Thermodynamics

Chem 211: Lecture 4

1st law of Thermodynamics

Energy Transfer

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Nonmechanical Work

- can be treated similarly by identifying a *generalized force* (*F*) acting in the direction of a *generalized displacement* (*x*).
- **Electrical work**, where F is the *voltage* (the *electrical potential*) and x is the *electrical charge*.
- **Magnetic work**, where F is the *magnetic field strength* and x is the *total magnetic dipole moment*.
- **Electrical polarization work**, where F is the *electric field strength* and x is *the polarization of the medium* (the sum of the electric dipole rotation moments of the molecules)

CYU

- Which of the following is *not* mechanical work?

(A) Spring work

(B) Shaft work

(C) Electrical work

(D) Work to accelerate a body

(E) Work for stretching of a liquid film

Answer √ **(C) Electrical work**

1^{st} Law of Thermodynamics

1st law of Thermodynamics

- It is also known as *the* ***conservation of energy principle***.
- It provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- Based on experimental observations, the first law of thermodynamics states that ***energy can be neither created nor destroyed during a process; it can only change forms***.
- Therefore, every bit of energy should be accounted for during a process.
- **Thermodynamics** provides no information about the **absolute** value of the total energy. It deals only with the change of the total energy

1st law: 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

- (no change in KE and PE under the influence of external (not internal) effects increasing the system's velocity or changing the system's height as a whole)

$$\Delta E = \Delta U$$

Note: U involves another internal type of KE and PE

- ΔE and ΔU of a system is inspired by
  - mass transfer (m),
  - heat transfer, Q
  - Work, W

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

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

or, in the rate form, as

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

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,

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

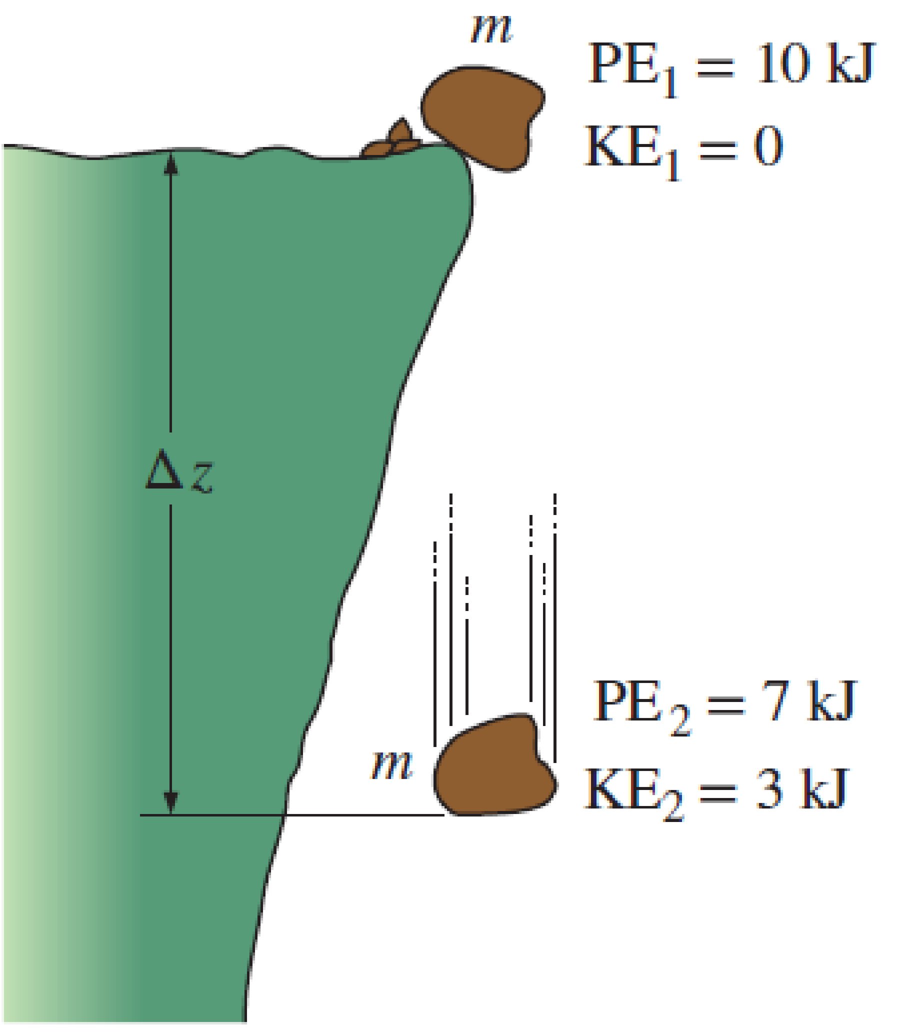
Equation of State

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

- The change in internal energy of a **closed system** is equal to the energy that passes through its boundary as heat 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).

Total Energy, E

- A major consequence of the first law is the existence and the definition of the property ***total energy, E***.
- Considering that the net work (that is **non-state** function or **pathway** dependent) is the same for all adiabatic processes of a closed system between two specified states, the value of 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*** (**W** is not a property as it is recognized at the interface).
- The first law also states that "the *change* in the total energy during an adiabatic process must be equal to the net work done".

Adiabatic Processes

- processes involving No **heat transfer**.
  - (Adiabatic + Closed) ≠ Adiabatic ≠ Isolated ($\Delta E=0$)

- may involve several kinds of work interactions.

- For all adiabatic (no heat transfer) ***processes*** (must involve a change in a property "total E") between Two specified states of a **closed system** (no mass transfer), the **net work** done is the same regardless of the nature of the closed system and the details of the process.

Closed Adiabatic Systems

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

- For all adiabatic processes (Q = 0) between two specified states of a closed system (no mass transfer), the net work (which is assumed path dependent) done is the same regardless of the nature of the closed system and the details of the process.

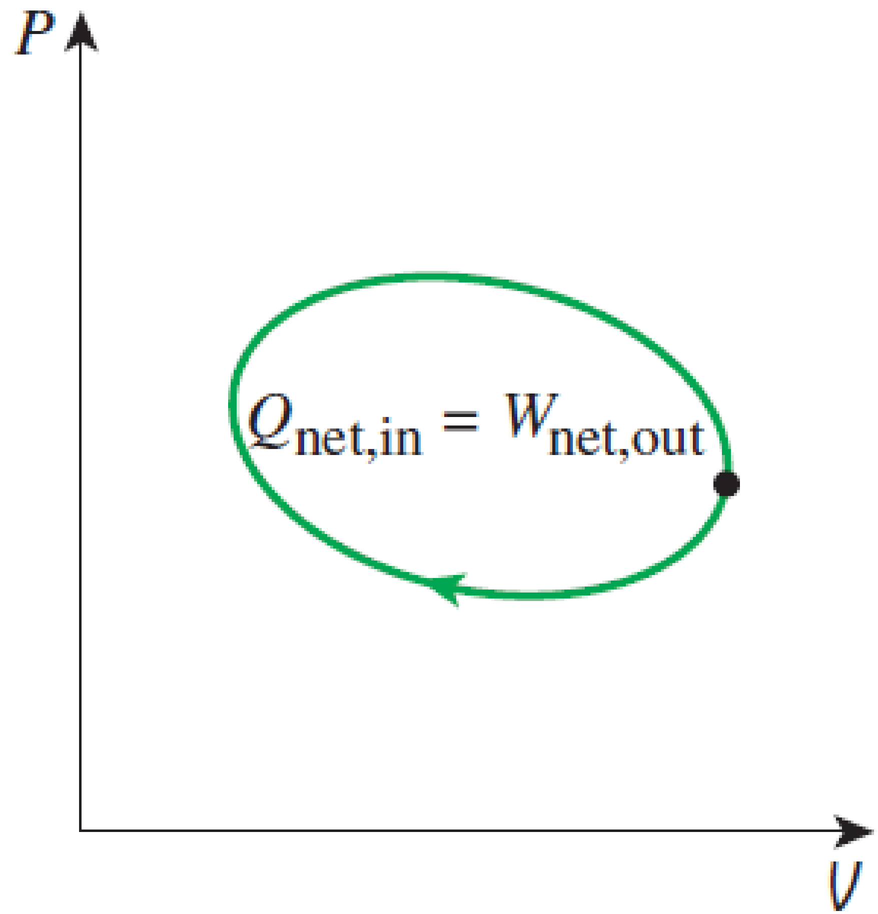
Closed Cycled Systems

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

- Net heat input is equal to net work output.

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

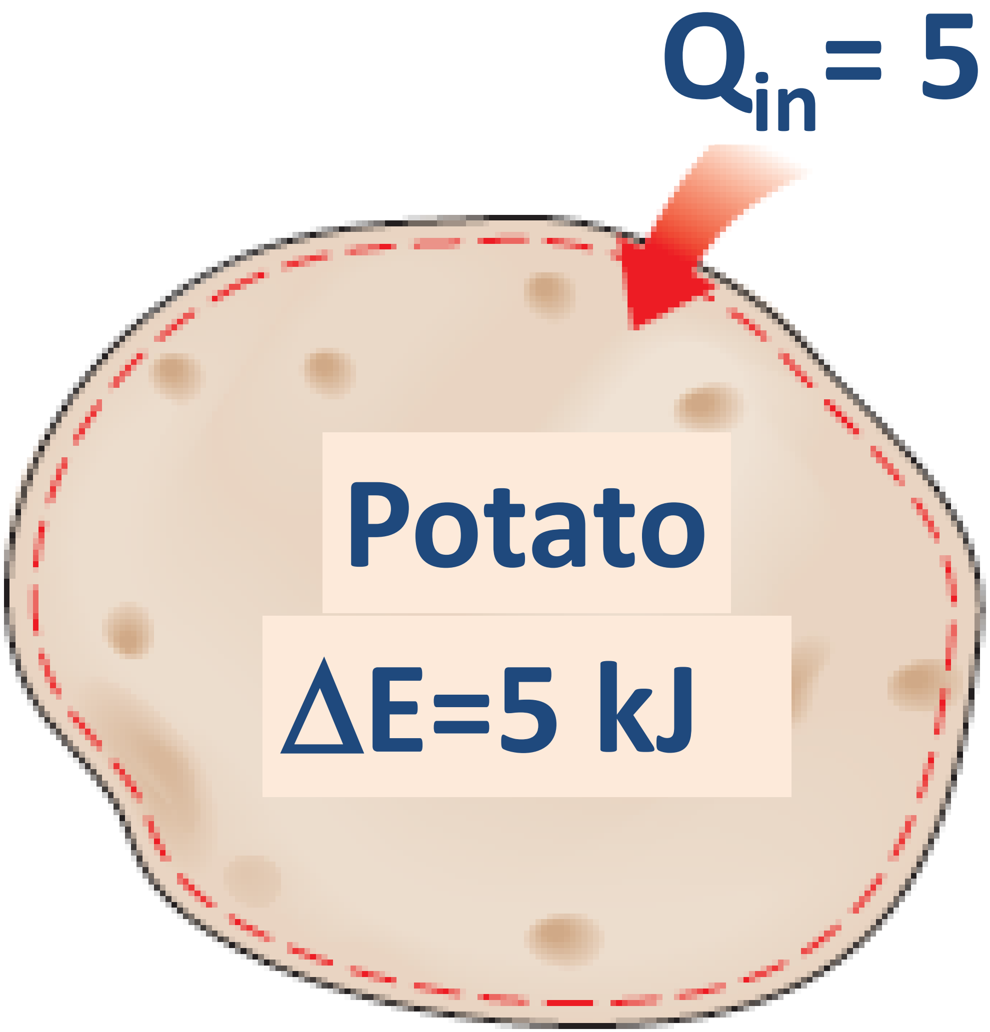
$$\dot{W}_{net,out} = \dot{Q}_{net,in}$$



Baked potato in an oven

Potato = sys

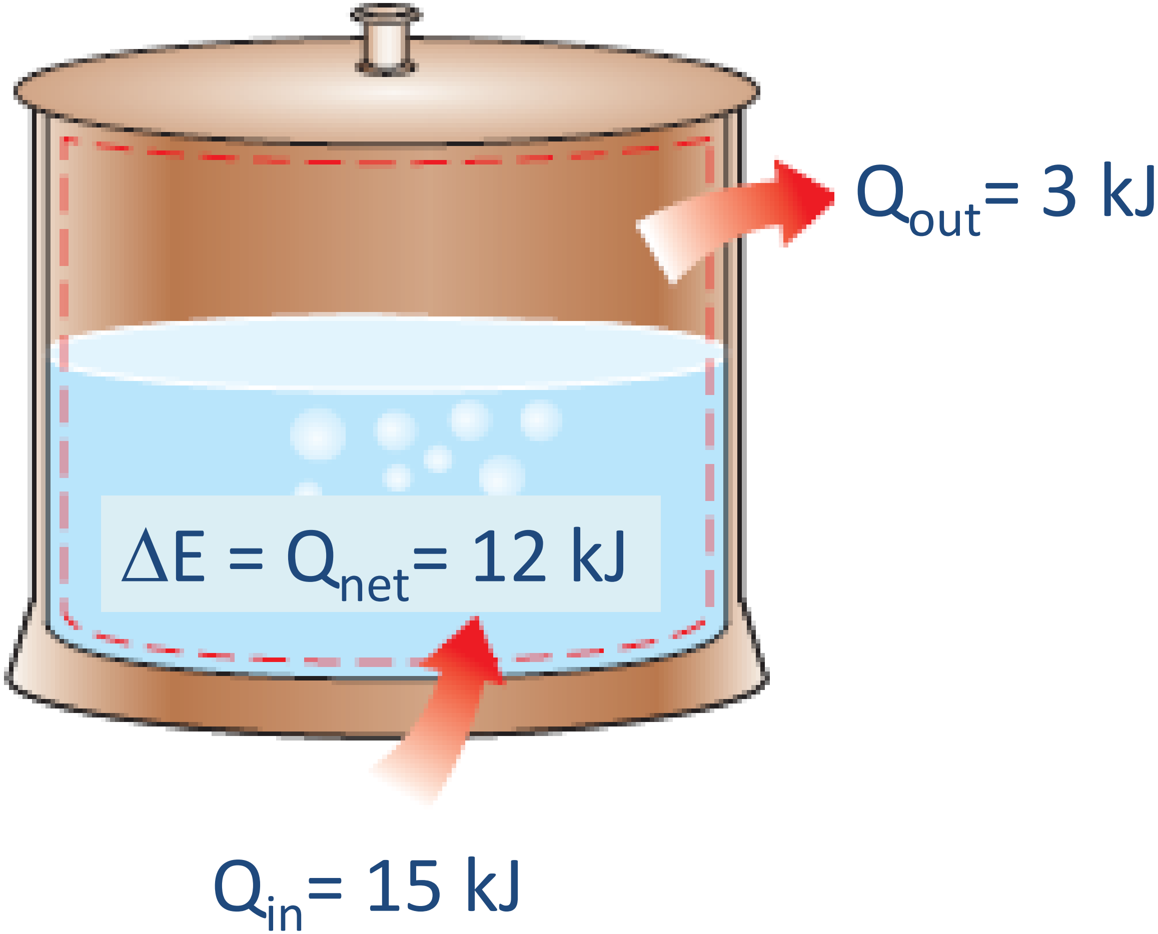
Disregarding any mass transfer (moisture loss from the potato),



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

Heating water in a pan on top of a range

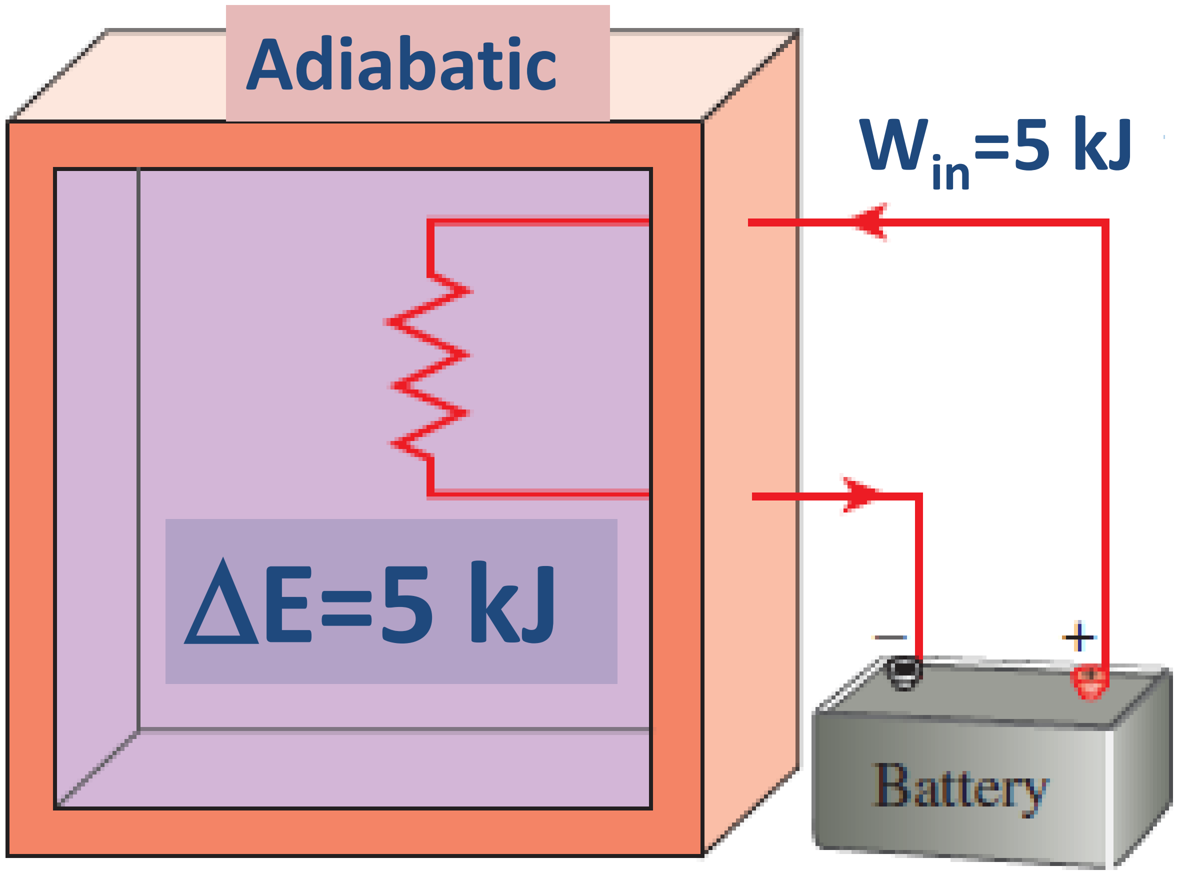
- 15 kJ of heat is transferred to the water from the heating element
- 3 kJ of heat is lost from the water to the surrounding air



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

Adiabatic room heated by an electric heater

- The electrical work done increases the system's energy.
- As Q=0, the electrical work done on the system must equal ΔE.

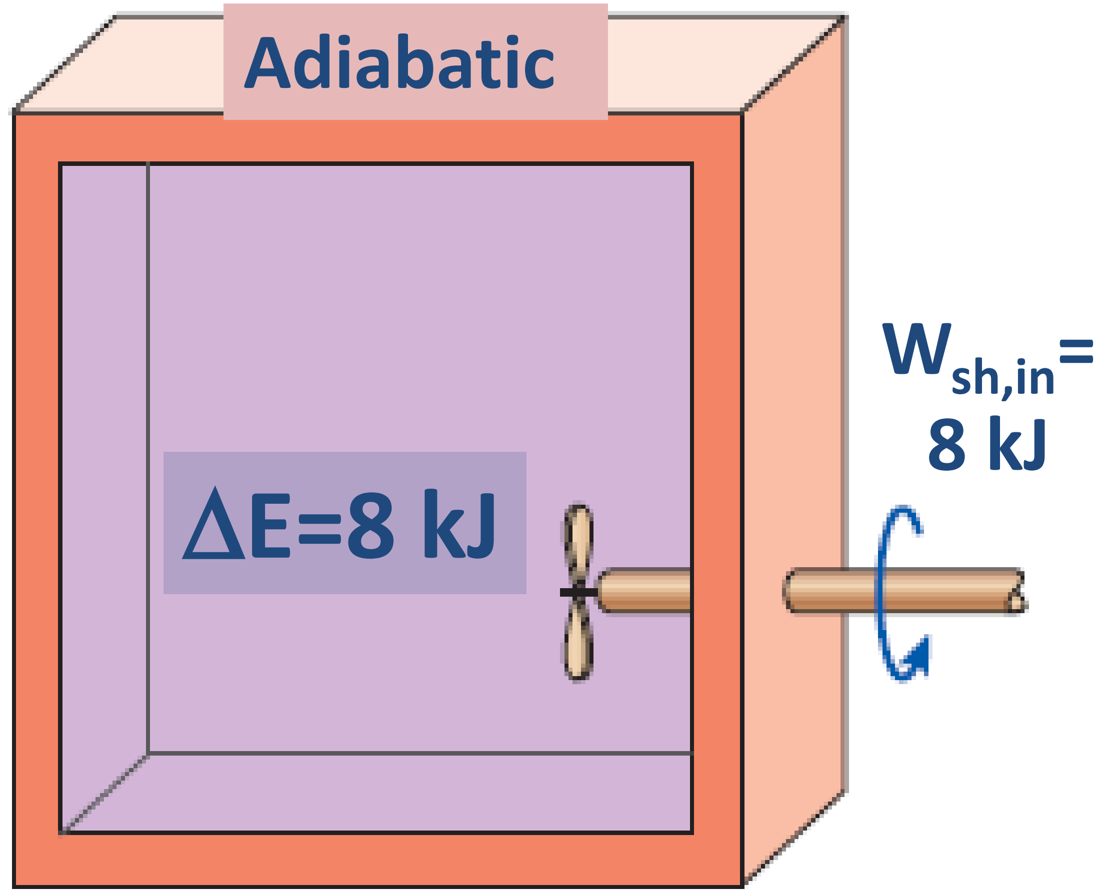


$$\Delta E_{system} = W_{electrical} = 5\ kJ$$

Adiabatic room with a paddle wheel

- The stirring process will increases the system's energy.

- As Q = 0, the shaft work done on the system must equal ΔE.

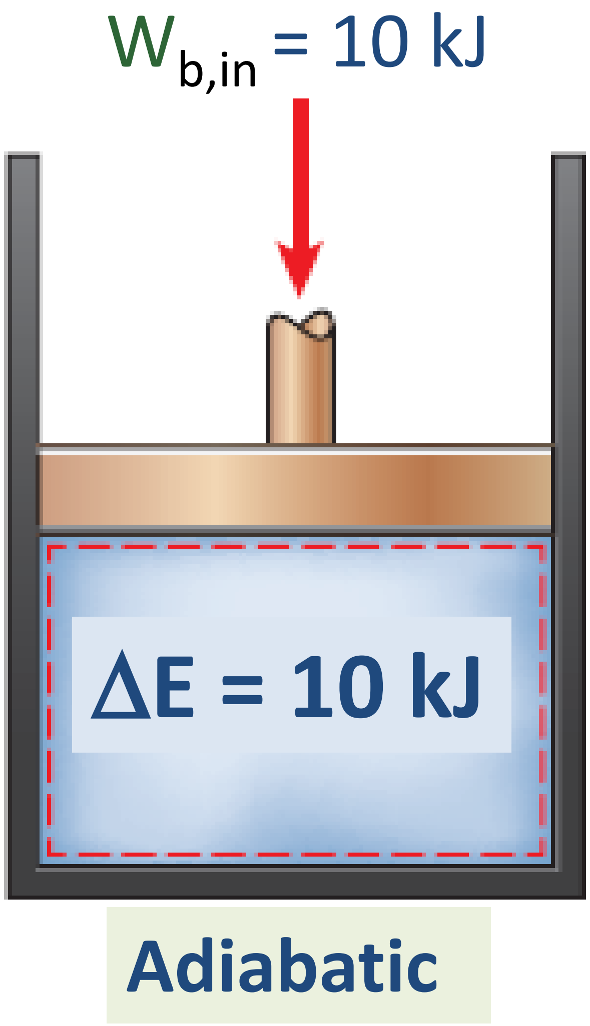


$$\Delta E_{system} = W_{shaft} = 8\ kJ$$

Rising of air T if adiabatically compressed

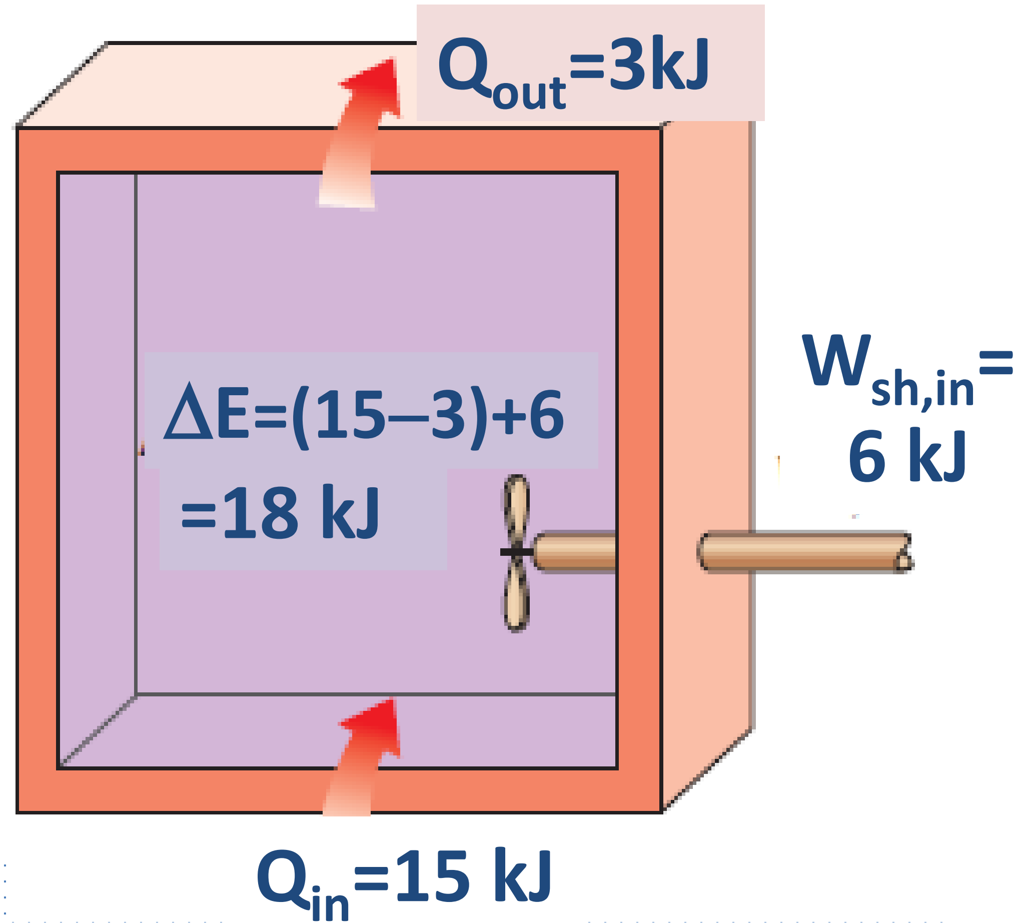
- Because energy is transferred to the air in the form of boundary work ($W_{b,in}$).
- As ($Q = 0$), the entire $W_{b,in}$ will be stored in the air as part of its *total energy*, *E*.

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



A room with a paddle wheel/heat transfer

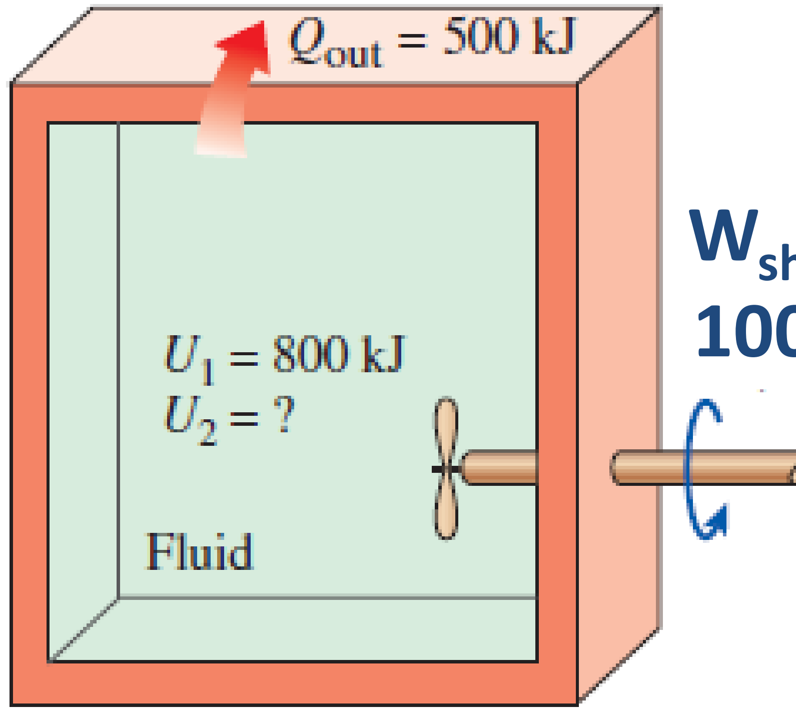
- The system gains 15 kJ of heat and loses 3 kJ of heat.
- 6 kJ of work is done on the system,



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

Cooling of a hot fluid in a tank

- 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. Neglect the energy stored in the paddle wheel.



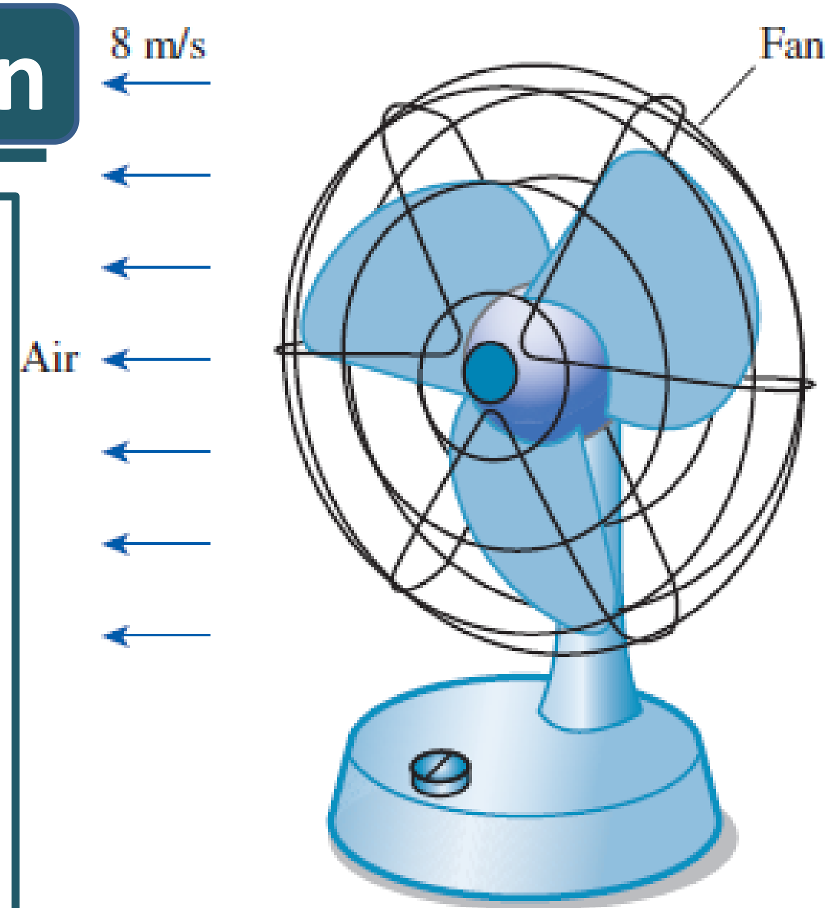
$W_{sh,in}$ = 100 kJ

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

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

Accelerated air by a fan

- A fan that consumes 20 W of electric power when operating is claimed to discharge air from a ventilated room at a rate of 1.0 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.

- Therefore, 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

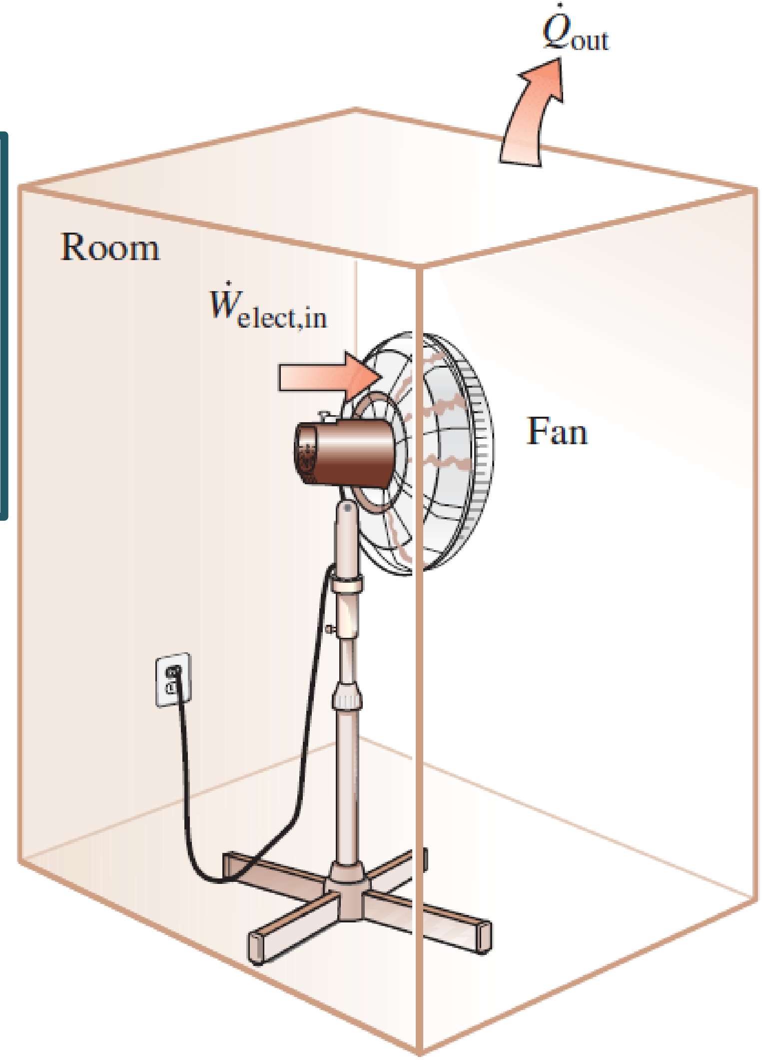
Heating Effect of a Fan

- 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/m².°C is the overall heat transfer coefficient, A = 30 m² 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).



$$\dot{E}_{in} - \dot{E}_{out} = {}^{dE_{system}}/_{dt}$$

At steady state $$\dot{E}_{in} - \dot{E}_{out} = {}^{dE_{system}}/_{dt} = 0$$

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

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

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

$$T_i = 26.1^oC$$

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

- For a fan, the motor converts part of the electric energy to mechanical energy in the form of a rotating shaft, while the remaining part is dissipated as heat to the room air because of the motor inefficiency (no motor converts 100 % of the electric energy it receives to mechanical energy, although some large motors come close with a conversion efficiency of over 97 %).
- Part of the mechanical energy of the shaft is converted to kinetic energy of air through the blades, which is then converted to thermal energy as air molecules slow down because of friction. At the end, the entire electric energy drawn by the fan motor is converted to thermal energy of air, which manifests itself as a rise in T.

Annual Lighting Cost 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 hours 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.

- The electric power consumed by the lamps when all are on and the number of hours they are kept on per year are

Lighting power = (Power per lamp) × (No. of lamps)

= (80 W/lamp)(30 lamps) = 2400 W = 2.4 kW

Operating hours = (12 h/day)(250 days/year) = 3000 h/year

Lighting energy = (Lighting power)(Operating hours)

= (2.4 kW)(3000 h/year) = 7200 kWh/year

Lighting cost = (Lighting energy)(Unit cost) =

(7200 kWh/year)($0.11 / kWh) = $792 / year

Note

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.
- Therefore, the lighting system in this room reduces the heating requirements by 2.4 kW but increases the 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 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**

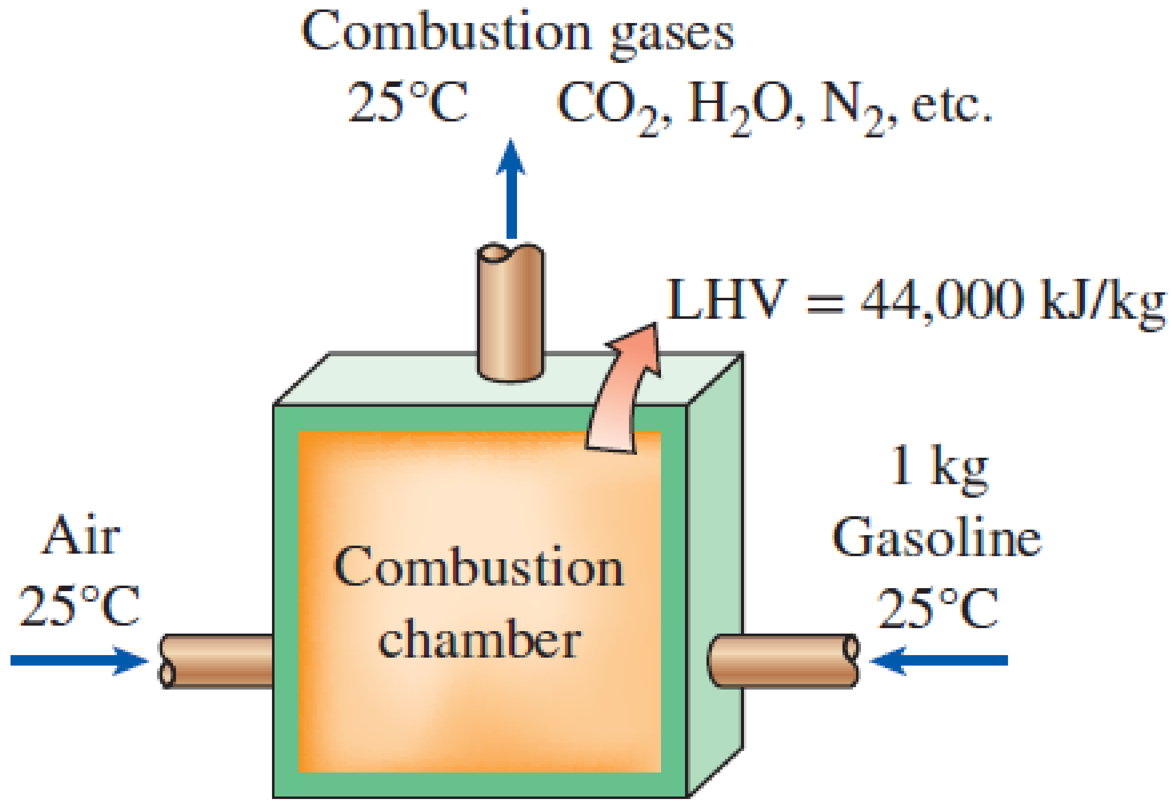
Energy Conversion Efficiency

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

- η of 90% of a conventional electric water heater (represents 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 of the fuel **(HV)**.



- **(HV):** 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*.

Combustion equipment efficiency η_{comb} of Gas water heaters

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

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

- 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.

- This efficiency can take different names, depending on the type of the combustion unit such as furnace efficiency, $\eta_{furnace}$, boiler efficiency, η_{boiler}, or heater efficiency, η_{heater}.

- Most fuels contain **hydrogen**, which forms water when burned, and the heating value of a fuel will be different depending on whether the water in combustion products is in the liquid or vapor form.

- The heating value is called the lower heating value, or **LHV**, when the water leaves as a vapor, and the higher heating value, or **HHV**, when the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

$$\mathbf{LHV = HHV - m\,\Delta H_{vap}} \Rightarrow \mathbf{LHV + m\Delta H_{vap} = HHV}$$

- 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.

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**, $\eta_{generator}$, 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 effects of other factors are incorporated by defining an **overall efficiency, η_{overall},** for the power plant as the ratio of the *net electrical power output* to the *rate of fuel energy input.*

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

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

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

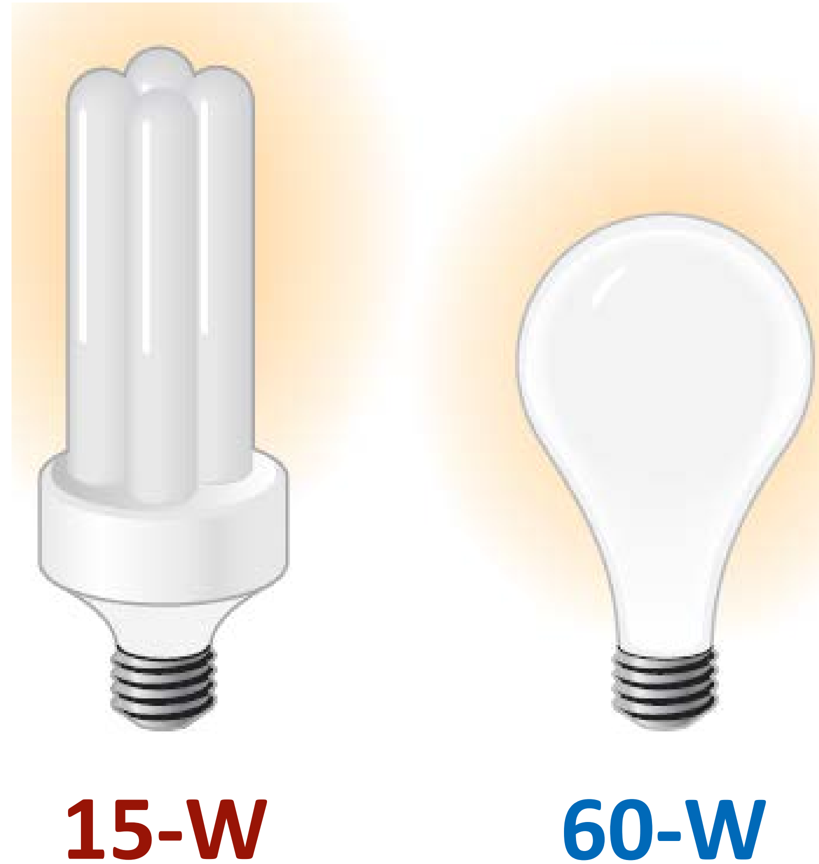
Electricity to light conversion

- This is known in incandescent lightbulbs, fluorescent tubes, and high-intensity discharge lamps.
- η is defined as the ratio of the energy converted to light to the electrical energy consumed.
  - **For example**, common incandescent lightbulbs convert about 5% of the electrical energy they consume to light; the rest of the energy consumed is dissipated as heat, which adds to the cooling load of the air conditioner in summer.
- It is more common to express the **effectiveness** of this conversion process by *lighting efficacy* (efəkəsē, فعالية), which is defined as the amount of light output in **lumens** per **W** of electricity consumed.

Efficacy (lm/W) of different lighting systems

Type of lighting	Examples	Efficacy, lumens/W
Combustion	Candle Kerosene lamp	0.3 1–2
Incandescent	Ordinary Halogen	6–20 15–35
Fluorescent	Compact Tube	40–87 60–120
High-intensity discharge	Mercury vapor Metal halide High-pressure sodium Low-pressure sodium	40–60 65–118 85–140 70–200
Solid-State	LED OLED	20–160 15–60
Theoretical limit		300*

- A 15-W compact fluorescent lamp provides as much light as a 60-W incandescent lamp.
- It also lasts about 10,000 h, which is 10 times as long as an incandescent bulb, and it plugs directly into the socket of an incandescent lamp.

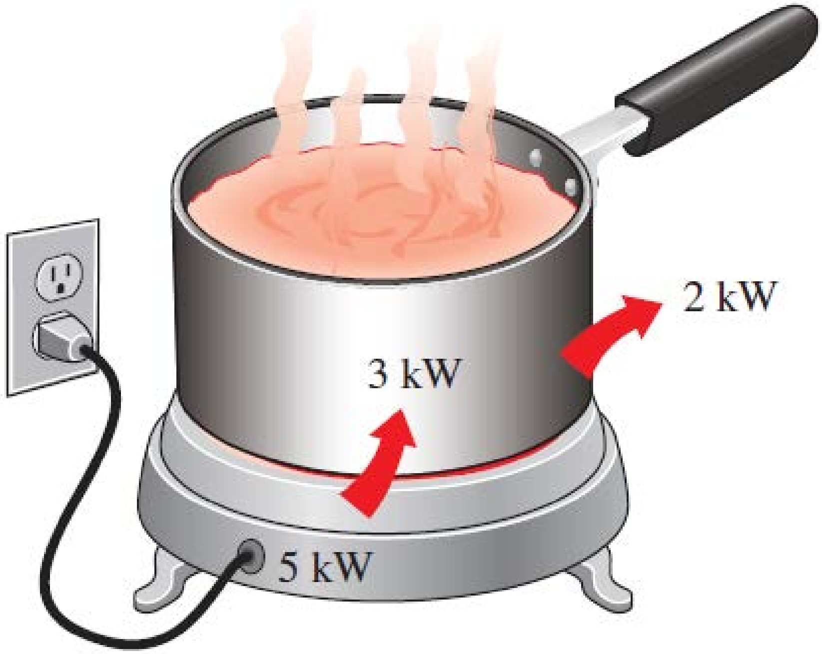


- Despite their *higher initial cost*, *compact fluorescents* reduce the lighting costs considerably through reduced electricity consumption.

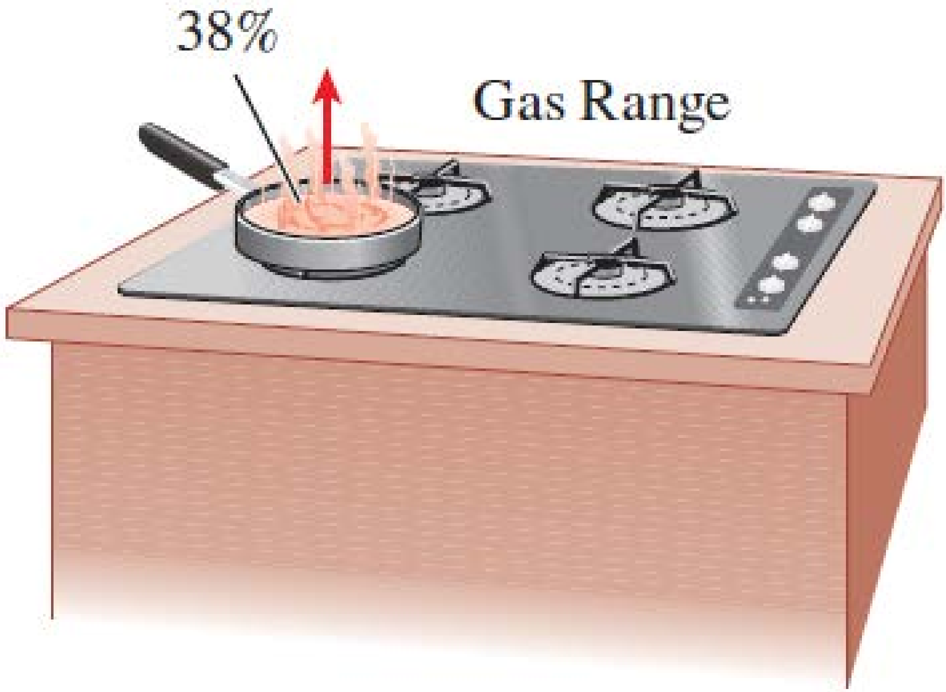
Electricity of cooking appliances

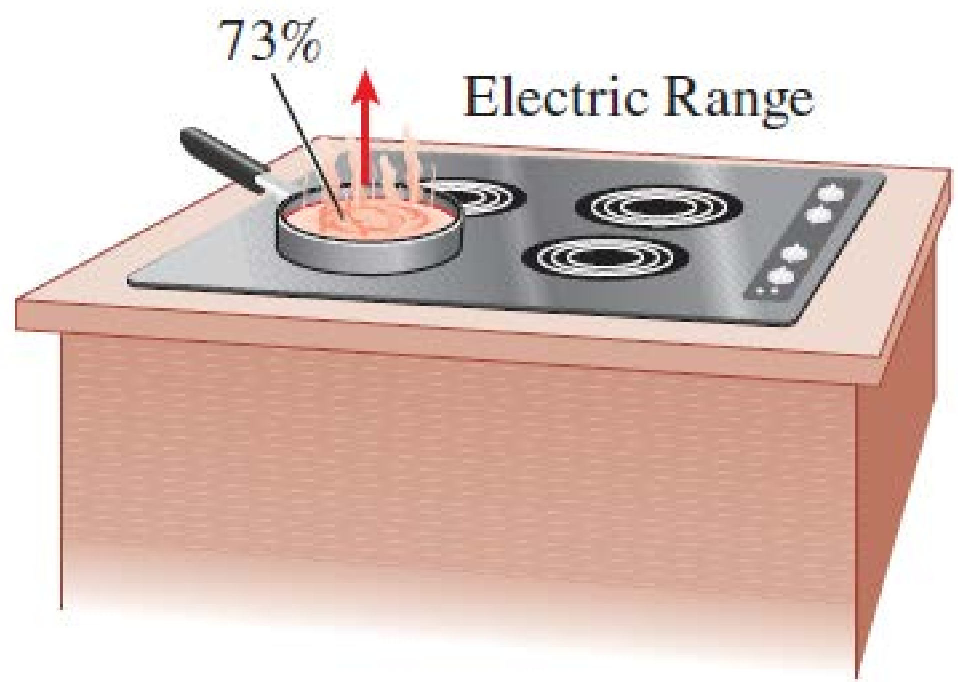
- They convert *electrical* or *chemical* energy to heat.
- η is defined as the ratio of the useful energy transferred to the food to the energy consumed by the appliance.

- Electric ***ranges*** are more efficient than gas ***ranges***, but it is much cheaper to cook with natural gas than with electricity because of the lower unit cost of natural gas



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


38%
Gas Range


73%
Electric Range

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) and **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 that will do the job,
- using the smaller heating element for small pans on electric ranges,
- using flat-bottomed pans on electric burners to assure good contact.

η can be increased by:

- 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.

Example: 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:

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

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

<u>Note:</u> **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, such as 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:

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

Pumps

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

- A mechanical efficiency of 97% indicates that 3% of the mechanical energy input is converted to thermal energy as a result of frictional heating, and this will manifest itself as a slight rise in the temperature of the fluid.
- 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).

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.

- The degree of perfection of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by :

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

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

$\dot{W}_{\text{pump,u}}$: **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.

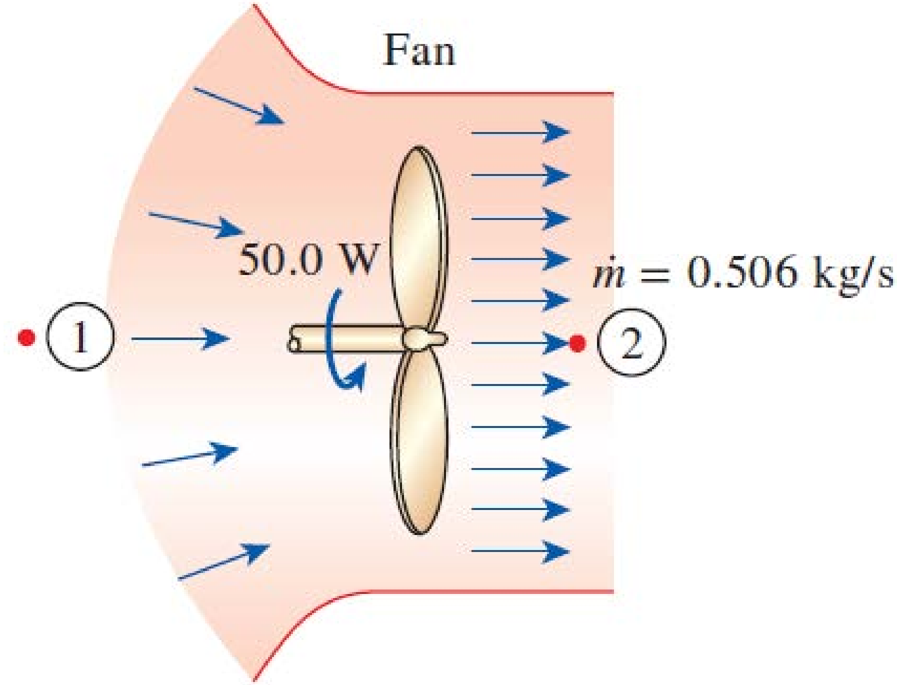
$$\eta_{\text{turbine}} = \frac{\text{Mech. E output}}{\text{Mech E decrease of fluid}}$$

$$= \frac{\dot{W}_{\text{shaft},in}}{\left|\Delta\dot{E}_{\text{mech,fluid}}\right|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine},e}}$$

where $\left|\Delta\dot{E}_{\text{mech,fluid}}\right| = \dot{E}_{\text{mech},in} - \dot{E}_{\text{mech},out}$ 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:

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

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

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

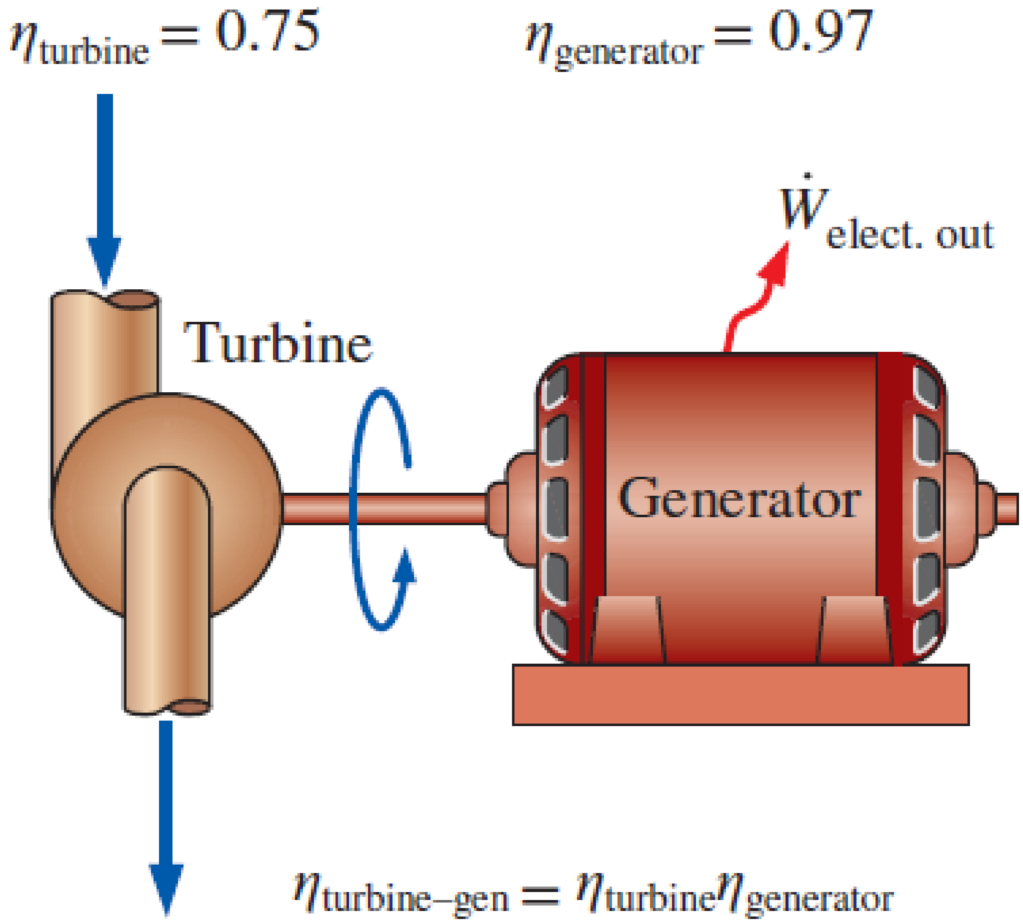
- A pump is usually packaged together with its motor, and a turbine with its generator.
- Therefore, we are usually interested in the ***combined*** or **overall** efficiency of pump–motor and turbine–generator combinations:

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

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

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

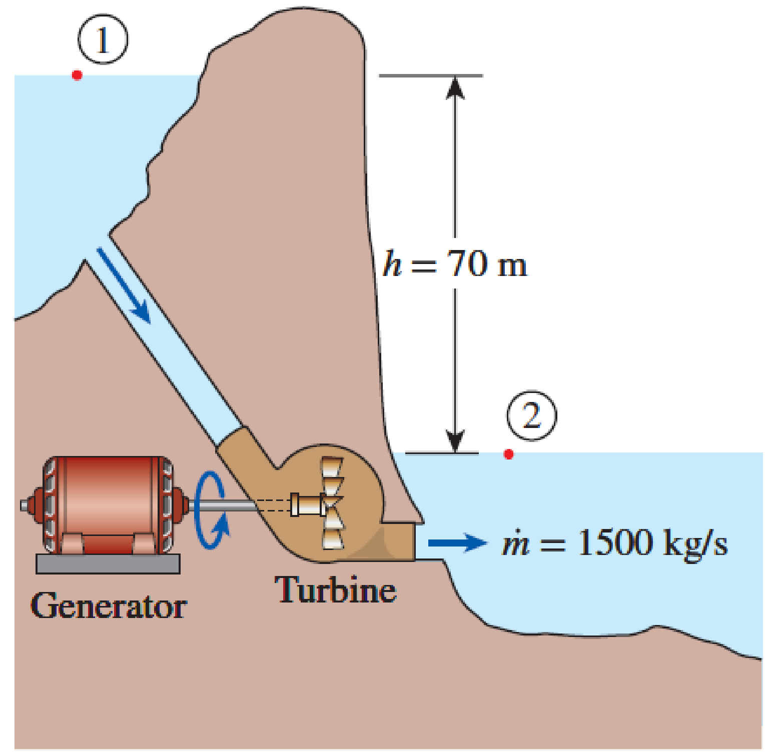
$$= \frac{\dot{W}_{\text{turbine},in}}{\dot{W}_{\text{turbine,e}}} \times \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},in}} = \frac{\dot{W}_{\text{elect,out}}}{\left|\Delta \dot{E}_{\text{mech,fluid}}\right|}$$



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

Example: 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

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

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

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

$$\eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect,out}}}{\left|\Delta \dot{E}_{\text{mech,fluid}}\right|} = \frac{750\text{ kW}}{1031\text{ kW}} = 0.727 \text{ or } 72.7\%$$

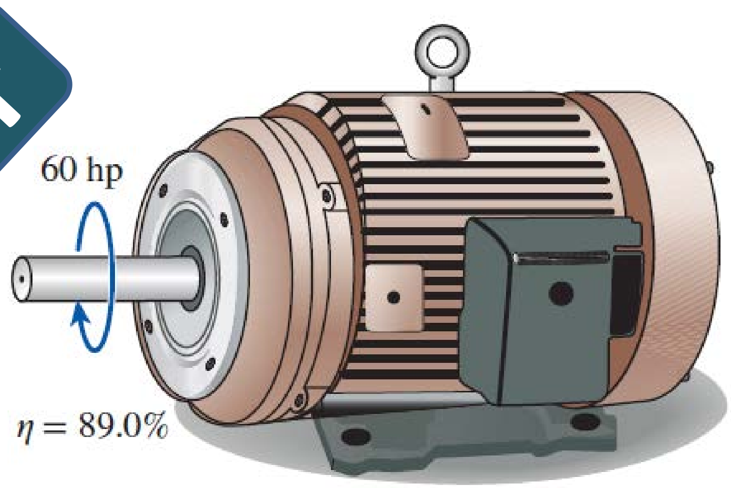
- The reservoir supplies 1031 kW of mechanical energy to the turbine, which converts 800 kW of it to shaft work that drives the generator, which then generates 750 kW of electric power.
- This problem can also be solved by taking point 1 to be at the turbine inlet and using flow energy instead of potential 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.

Example: Cost Saving of High-Efficiency Motors

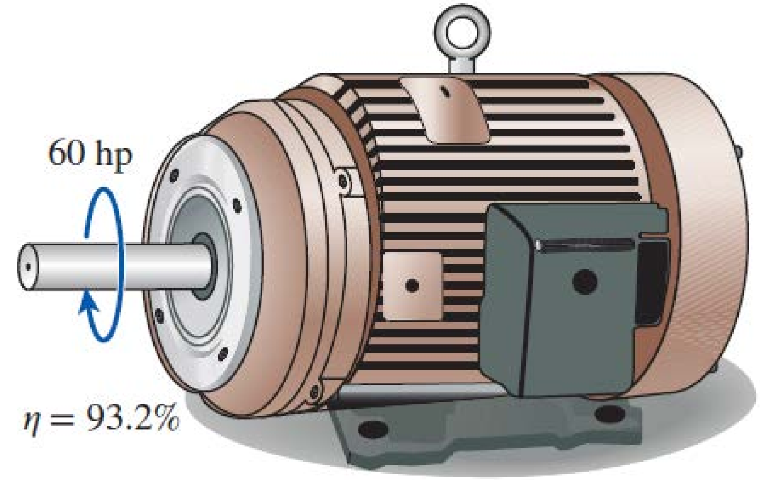
- A 60-hp electric motor (*a motor that delivers 60 hp of shaft power at full load*) that has an efficiency of 89.0 % is worn out and is to be replaced by a 93.2 % efficient high-efficiency motor. The motor operates 3500 h a year at full load. Taking the unit cost of electricity to be \$0.08/kWh, determine the amount of energy and money saved as a result of 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 of the motor remains constant at 1 (full load) when operating.

Answer



Standard motor



High-Eff. motor

The electric power drawn by motors

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

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

$$\text{Power Saving} = \dot{W}_{\text{electric,in,standard}} - \dot{W}_{\text{electric,in,eff}}$$
$$= (\text{Rated power})\,(\text{Load factor})\left(\frac{1}{\eta_{\text{st}}} - \frac{1}{\eta_{\text{eff}}}\right)$$

$$\text{Energy Saving} = (\text{Power Saving})\,(\text{Operating hours})$$
$$= (\text{Rated power})(\text{Operating hours})(\text{Load factor})\left(\frac{1}{\eta_{\text{st}}} - \frac{1}{\eta_{\text{eff}}}\right)$$
$$= (60\ \text{hp})\left(\frac{0.7457\ \text{kW}}{\text{hp}}\right)(3500\text{h/year})(1)\left(\frac{1}{0.89} - \frac{1}{0.932}\right)$$
$$= 7929\ \text{kWh/year}$$

$$\text{Cost Savings} = (\text{Energy Saving})\,(\text{Unit Cost})$$
$$= (7929\ \text{kWh/year})(\$0.08/\text{kWh}) = \$634/\text{year}$$

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

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

Mechanisms

of

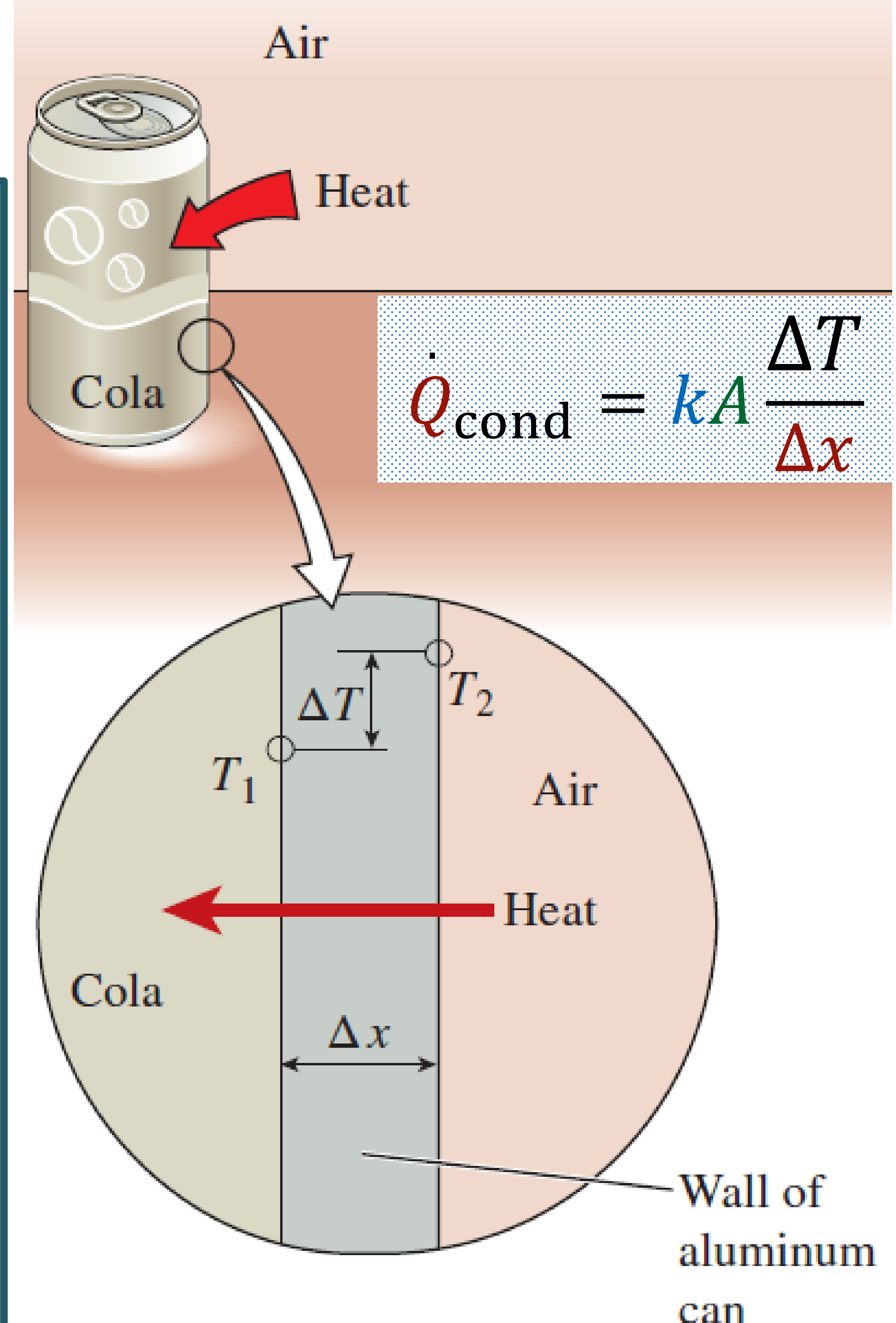
Heat Transfer

Conduction, Convection & Radiation

Conduction

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

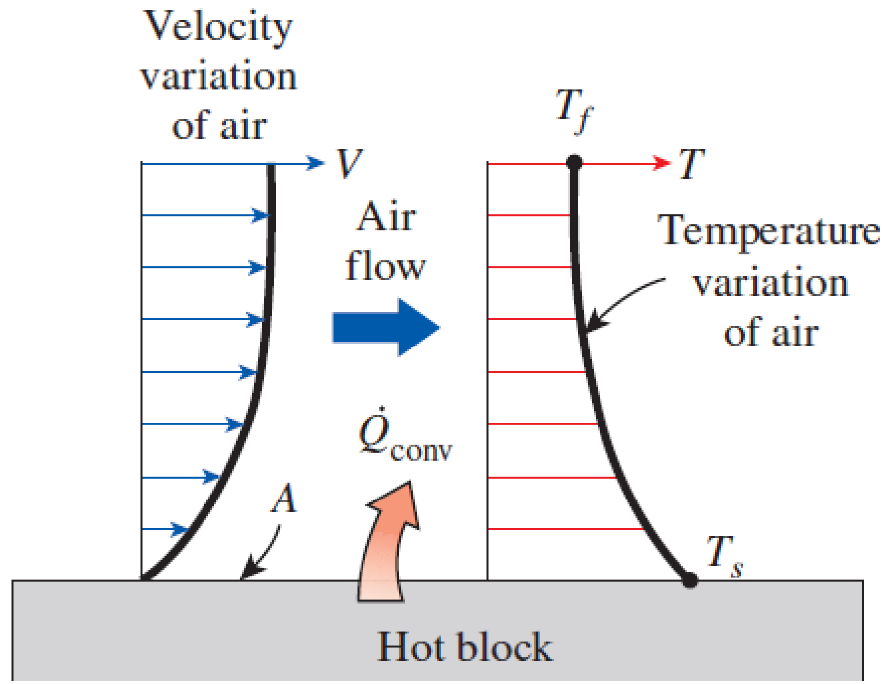
- $\dot{Q}_{\text{cond}}$ is the rate of heat conduction, k is the thermal conductivity, A is the area and Δx is the thickness



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

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*.



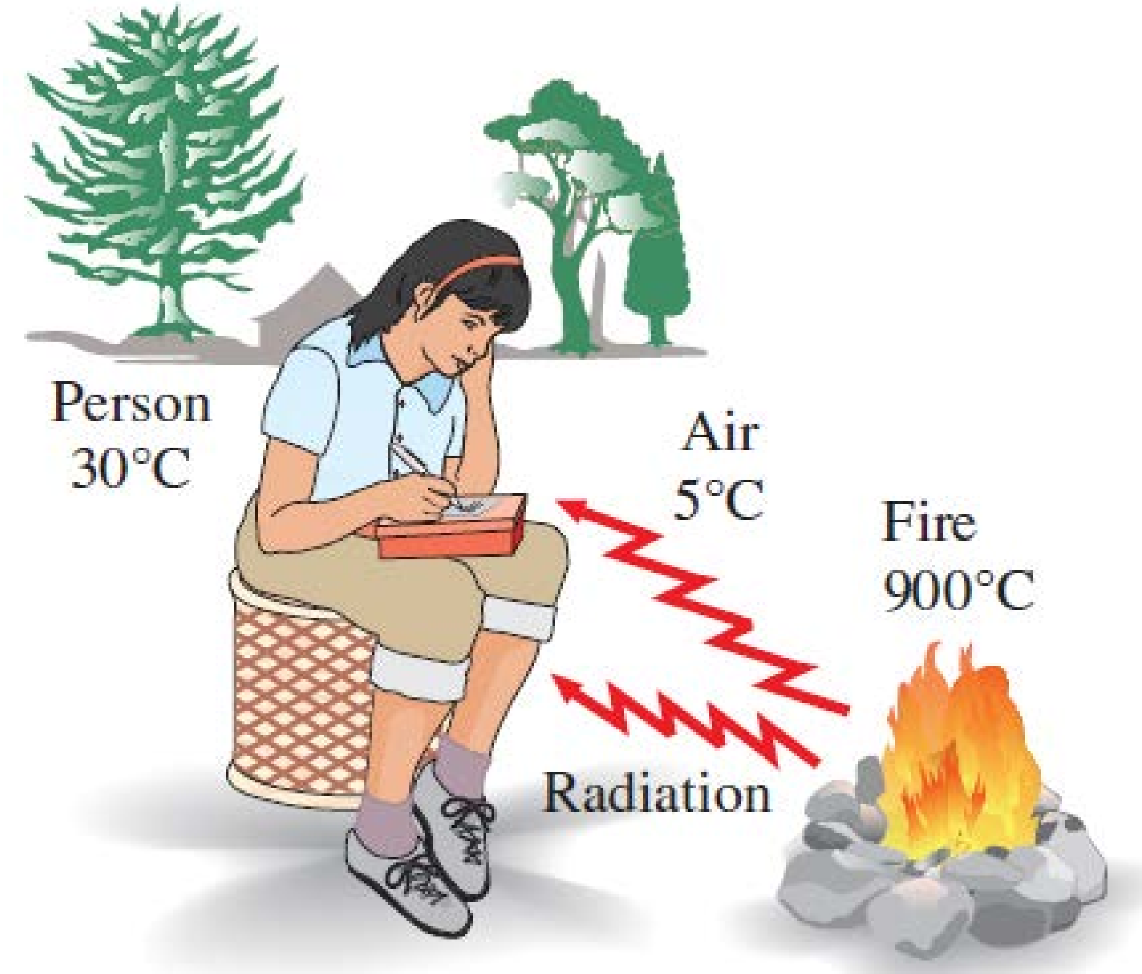
Cooling of a hot block by blowing cool air over its top surface.

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**) as a result of 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.