Thermodynamics I
Chapter 3
Energy, Heat and Work

Mohsin Mohd Sies

Fakulti Kejuruteraan Mekanikal, Universiti Teknologi Malaysia

Energy, Heat and Work (Motivation)

A system changes due to interaction with its surroundings.

Energy interaction is a major factor.

This chapter studies the nature of energy and its various forms and transfers so that we are able to follow its interaction with a system.

ENERGY & THE 1st LAW OF THERMO.

1st Law : concerning **quantity of energy**

Energy is **conserved**
(Amount of energy is constant, but can change forms)
(e.g. potential, kinetic, electrical, chemical, etc.)

$$E = Total\ system\ energy[J, kJ]$$

$$e = \frac{E}{m}\left[\frac{kJ}{kg}\right](specific\ energy)$$

Energy

- Macroscopic – system energy which value depends on a *reference point* (Kinetic Energy (KE), Potential Energy (PE)
- Microscopic – energy due to *molecular interactions & activity* (independent of any reference point) (Internal Energy, U)

Total System Energy

$$E = KE + PE + U \quad [\mathrm{kJ}]$$

$$e = ke + pe + u \quad [\mathrm{kJ/kg}]$$

Kinetic Energy (KE)

$$KE = \frac{m\vec{V}^2}{2} \qquad \Delta KE = \frac{m}{2}\left[\vec{V}_2^2 - \vec{V}_1^2\right]$$

$$ke = \frac{KE}{m} = \frac{\vec{V}^2}{2} \qquad \Delta ke = \frac{\Delta KE}{m} = \frac{(\vec{V}_2^2 - \vec{V}_1^2)}{2}$$

Potential Energy (PE)

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

$$pe = \frac{PE}{m} = gz \qquad \Delta pe = \frac{\Delta PE}{m} = g(z_2 - z_1)$$

Internal Energy, U

- Molecular movement (vibration, collision, etc) *sensible energy* (molecular activity temperature)
- Bond Energy between molecules (phase change) *latent energy* (constant temperature)
- Bond Energy between atoms in a molecule *chemical energy*
- Bond Energy between protons & neutrons in the nucleus *nuclear energy*

Specific Heats

Specific heat at constant volume, c_v: The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

Specific heat at constant pressure, c_p: The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.

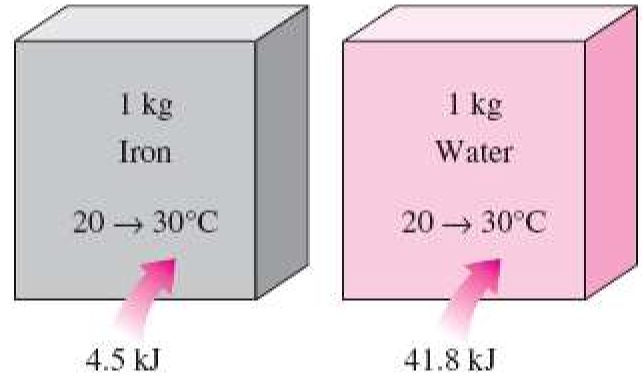


FIGURE 4–17
It takes different amounts of energy to raise the temperature of different substances by the same amount.

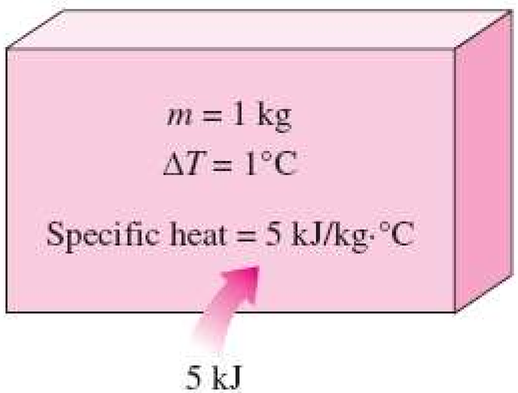
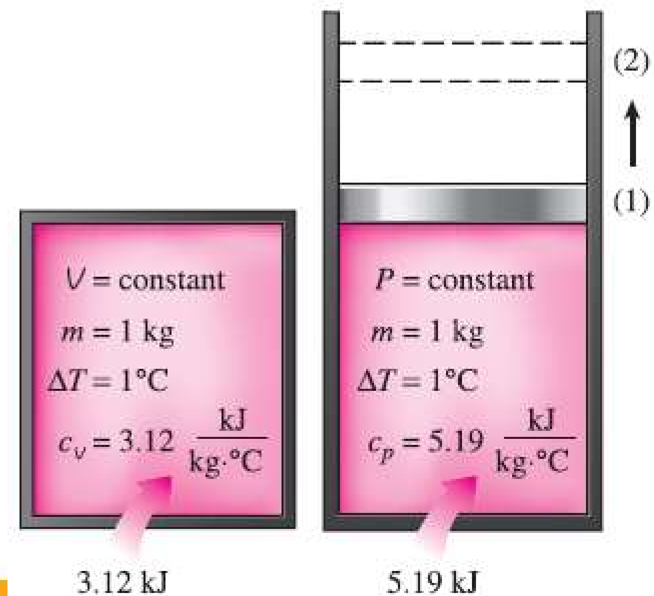


FIGURE 4–18
Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

Constant-volume and constant-pressure specific heats c_v and c_p (values are for helium gas).



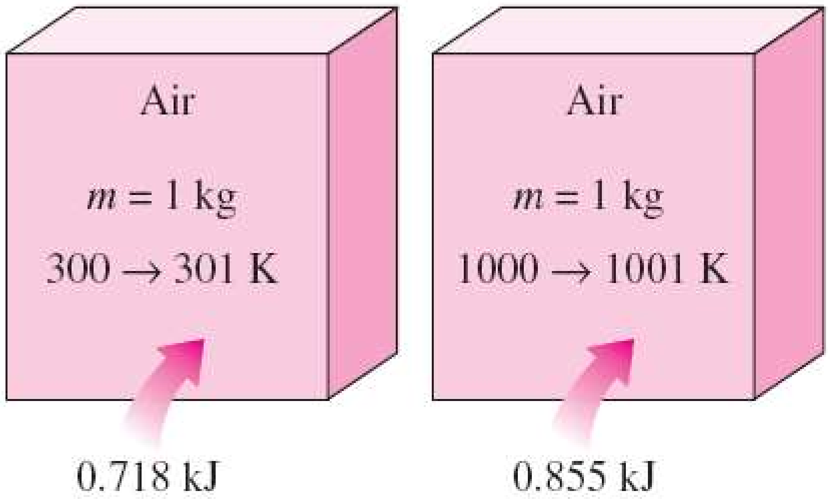


FIGURE 4–21
The specific heat of a substance changes with temperature.

- The equations in the figure are valid for *any* substance undergoing *any* process.
- c_v and c_p are properties.
- c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.
- A common unit for specific heats is kJ/kg·°C or kJ/kg·K. **Are these units identical?**

True or False?
c_p is always greater than c_v

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

= the chage in internal energy with temperature at constant volume

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

= the chage in enthalpy with temperature at constant pressure

Formal definitions of c_v and c_p.

Three ways of calculating Δu *and* Δh

1. By using the ***tabulated u and h data***. This is the easiest and **most accurate** way when tables are readily available.
2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are **very accurate**.
3. By using ***average specific heats***. This is very simple and certainly very convenient when property tables are not available. The results obtained are **reasonably accurate** if the temperature interval is not very large.

$$\Delta u = u_2 - u_1 \text{ (table)}$$

$$\Delta u = \int_1^2 c_v(T)\, dT$$

$$\Delta u \cong c_{v,\text{avg}}\, \Delta T$$

Three ways of calculating Δu.

Specific Heats for Solids & Liquids

- For *incompressible* substances (solids & liquids)

$$c_v = c_p$$

- Thus it can just be stated as *c*.

Modes of Energy Transfer

Energy Interaction between
System and Surrounding

Energy can cross the boundary (transferred) of a closed system by **2 methods**;

HEAT & WORK

<u>HEAT</u>, Q [J, kJ]

Heat - Energy that is *being transferred* due to a <u>temperature difference</u>

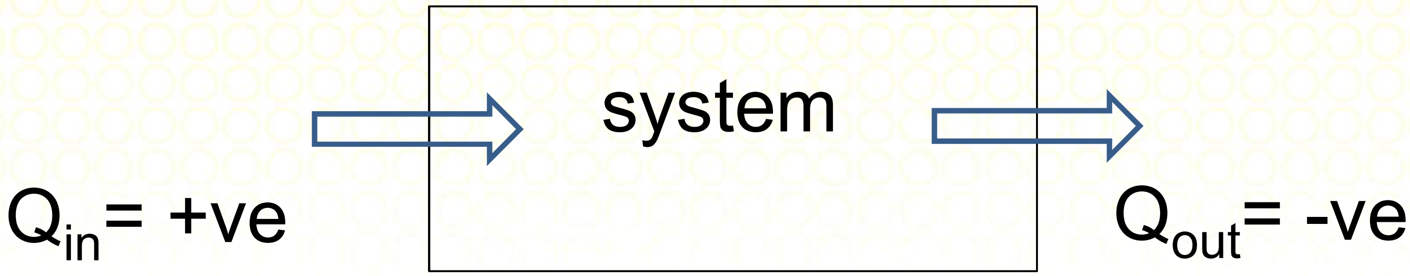
- Heat is a <u>mode</u> of energy transfer
- Heat is not a property
- Energy is related to <u>states</u> (property)
- Heat is related to <u>processes</u> (not a property, depends on the path)

$$q = \frac{Q}{m}$$

$$\dot{Q} = \frac{Q}{t}\left[\frac{kJ}{s} = kW\right]$$ = rate of heat transfer

$$\int_1^2 \delta Q = Q_{12}$$ Amount of heat transferred during a process (depends on the path)

Heat (ctd.)



Adiabatic Process (Q = 0)

- insulated
- $T_{system} = T_{surrounding}$

Adiabatic $\neq$ Isothermal!

(T can change by other methods; energy can enter system by *work*)

WORK, W [J, kJ]

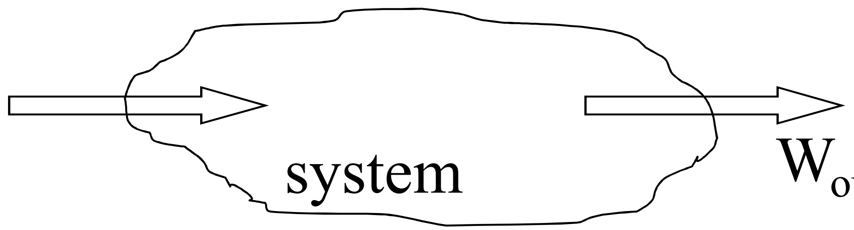
Work -–Energy that is *crossing the boundary* other than heat (electrical, stirrer, shaft, moving piston, etc.)

Also stated as the energy transfer associated with a force acting for a distance.

-Not a property (related to *process*)

-Mode of energy *transfer*

W_{in} = -ve



W_{out} = +ve

$$w = \frac{W}{m}\left[\frac{kJ}{kg}\right]$$

$$\dot{W}[kW] = \frac{W}{t}\left[\frac{kJ}{s}\right]$$ = rate of work = power

$$\int_1^2 \delta W = W_{12}$$ ← Depends on path

Types of Work

Work

- Electrical $W_{el} = \int_1^2 VIdt$
- Mechanical $W = \int_1^2 F \cdot ds$
  - Boundary $W_b = \int_1^2 p \cdot dV$
  - Gravitational $W_g = mg\,(z_2 - z_1)$
  - Acceleration $W = \frac{m}{2}(\vec{V}_2^2 - \vec{V}_1^2)$
  - Shaft $W = 2\pi n \tau$
  - Spring $W = \frac{1}{2}k\,(x_2^2 - x_1^2)$

MOVING BOUNDARY WORK

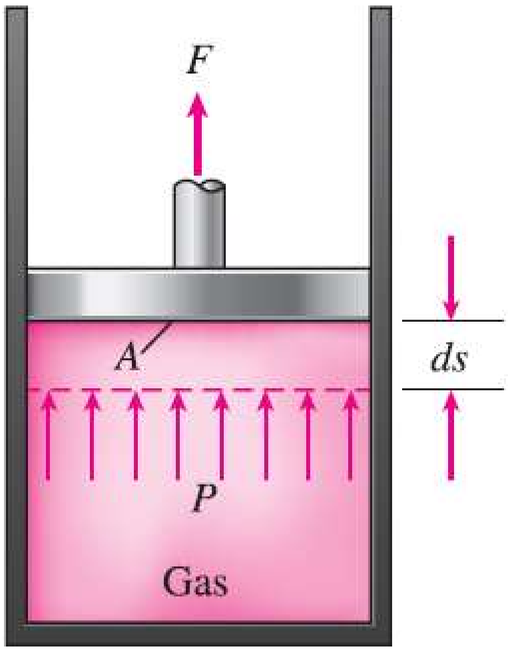
Moving boundary work ($P\,dV$ work): The expansion and compression work in a piston-cylinder device.

$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV \qquad (\text{kJ})$$

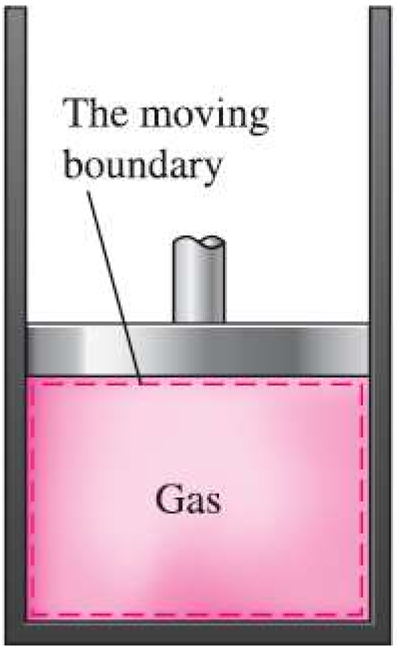
Quasi-equilibrium process: A process during which the system remains nearly in equilibrium at all times.

W_b is positive $\rightarrow$ for expansion
W_b is negative $\rightarrow$ for compression



A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.

The work associated with a moving boundary is called *boundary work.*



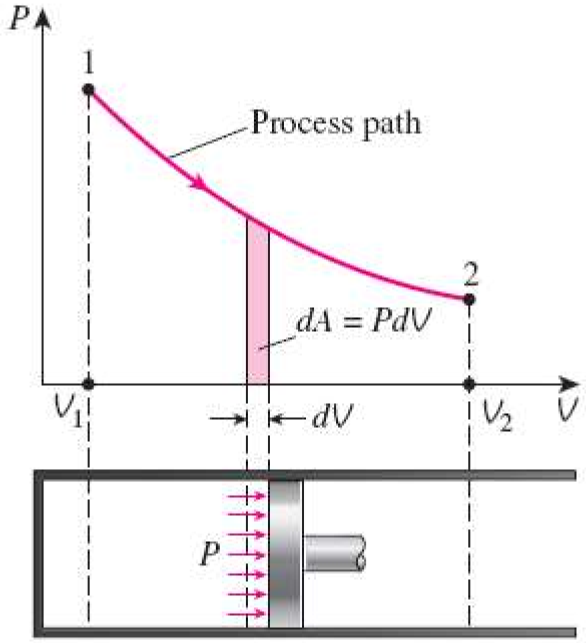


FIGURE 4–3
The area under the process curve on a *P*-*V* diagram represents the boundary work.

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$

The area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.

The boundary work done during a process depends on the path followed as well as the end states.

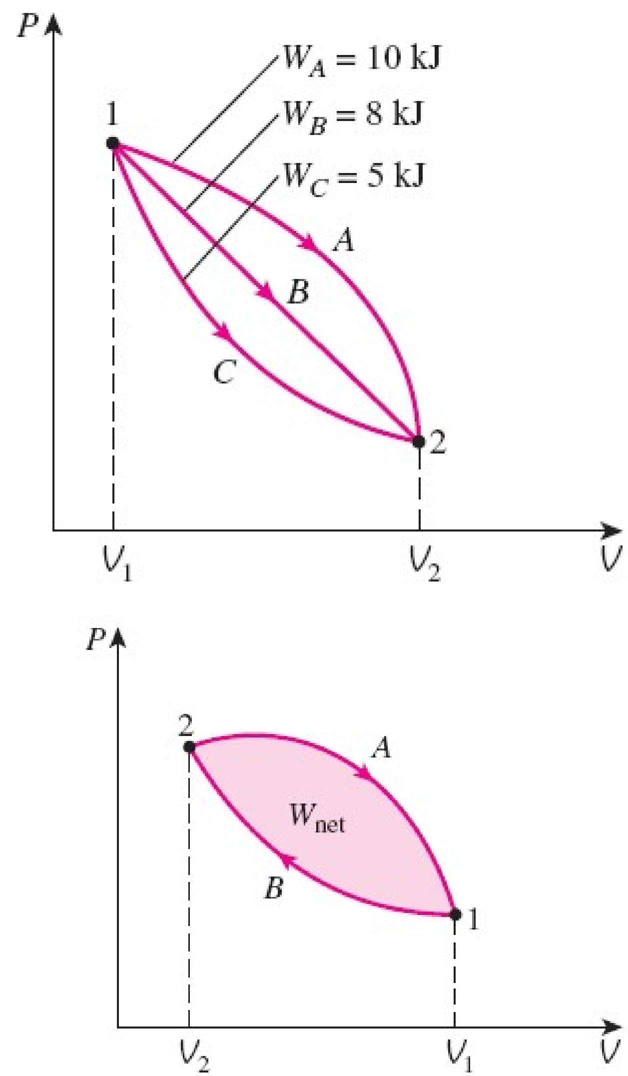


FIGURE 4–5
The net work done during a cycle is the difference between the work done by the system and the work done on the system.

Boundary Work for Polytropic Processes

Boundary Work

$$\boxed{W_B = \int_{V_1}^{V_2} P dV}$$

Area under P-v graph

General Polytropic Work

$$W = \frac{P_2 V_2 - P_1 V_1}{1 - n} \qquad (n \neq 1)$$

Const. Pressure Work (n=0)

$$W = p(V_2 - V_1)$$

Isothermal Work (n=1) *ideal gas*

$$W = mRT ln\left(\frac{V_2}{V_1}\right) = mRT ln\left(\frac{P_1}{P_2}\right)$$

Const. Volume Work (dv=0)

$$W_{\text{b const. vol}} = 0$$

ENERGY CONVERSION & TRANSMISSION EFFICIENCIES

Efficiency is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished.

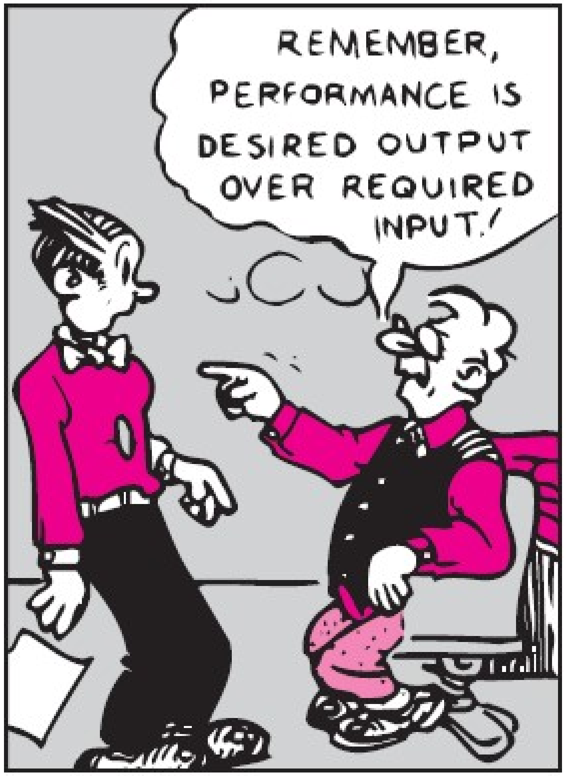


FIGURE 2–54
The definition of performance is not limited to thermodynamics only.

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

Efficiency of a water heater: The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater.

Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%

Water heater

$$\eta_{\text{combustion}} = \frac{Q}{\text{HV}} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: 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.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

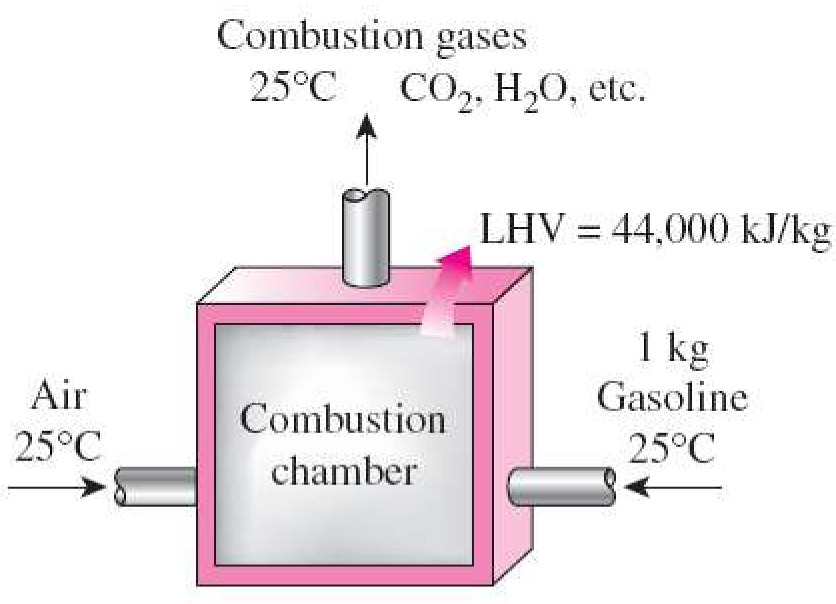


FIGURE 2–56
The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the **annual fuel utilization efficiency (AFUE)**, which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cool down losses.

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:** The ratio of the net electrical power output to the rate of fuel energy input.

Overall efficiency of a power plant

$$\eta_{\text{overall}} = \eta_{\text{combustion}}\,\eta_{\text{thermal}}\,\eta_{\text{generator}} = \frac{\dot{W}_{\text{net,electric}}}{\text{HHV} \times \dot{m}_{\text{net}}}$$

TABLE 2–1

The efficacy of different lighting systems

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

Lighting efficacy: The amount of light output in lumens per W of electricity consumed.

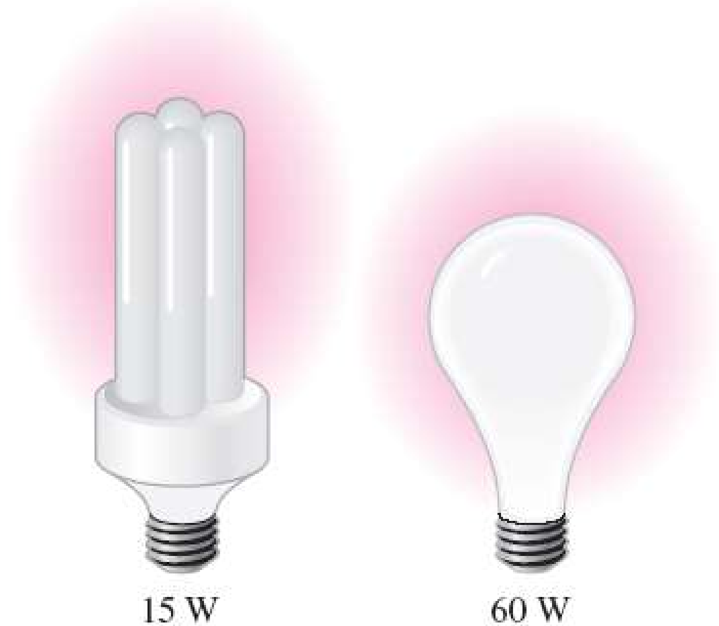


FIGURE 2–57

A 15-W compact fluorescent lamp provides as much light as a 60-W incandescent lamp.

TABLE 2–2

Energy costs of cooking a casserole with different appliances*

[From J. T. Amann, A. Wilson, and K. Ackerly, *Consumer Guide to Home Energy Savings*, 9th ed., American Council for an Energy-Efficient Economy, Washington, D.C., 2007, p. 163.]

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.

- Using energy-efficient appliances conserve energy.
- It helps the **environment** by reducing the amount of pollutants emitted to the atmosphere during the combustion of fuel.
- The combustion of fuel produces
  - carbon dioxide, causes global warming
  - nitrogen oxides and hydrocarbons, cause smog
  - carbon monoxide, toxic
  - sulfur dioxide, causes acid rain.

$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

$$= \frac{3\text{ kWh}}{5\text{ kWh}} = 0.60$$

FIGURE 2–58

The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

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

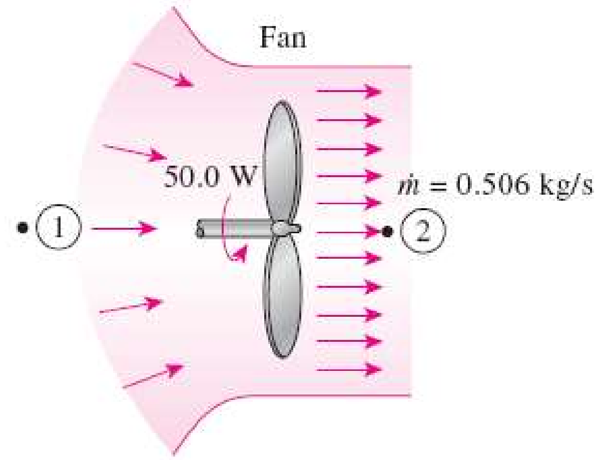
The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the **pump efficiency** and **turbine efficiency**,

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

$$\Delta \dot{E}_{\text{mech,fluid}} = \dot{E}_{\text{mech,out}} - \dot{E}_{\text{mech,in}}$$

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

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



$V_1 \times 0,\ V_2 = 12.1$ m/s
$z_1 = z_2$
$P_1 \times P_{\text{atm}}$ and $P_2 \times P_{\text{atm}}$

$$\eta_{\text{mech, fan}} = \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{shaft, in}}} = \frac{\dot{m}V_2^2/2}{\dot{W}_{\text{shaft, in}}} = \frac{(0.506\ \text{kg/s})(12.1\ \text{m/s})^2/2}{50.0\ \text{W}} = 0.741$$

FIGURE 2–60
The mechanical efficiency of a fan is the ratio of the rate of increase of the mechanical energy of air to the mechanical power input.

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

Pump efficiency

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

Generator efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$

Turbine-Generator overall efficiency

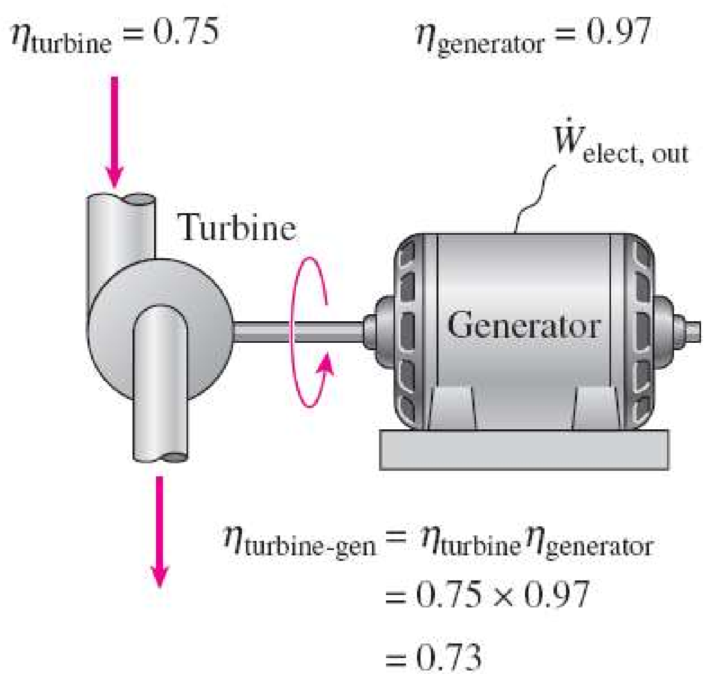
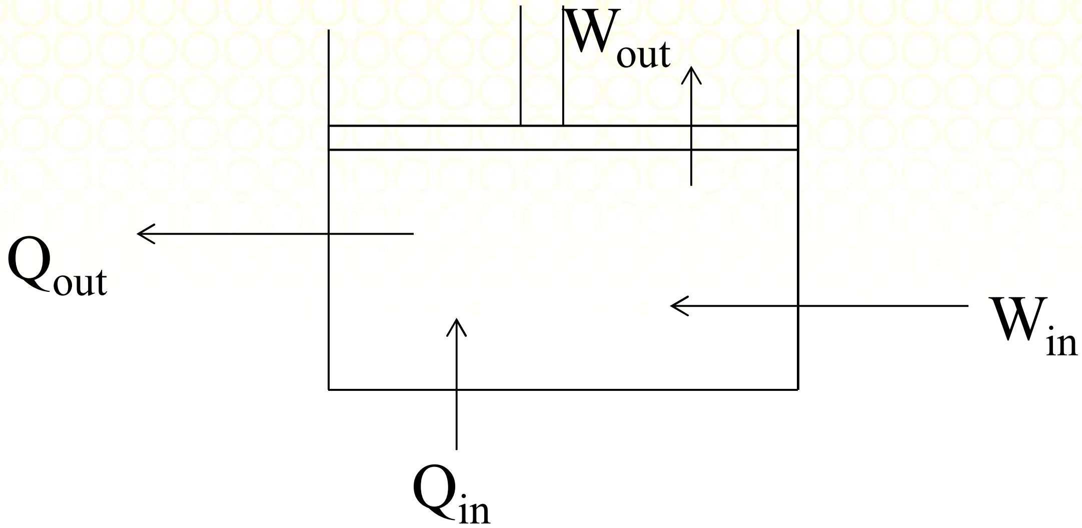


FIGURE 2–61
The overall efficiency of a turbine–generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical power of the fluid converted to electrical power.

1st Law Closed System



$$\Delta E = \underbrace{\sum Q - \sum W}$$

Net change of system energy

Net total energy transfer in the form of heat and work

- Recall that System Energy consists of:

$$E_{system} = U + KE + PE$$

or

$$\Delta E_{system} = \Delta U + \Delta KE + \Delta PE$$

thus;

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

Or can be called as the

<u>1st Law/Energy Balance of a Closed System</u>;

$$\boxed{\underbrace{Q - W}_{\text{Net } \textit{transfer} \text{ of energy}} = \underbrace{\Delta U + \Delta KE + \Delta PE}_{\text{Energy } \textit{storage} \text{ in different modes}}}$$

1st Law for Closed System in different forms;

$$Q - W = \Delta U + \Delta KE + \Delta PE \qquad [kJ]$$

per unit mass;

$$q - w = \Delta u + \Delta ke + \Delta pe \qquad [kJ/kg]$$

Rate form;

$$\dot{Q} - \dot{W} = \frac{dU}{dt} + \frac{d(KE)}{dt} + \frac{d(PE)}{dt} \qquad [kW]$$

Cyclic Process $\Delta E = 0$

$$Q - W = 0$$

$$Q_{cycle} = W_{cycle}$$

$$\oint Q = \oint W$$

summary;

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

- ΔPE: $mg(z_2 - z_1)$
- ΔKE: $\dfrac{m(V_2^2 - V_1^2)}{2}$
- ΔU:
  - $m(u_2 - u_1)$ water (Table)
  - $mC_v(T_2 - T_1)$ ideal gas
- W:
  - Electrical $W_{el} = \int_1^2 VIdt$
  - Mechanical $W = \int_1^2 F \cdot ds$
    - Boundary $W_b = \int_1^2 p \cdot dV$
    - etc…