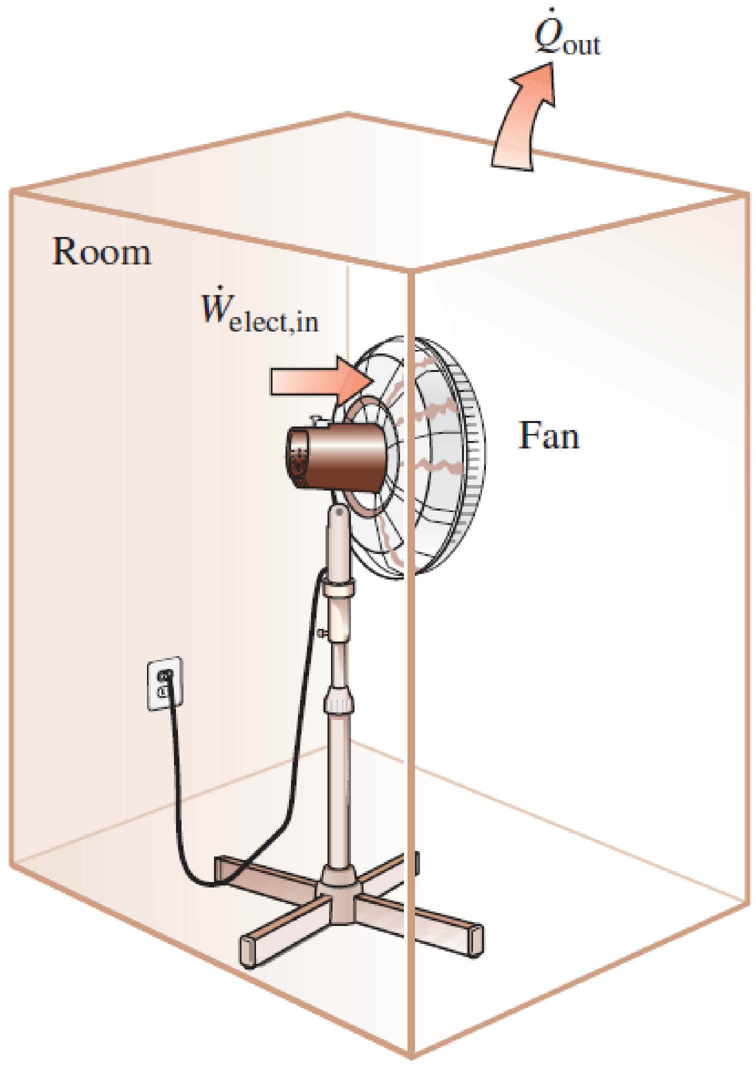
Exercise <u>Heating Effect of a Fan</u>

- 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 as $\dot{Q} = UA(T_i - T_o)$ where U = 6 W/m^2.°C is the overall heat transfer coefficient, A = 30 m^2 is the exposed surface area of the room, and T_i and T_o are the indoor and outdoor air temperatures, respectively. Determine the indoor air temperature when steady operating conditions are established.

Assumption

- Heat transfer through the floor is negligible.
- There are no other energy interactions involved.

- The electricity consumed by the fan increases the room T.
- As the room T rises, the rate of heat loss from the room increases until the rate of heat loss equals the electric power consumption (Steady equilibrium).



At steady state

$$\dot{E}_{in} - \dot{E}_{out} = {}^{\mathrm{d}E_{system}}\!/_{dt} = 0$$

$$\Rightarrow \quad \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{elect,in} = \dot{Q}_{out} = UA(T_i - T_o)$$

$$200\ W = \left(\frac{6\ W}{m^2 . {}^oC}\right)(30\ m^2)(T_i - 25^oC)$$

$$T_i = 26.1^oC$$

A 200-W fan heats a room just like a 200-W resistance heater.

Exercise Lighting of a Classroom

- The lighting needs of a classroom are met by 30 fluorescent lamps, each consuming 80 W of electricity. The lights in the classroom are kept on for 12 h a day and 250 days a year. For a unit electricity cost of 11 cents per kWh, determine the annual energy cost of lighting for this classroom? Also, discuss the effect of lighting on the heating and air-conditioning requirements of the room?

Assumption

Negligible effect of voltage fluctuations, so each lamp consumes its rated power.

$$\text{Lighting power} = (\text{Power/lamp}) \times (\text{No. of lamps})$$
$$= (80 \text{ W/lamp})(30 \text{ lamps}) = 2400 \text{ W} = 2.4 \text{ kW}$$

$$\text{Operating hours} = (12 \text{ h/d})(250 \text{ d/year}) = 3000 \text{ h/year}$$

$$\text{Lighting energy} = (\text{Lighting power})(\text{Operating hours})$$
$$= (2.4 \text{ kW})(3000 \text{ h/year}) = 7200 \text{ kWh/year}$$

$$\text{Lighting cost} = (\text{Lighting energy})(\text{Unit cost}) =$$
$$(7200 \text{ kWh/year})(\$0.11 / \text{kWh}) = \$792 / \text{year}$$

- Light is absorbed by the surfaces it strikes and is converted to thermal energy.
- Disregarding the light that escapes through the windows, the entire 2.4 kW of electric power consumed by the lamps eventually becomes part of thermal energy of the classroom; reducing heating requirements by 2.4 kW and increasing air-conditioning load by 2.4 kW.
- The annual lighting cost of this classroom alone is close to $800.
- If incandescent lightbulbs were used instead, the lighting costs would be **four times higher** since incandescent lamps use four times as much power for the same amount of light produced.

CYU

- Heat is transferred to a closed system in the amount of 13 kJ while 8 kJ electrical work is done on the system. If there are no macroscopic kinetic and potential energy changes, what is the internal energy change of the system?

(A) 21 kJ (B) −21 kJ (C) 5 kJ (D) −5 kJ (E) 8 kJ

Answer

√ **(C) 21 kJ**

Energy Conversion

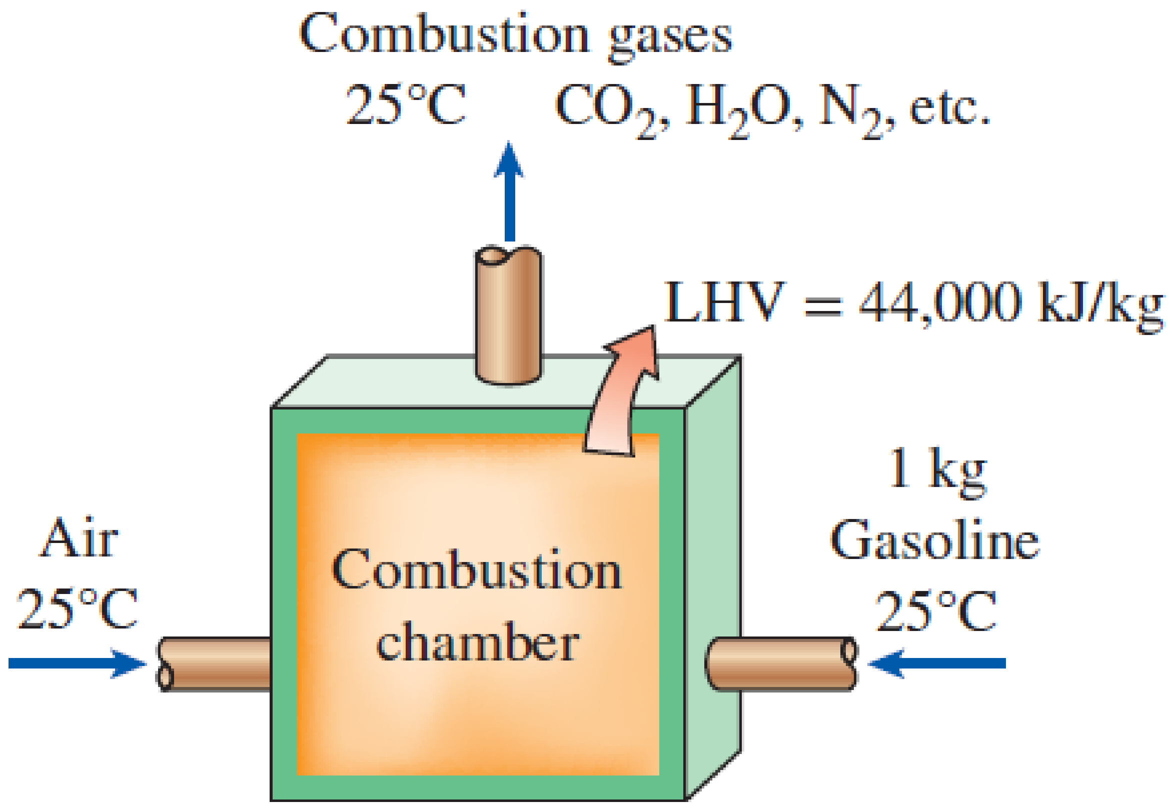
Efficiency

$$\text{Efficiency, } \eta = \frac{\text{desired output}}{\text{required input}}$$

- η of 90% of a conventional electric water heater (the ratio of the *energy delivered to the house by hot water* to the *energy supplied to the water heater*) means the existence of 10% heat losses from the hot-water tank to the surrounding air.
- Better (thicker) insulation of water heaters may increase η.
- A gas water heater whose η is only 55% although may cost the same as an electric unit to purchase and install, but the annual energy cost of a gas unit will be much **less** than that of an electric unit.

Gas water heaters

- η of equipment that involves the combustion of a fuel is based on the heating value **(HV)** of the fuel.



- **HHV** (higher heating value) is *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*.

- η_{comb} takes different names, depending on the combustion unit (furnace efficiency, $\eta_{furnace}$, boiler efficiency, η_{boiler}, or heater efficiency, η_{heater})

- Fuels containing **hydrogen** forms water when burned, and the HV of a fuel will be different depending on whether this water is in the liquid (higher HV, HHV) or vapor (lower HV, LHV) form.

- The **HHV** considers the extra (+ combustion heat) heat produced from the complete condensation (exothermic, recovery of heat of vaporization) of water.

$$LHV + m\Delta H_{vap} = HHV$$

- LHV and HHV of gasoline are 44,000 kJ/kg and 47,300 kJ/kg, respectively.
- An efficiency definition should make it clear whether it is based on LHV and HHV of the fuel.
- Efficiencies of cars and jet engines are normally based on LHV since water normally leaves as a vapor in the exhaust gases, and it is not practical to try to recover the heat of vaporization.
- Efficiencies of furnaces, on the other hand, are based on HHV.

Combustion equipment efficiency η_{comb} of Gas water heaters

$$\eta_{\text{comb}} = \frac{\dot{Q}_{\text{useful}}}{\dot{E}_{\text{fule}}} = \frac{\dot{Q}_{\text{useful}}}{\dot{m}_{\text{fule}} HV_{\text{fuel}}}$$

$$= \frac{\text{Rate of useful heat delivered, kJ/s}}{\text{Rate of chemical fuel energy consumed, kJ/s}}$$

- where $\dot{m}_{\text{fule}}$ is the amount of fuel burned in the combustion equipment per unit time in kg/s, and HV_{fuel} is the heating value of the fuel in kJ/kg.

Work output

- For *car engines*, the work output is understood to be the power delivered by the crankshaft.
- For power plants, the work output can be the mechanical power at the turbine exit, or the electrical power output of the generator.
- A generator is a device that converts mechanical energy to electrical energy, and the effectiveness of a generator is characterized by the **generator efficiency**, $\eta_{\text{generator}}$, which is the ratio of the *electrical power output* to the *mechanical power input.*

Thermal efficiency of a power plant

- η_{thermal} is usually defined as the ratio of the net shaft work output of the turbine to the heat input to the working fluid.
- The **overall efficiency, η_{overall},** for the power plant is the ratio of the *net electrical power output* to the *rate of fuel energy input.*

$$\eta_{\text{overall}} = \eta_{\text{comb}} \times \eta_{\text{thermal}} \times \eta_{\text{generator}}$$

$$\eta_{\text{overall}} = \frac{\dot{W}_{\text{net,electric}}}{\dot{m}_{\text{fule}} HHV_{\text{fuel}}}$$

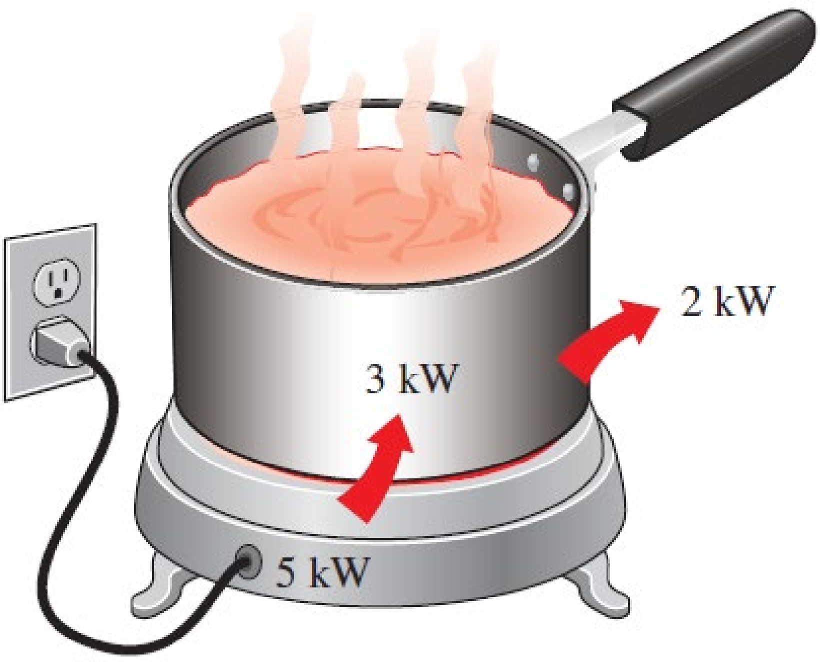
η_{overall} are about 25–35 % for gasoline automotive engines, 35–40 % for diesel engines, and up to 60 % for large power plants.

Electricity of cooking appliances

- convert *electrical* or *chemical* energy to heat.
- η is the ratio of the useful energy transferred to the food to the energy consumed by the appliance.

Electric ***ranges*** (~73 %) are more efficient than natural gas ***ranges*** (~38 %) , but more expensive

$$\eta = \frac{3\ kW}{5\ kW} = 0.6$$



Energy costs of cooking a casserole with different appliances*

Cooking appliance	Cooking temperature	Cooking time	Energy used	Cost of energy
Electric oven	350°F (177°C)	1 h	2.0 kWh	$0.19
Convection oven (elect.)	325°F (163°C)	45 min	1.39 kWh	$0.13
Gas oven	350°F (177°C)	1 h	0.112 therm	$0.13
Frying pan	420°F (216°C)	1 h	0.9 kWh	$0.09
Toaster oven	425°F (218°C)	50 min	0.95 kWh	$0.09
Crockpot	200°F (93°C)	7 h	0.7 kWh	$0.07
Microwave oven	"High"	15 min	0.36 kWh	$0.03

*Assumes a unit cost of $0.095/kWh for electricity and $1.20/therm for gas.

$$1 \text{ US therm} = 1.055 \times 10^{8} \text{ J}$$

- **Convection** (use a fan and exhaust system to circulate air distributed from the heating element, ~ 1/3 saving)
- **Microwave** (~ 2/3 saving) ovens are more efficient than conventional ovens.

η can be increased by:

- using the smallest oven for baking,
- using a pressure cooker,
- using an electric slow cooker for stews and soups,
- using the smallest pan,
- using the smaller heating element for small pans on electric ranges,
- using flat-bottomed pans on electric burners to assure good contact.

- keeping burner drip pans clean and shiny,
- defrosting frozen foods in the refrigerator before cooking,
- avoiding preheating unless it is necessary,
- keeping the pans covered during cooking,
- using timers and thermometers to avoid overcooking,
- using the self-cleaning feature of ovens right after cooking,
- keeping inside surfaces of microwave ovens clean.

This reduces our utility bills and reduces pollution.

Ex. Cooking with Electric and Gas Ranges

- The efficiency of open burners is determined to be 73% for electric units and 38% for gas units. Consider a 2 kW electric burner at a location where the unit costs of electricity and natural gas are \$0.12/kWh and \$1.20/therm, respectively. Determine the rate of energy consumption by the burner and the unit cost of utilized energy for both electric and gas burners?

Answer

$$\dot{Q}_{\text{utilized}} = \dot{E}_{input} \times \eta$$

$$\dot{Q}_{\text{elec.}} = 2\text{ kW} \times 0.73 = 1.46\text{ kW}$$

$$\text{Cost}_{\text{elec.}} = \frac{\text{input Cost}}{\eta} = \frac{\$0.12/\text{kWh}}{0.73} = \$0.164/\text{kWh}$$

- The energy input to a gas burner that supplies utilized energy at the same rate (1.46 kW) is:

$$\dot{Q}_{\text{input,gas}} = \frac{\dot{Q}_{\text{utilized}}}{\eta} = \frac{1.46\ \text{kWh}}{0.38}$$

$$= 3.84\ \text{kW} = 13{,}100\ \text{Btu/h}$$

Note: **Btu/h:** British Thermal Units per Hour

$$1\ \text{kW} = 3{,}412\ \text{Btu/h} \qquad 1\ \text{therm} = 29.3\ \text{kWh}$$

$$\text{Cost}_{\text{gas}} = \frac{\text{input Cost}}{\eta} = \frac{\$1.20/29.3\text{kWh}}{0.38} = \$0.108/\text{kWh}$$

Cooking with an electric burner will cost about 52% more compared to a gas burner in this case

η of Mechanical and Electrical Devices

- The transfer of mechanical energy is usually accomplished by a rotating shaft, and thus mechanical work is often referred to as **shaft work**.
- A pump or a fan **receives** shaft work (*usually from an electric motor*) and transfers it to the fluid as mechanical energy (less frictional losses).
- A turbine, on the other hand, converts the mechanical energy of a fluid to shaft work.
- In the absence of any irreversibilities (friction), mechanical energy can be converted entirely from one mechanical form to another, and the **mechanical efficiency** of a device or process can be defined as:

$$\eta_{\text{mech}} = \frac{E_{\text{mech,out}}}{E_{\text{mech,in}}} = 1 - \frac{E_{\text{mech,loss}}}{E_{\text{mech,in}}}$$

Pumps

- η_{mech} of 97% indicates that 3% of the mechanical energy input is converted to thermal energy (frictional heating), rising the fluid T.
- In fluid systems, we are usually interested in increasing the pressure, velocity, and/or elevation of a fluid. This is done by supplying mechanical energy to the fluid by a pump, a fan, or a compressor (we will refer to all of them as pumps).

$$\eta_{\text{pumb}} = \frac{\text{Mech. E increase of fluid}}{\text{Mech E input}}$$

$$= \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump,u}}}{\dot{W}_{\text{pump}}}$$

$\dot{W}_{\text{pump,u}}$: **useful pumping power**

$\Delta \dot{E}_{\text{mech,fluid}} = \dot{E}_{\text{mech,out}} - \dot{E}_{\text{mech,in}}$ is the rate of increase in the mechanical energy of the fluid, which is equivalent to the **useful pumping power** $\dot{W}_{\text{pump,u}}$ supplied to the fluid.

Turbine:

extracting mechanical energy from a fluid

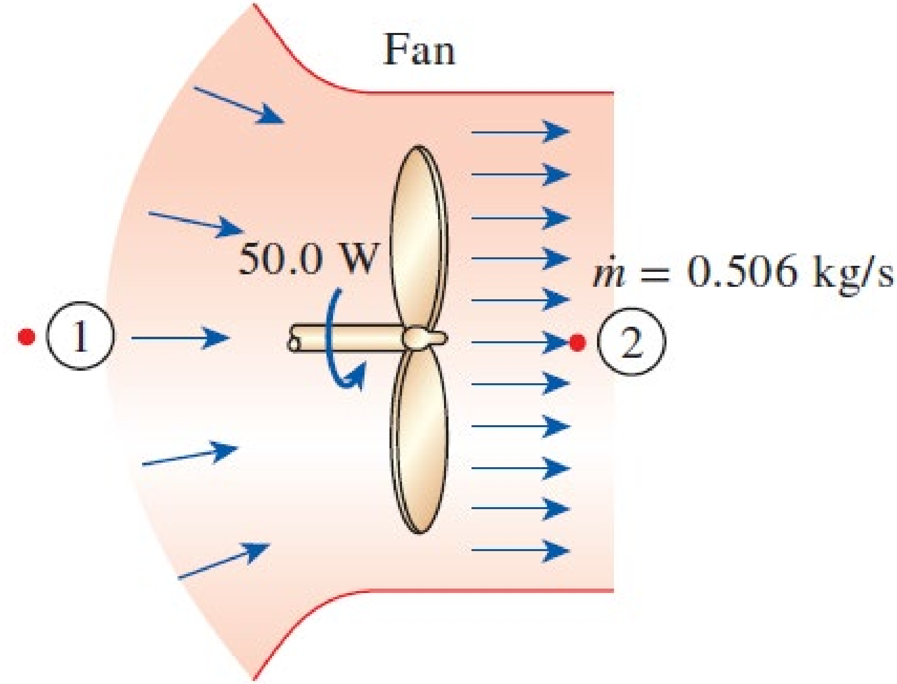
- producing mechanical power in the form of a rotating shaft that can drive a generator or any other rotary device.

$$\eta_{\text{turbine}} = \frac{\text{Mech. E output}}{\text{Mech E decrease of fluid}} = \frac{\dot{W}_{\text{shaft},in}}{|\Delta\dot{E}_{\text{mech,fluid}}|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine},e}}$$

where $|\Delta\dot{E}_{\text{mech,fluid}}| = \dot{E}_{\text{mech},in} - \dot{E}_{\text{mech},out}$ is the rate of decrease in the mechanical energy of the fluid, which is equivalent to the mechanical power **extracted** from the fluid by the turbine $\dot{W}_{\text{turbine,e}}$.

η_{mech} of a fan

- is the ratio of the rate of increase of the mechanical energy of air to the mechanical power input.



$V_1 \approx 0, V_2 \approx 12.1 \text{ m/s},$

$z_1 \approx z_2 \qquad P_1 = P_2 \approx P_{atm}$

$$\eta_{\text{mech, fan}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{m} V_2^2/2}{\dot{W}_{\text{shaft,in}}}$$

$$\eta_{\text{mech, fan}} = \frac{(0.506 \text{ kg/s})(12.1 \text{ m/s})^2/2}{50.0 \text{ W}} = 0.741$$

Electrical → Mechanical E Conversions

- Electrical energy is commonly converted to rotating mechanical energy by **electric motors** to drive fans, compressors, robot arms, car starters, and so forth.
- The effectiveness of this conversion process is characterized by the motor efficiency, η_{motor}, which is the *ratio of the mechanical energy output of the motor to the electrical energy input*.
- The full-load **motor** range from about 35 % for small motors to over 97 % for large high-efficiency motors.
- The difference between the electrical energy consumed and the mechanical energy delivered is dissipated as waste heat.

- The mechanical efficiency should not be confused with the **motor** efficiency and the **generator** efficiency, which are defined as:

$$\eta_{\text{mech}} = \frac{\text{Mech. E output}}{\text{Mech. E input}}$$

$$\eta_{\text{motor}} = \frac{\text{Mech. power output}}{\text{Elec. power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

$$\eta_{\text{generator}} = \frac{\text{Elec. power output}}{\text{Mech.power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

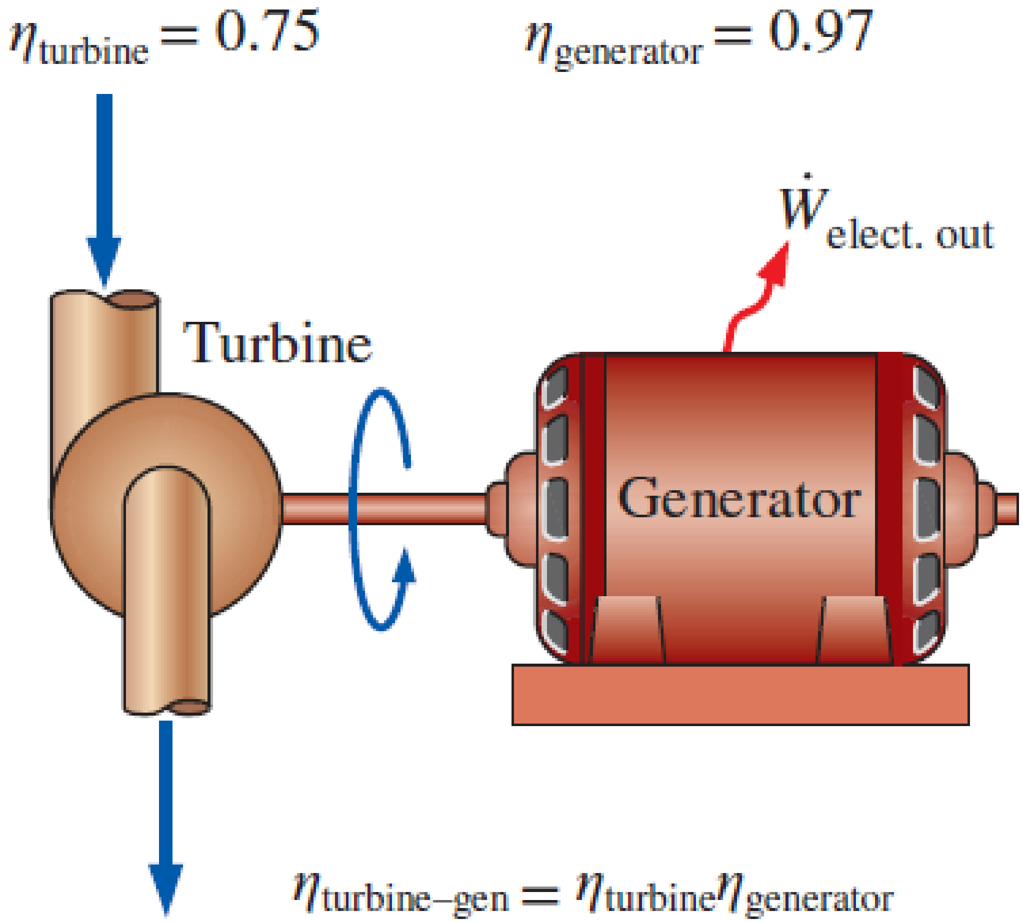
- A pump is usually packaged together with its motor, and a turbine with its generator.
- The ***combined*** or **overall** efficiency of pump–motor and turbine–generator combinations is:

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}} \times \eta_{\text{motor}}$$

$$= \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump,out}}} \times \frac{\dot{W}_{\text{pump,out}}}{\dot{W}_{\text{elect},in}} = \frac{\dot{W}_{\text{pump,in}}}{\dot{W}_{\text{elect,in}}}$$

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}} \times \eta_{\text{gen}}$$

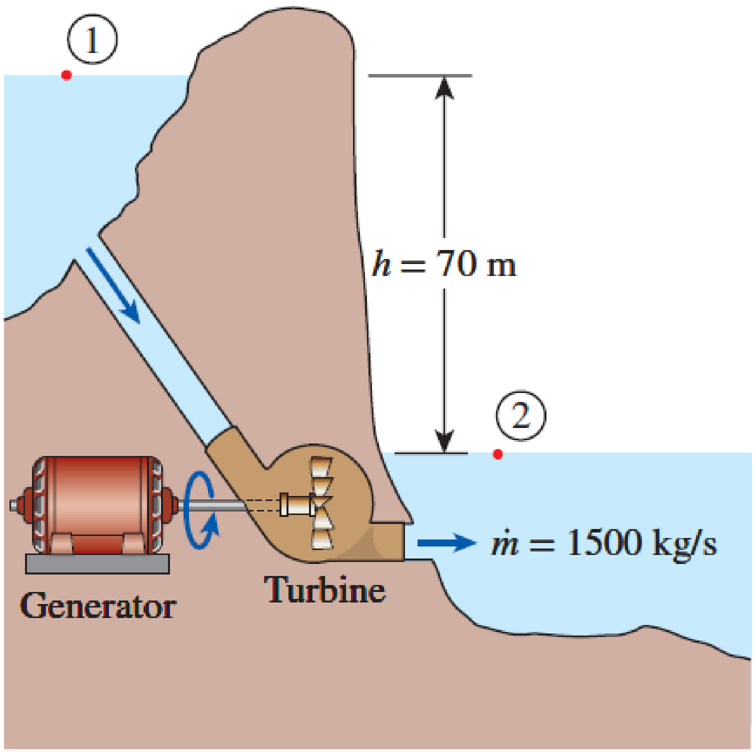
$$= \frac{\dot{W}_{\text{turbine},in}}{\dot{W}_{\text{turbine,e}}} \times \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},in}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$



$$\eta_{turbine-gen} = \eta_{turbine}\eta_{gen}$$
$$= 0.75 \times 0.97 = 0.73$$

Ex. Power Generation/Hydroelectric Plant

- Electric power is to be generated by installing a hydraulic turbine–generator at a site 70 m below the free surface of a large water reservoir that can supply water at a rate of 1500 kg/s steadily. If the mechanical power output of the turbine is 800 kW and the electric power generation is 750 kW, determine the turbine efficiency and the combined turbine–generator efficiency of this plant. Neglect losses in the pipes.



Answer

$$pe_1 = gz_1 = (9.81\ \mathrm{m/s^2})\,(70\ \mathrm{m})\left(\frac{1\ \mathrm{kJ/kg}}{1000\ \mathrm{m^2/s^2}}\right)$$

$$\boxed{pe_1 = 0.687\ \mathrm{kJ/kg}}$$

The rate at which the mechanical energy of water is supplied to the turbine becomes:

$$\left|\Delta \dot{E}_{\mathrm{mech,fluid}}\right| = \dot{m}\left(e_{mech,in} - e_{mech,out}\right)$$

$$= \dot{m}\left(pe_1 - 0\right) = \dot{m}pe_1 = (1500\ \mathrm{kg/s})(0.687\ \mathrm{kJ/kg}) = 1031\ \mathrm{kW}$$

$$\eta_{\mathrm{turbine}} = \frac{\dot{W}_{\mathrm{elect,out}}}{\left|\Delta \dot{E}_{\mathrm{mech,fluid}}\right|} = \frac{800\ \mathrm{kW}}{1031\ \mathrm{kW}} = 0.776 \text{ or } 77.6\%$$

$$\eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|} = \frac{750 \text{ kW}}{1031 \text{ kW}} = 0.727$$

or 72.7%

- The reservoir supplies 1031 kW of mechanical energy to the turbine, which converts 800 kW of it to shaft work that drives the generator, which then generates 750 kW of electric power.

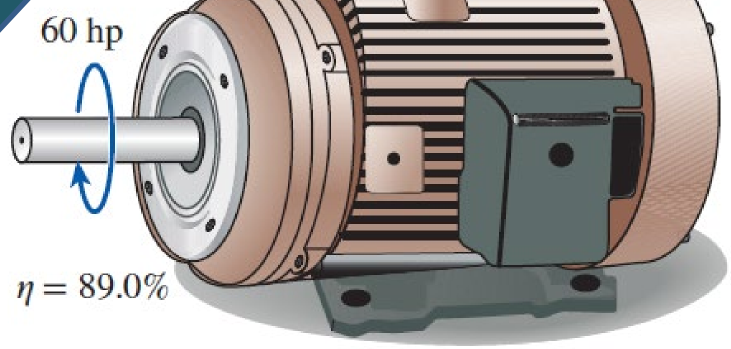
- This problem can also be solved by taking point 1 to be at the turbine inlet and using flow energy instead of potential energy. It would give the same result since the flow energy at the turbine inlet is equal to the potential energy at the free surface of the reservoir.

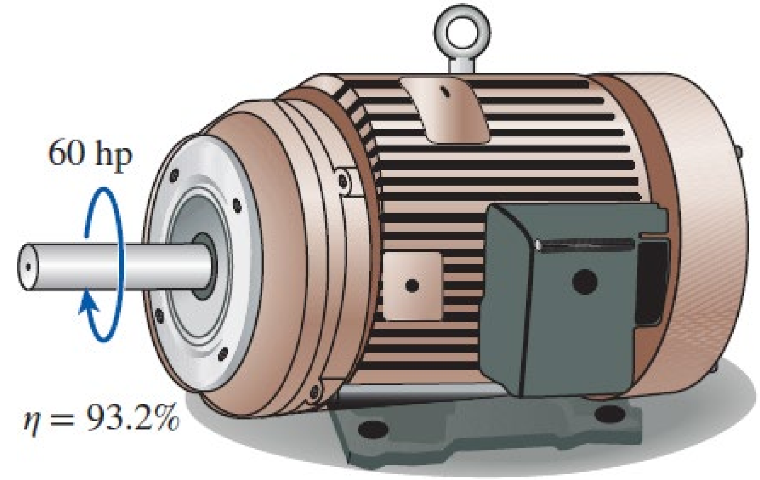
Ex. Cost Saving of High-Efficiency Motors

- A 60-hp electric motor (*i.e., delivers 60 hp of shaft power at full load*) that has an efficiency of 89.0 % is worn out and is to be replaced by a 93.2 % efficient high-efficiency motor. The motor operates 3500 h a year at full load. Taking the unit cost of electricity to be $0.08/kWh, determine the amount of energy and money saved by installing the high-efficiency motor instead of the standard motor. Also, determine the simple payback period if the purchase prices of the standard and high-efficiency motors are $4520 and $5160, respectively.

Assumptions The load factor (LF) of the motor remains constant at 1 (full load) when operating.

Answer





Standard motor High-Eff. motor

The electric power drawn by motors

$$\dot{W}_{\text{electric,in,standard}} = \frac{\dot{W}_{\text{shaft}}}{\eta_{\text{st}}} = \frac{(\text{Rated power})\,(\text{LF})}{\eta_{\text{st}}}$$

$$\dot{W}_{\text{electric,in,eff}} = \frac{\dot{W}_{\text{shaft}}}{\eta_{\text{eff}}} = \frac{(\text{Rated power})\,(\text{LF})}{\eta_{\text{eff}}}$$

$$\text{Power Saving} = \dot{W}_{\text{electric,in,standard}} - \dot{W}_{\text{electric,in,eff}}$$

$$= (\text{Rated power})\,(\text{LF})\left(\frac{1}{\eta_{\text{st}}} - \frac{1}{\eta_{\text{eff}}}\right)$$

$$\text{Energy Saving} = (\text{Power Saving})\,(\text{Operating hours})$$

$$= (\text{Rated power})(\text{Operating hours})(\text{LF})\left(\frac{1}{\eta_{\text{st}}} - \frac{1}{\eta_{\text{eff}}}\right) =$$

$$(60\ \text{hp})\left(\frac{0.7457\ \text{kW}}{\text{hp}}\right)(3500\ \text{h/year})(1)\left(\frac{1}{0.89} - \frac{1}{0.932}\right) =$$

$$7929\ \text{kWh/year}$$

$$\text{Cost Savings} = (\text{Energy Saving})\,(\text{Unit Cost})$$

$$= (7929\ \text{kWh/year})(\$0.08/\text{kWh}) = \$634/\text{year}$$

$$\text{Excess Initial Cost} = \text{Purchase Price diff.} = \$5160 - \$4520 = \$640$$

$$\text{Simple payback period} = \frac{\text{Excess Initial Cost}}{\text{Annual cost savings}} = \frac{\$640}{\$634/\text{year}} = 1.01\ \text{y}$$

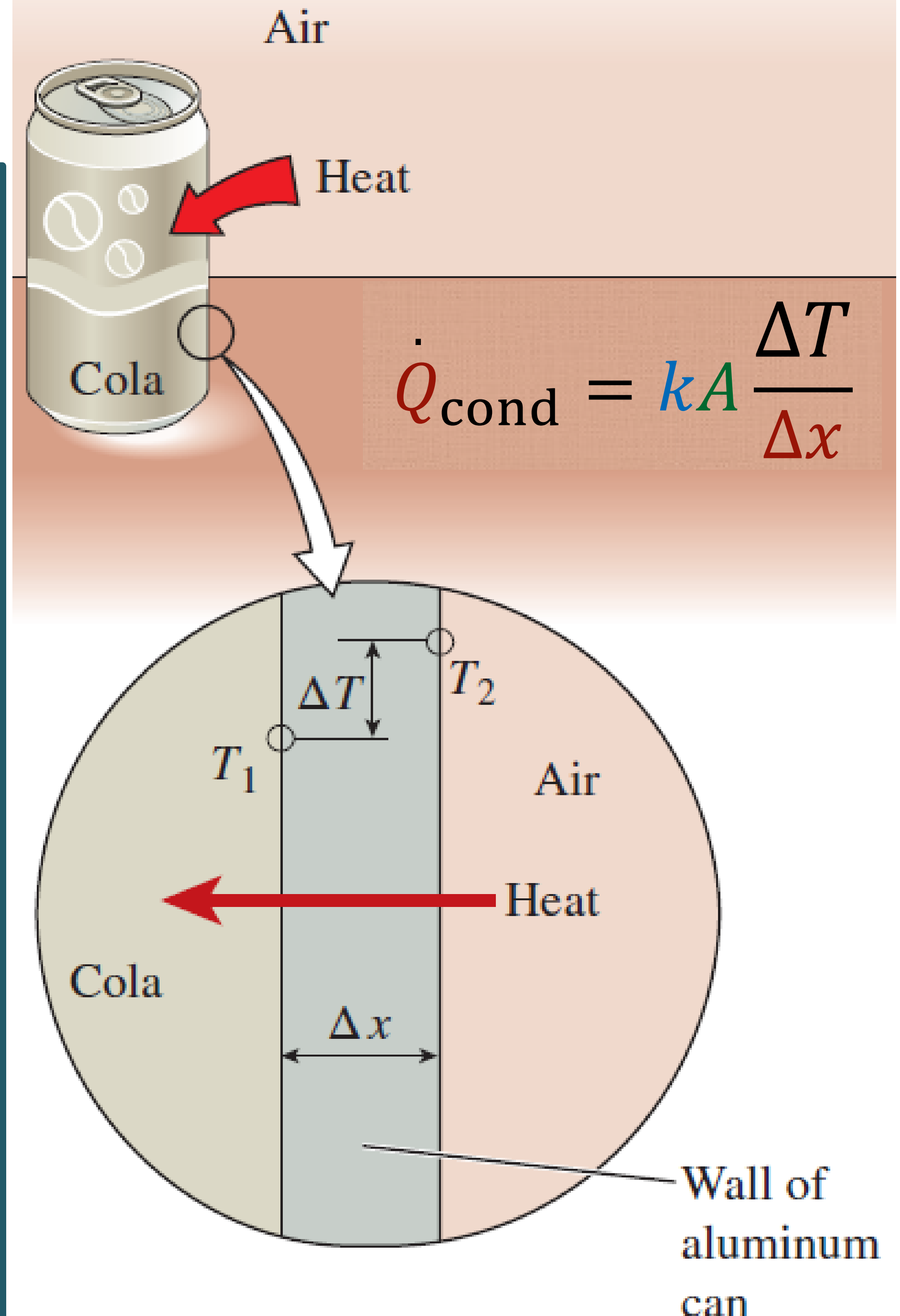
Mechanisms
of
Heat Transfer

Conduction, Convection & Radiation

Conduction

- is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones by interactions between the particles.

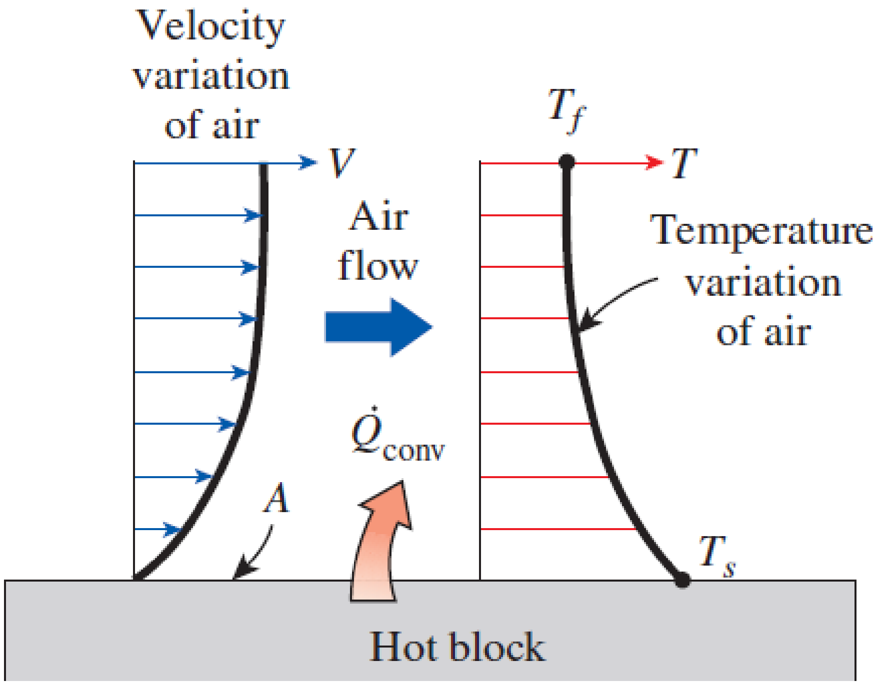
- $\dot{Q}_{\text{cond}}$ is the rate of heat conduction, k is the thermal conductivity, A is the area and Δx is the thickness



$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{\Delta x}$$

Convection

- is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion.
- It involves the combined effects of *conduction* and *fluid motion*.



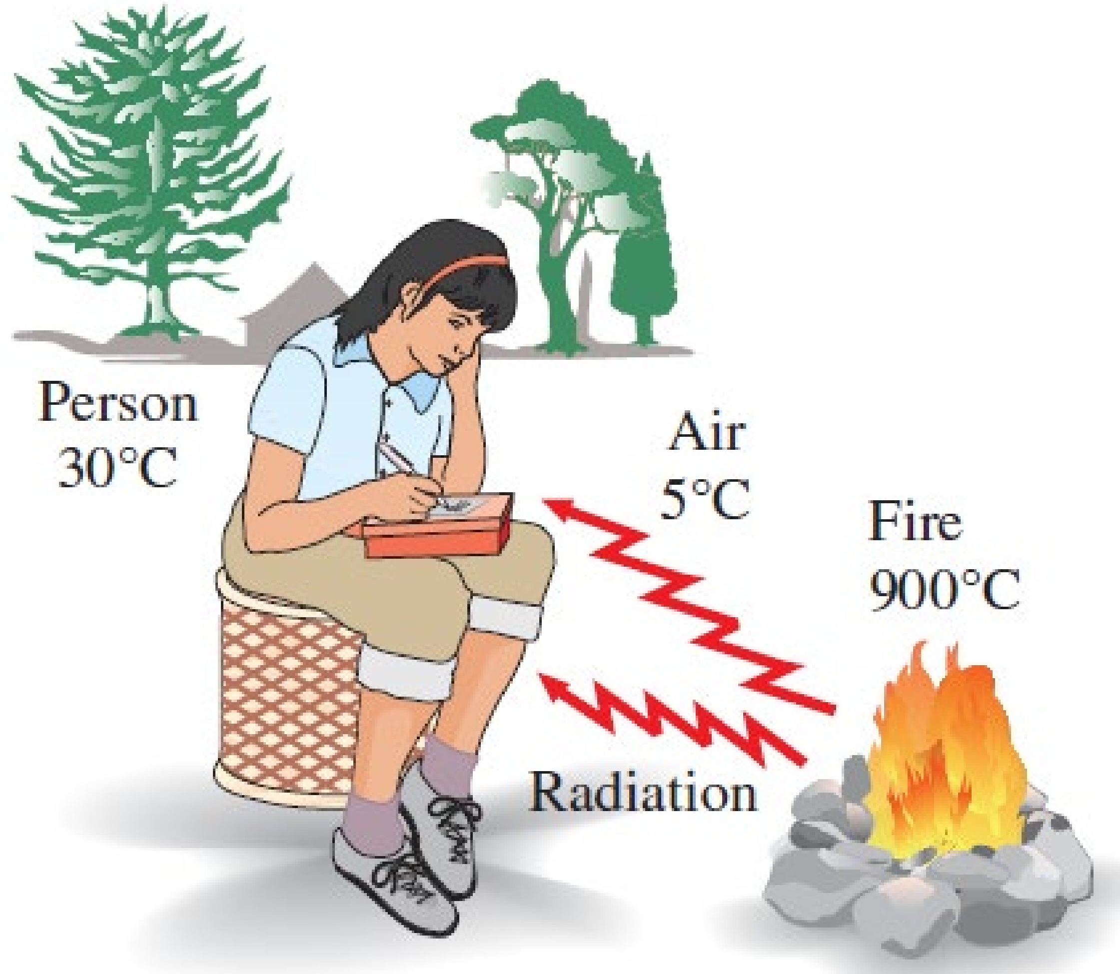
Cooling of a hot block by blowing cool air over its top surface.

Energy is first transferred to the air layer adjacent to the surface of the block by **conduction**. This energy is then carried away from the surface by the combined effects of **conduction** and convection (bulk **motion** ↑) within the air.

Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection

Radiation

- is the energy emitted by matter in the form of electromagnetic waves (or **photons**) by the changes in the electronic configurations of the atoms or molecules.



- Unlike conduction and convection, the transfer of energy by radiation is much faster and does not require the presence of an intervening medium.