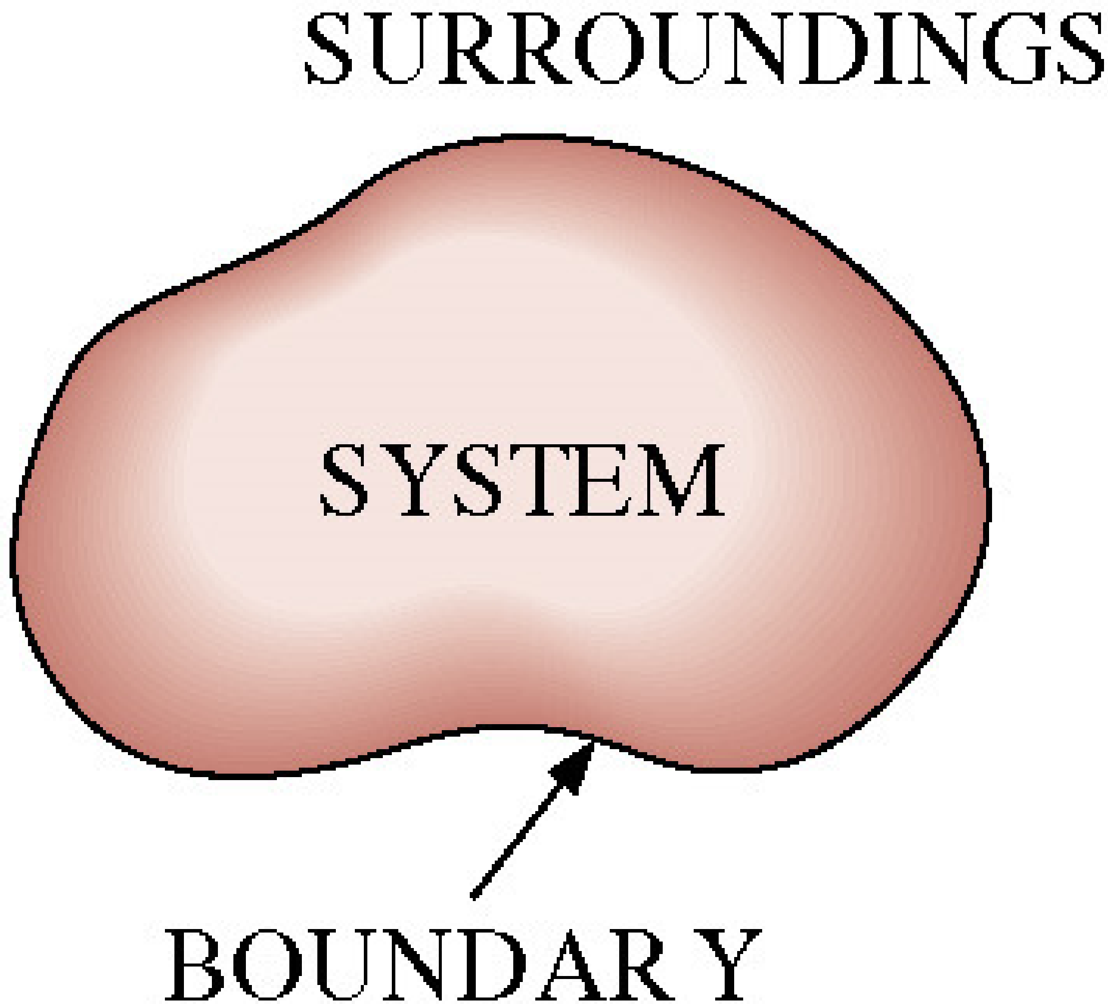
Introduction to Thermodynamics

Thermodynamics is the study of energy and its transformation. Most studies of thermodynamics are primarily concerned with two forms of energy – heat and work. Thermodynamics study includes quantitative analysis of machine and processes for transformation of energy and between work and heat. In classical thermodynamics a macroscopic viewpoint is taken regarding such matters.

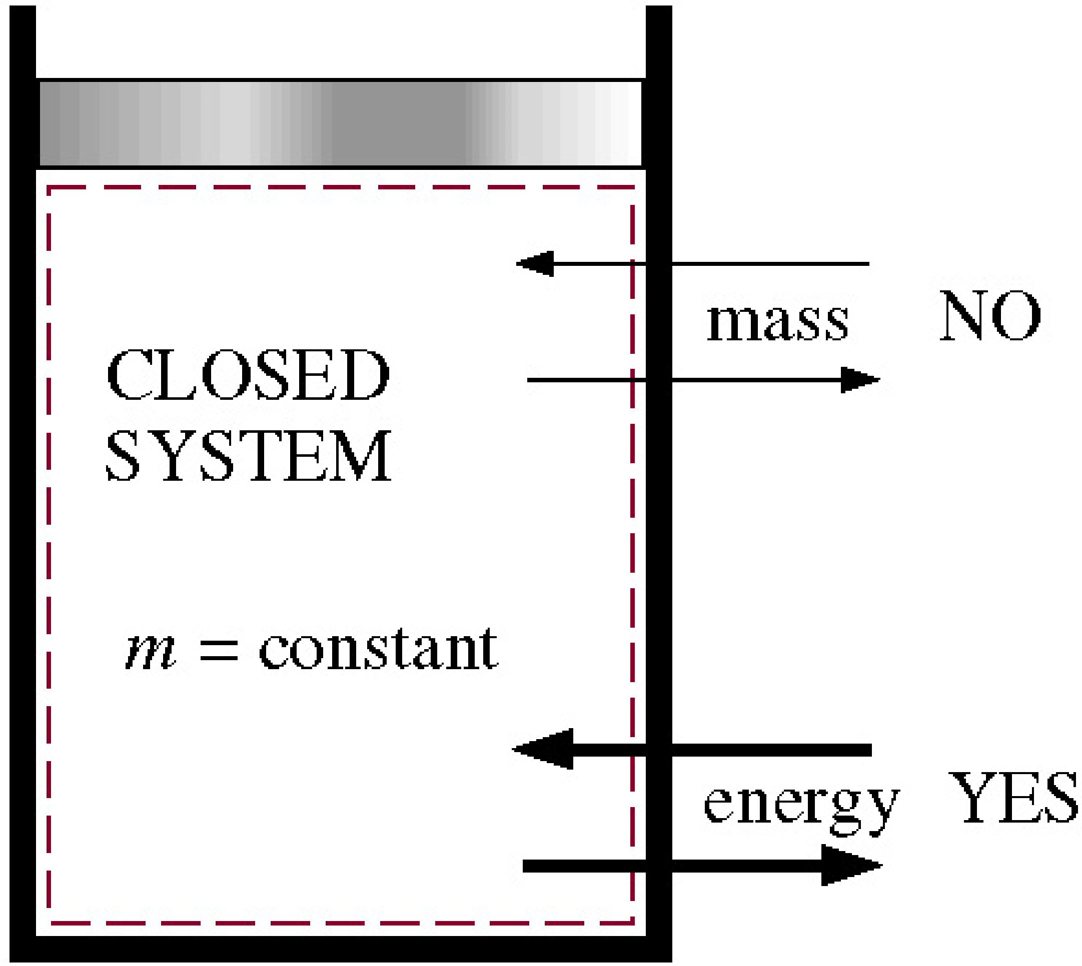
The First Law of Thermodynamics

The first law of thermodynamics is an expression of the conservation of energy principle. Energy can cross the boundaries of a closed system in the form of heat or work. Energy transfer across a system boundary due solely to the temperature difference between a system and its surroundings is called heat.

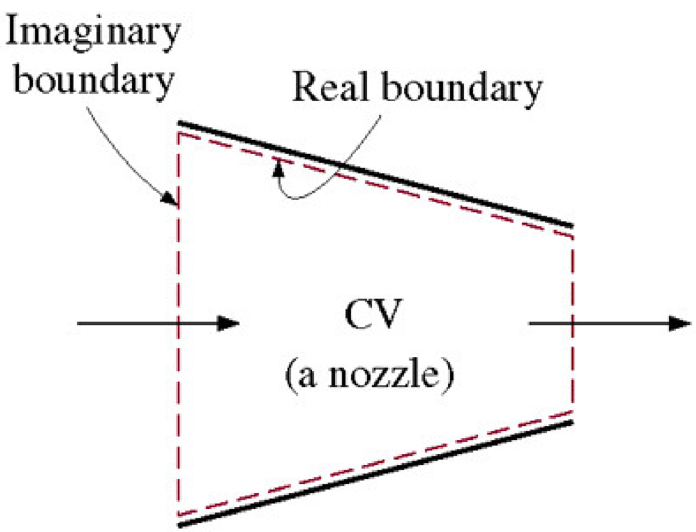
System, surroundings, and boundary.



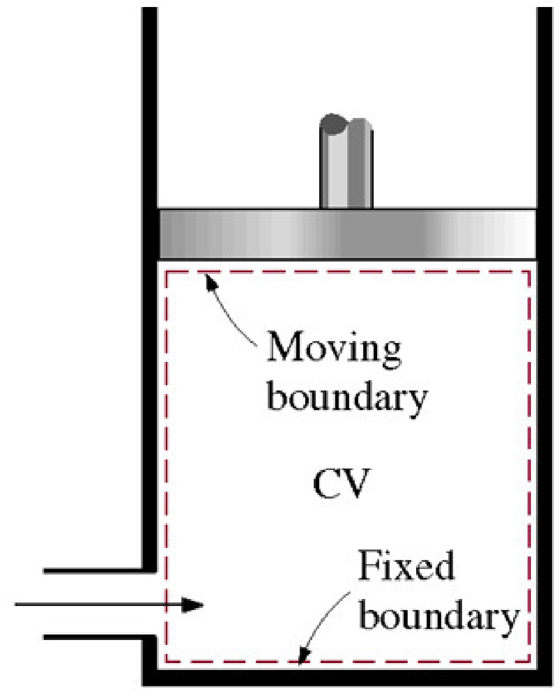
Mass cannot cross the boundaries of a closed system, but energy can.



A control volume may involve fixed, moving, real, and imaginary boundaries.



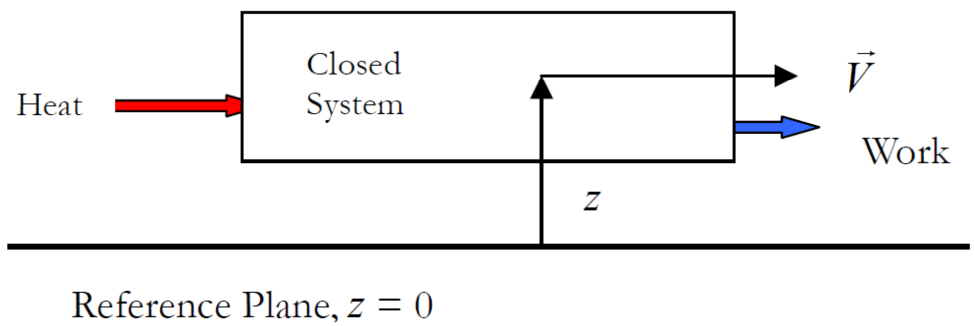
(*a*) A control volume with real and imaginary boundaries



(*b*) A control volume with fixed and moving boundaries

Closed System First Law

A closed system moving relative to a reference plane is shown below where z is the elevation of the center of mass above the reference plane and $\vec{V}$ is the velocity of the center of mass.



For the closed system shown above, the **conservation of energy principle** or **the first law of thermodynamics** is expressed as

$$\begin{pmatrix}\text{Total energy} \\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy} \\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{The change in total} \\ \text{energy of the system}\end{pmatrix}$$

or

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

According to classical thermodynamics, we consider the energy added to be net heat transfer to the closed system and the energy leaving the closed system to be net work done by the closed system. So

$$Q_{net} - W_{net} = \Delta E_{system}$$

Normally the stored energy, or total energy, of a system is expressed as the sum of three separate energies. The **total energy of the system**, $\boldsymbol{E_{\mathrm{system}}}$, is given as

$$E = Internal\ energy\ +\ Kinetic\ energy\ +\ Potential\ energy$$
$$E = U + KE + PE$$

The change in stored energy for the system is

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

conservation of energy principle, or the **first law of thermodynamics for closed systems,** is written as

$$Q_{net} - W_{net} = \Delta U + \Delta KE + \Delta PE$$

If the system does not move with a velocity and has no change in elevation, the conservation of energy equation reduces to

$$Q_{net} - W_{net} = \Delta U$$

Closed System First Law for a Cycle

Since a thermodynamic cycle is composed of processes that cause the working fluid to undergo a series of state changes through a series of processes such that the final and initial states are identical, the change in internal energy of the working fluid is zero for whole numbers of cycles. The first law for a closed system operating in a thermodynamic cycle becomes

$$Q_{net} - W_{net} = \cancelto{0}{\Delta U_{cycle}}$$

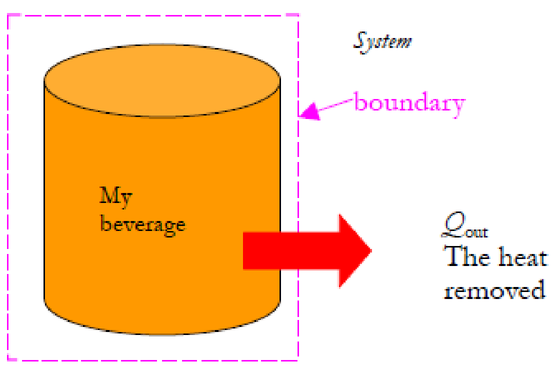
$$Q_{net} = W_{net}$$

Example Incompressible Liquid

A two-liter bottle of your favorite beverage has just been removed from the trunk of your car. The temperature of the beverage is 35°C, and you always drink your beverage at 10°C.

a. How much heat energy must be removed from your two liters of beverage?
b. You are having a party and need to cool 10 of these two-liter bottles in one-half hour. What rate of heat removal, in kW, is required? Assuming that your refrigerator can accomplish this and that electricity costs 8.5 cents per kW-hr, how much will it cost to cool these 10 bottles?

<u>**System:**</u> The liquid in the constant volume, closed system container



Property Relation: Incompressible liquid relations, let's assume that the beverage is mostly water and takes on the properties of liquid water. The specific volume is 0.001 m^3/kg, $C = 4.18$ kJ/kg·K.

Process: Constant volume

$$V_2 = V_1$$

Conservation of Mass:

$$m_2 = m_1 = m$$

$$m = \frac{V}{v} = \frac{2\,L}{0.001\frac{m^3}{kg}}\left(\frac{m^3}{1000\,L}\right) = 2\,kg$$

Conservation of Energy:

The first law closed system is

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

Since the container is constant volume and there is no "other" work done on the container during the cooling process, we have

$$W_{net} = \left(W_{net}\right)_{other} + W_b = 0$$

The only energy crossing the boundary is the heat transfer leaving the container. Assuming the container to be stationary, the conservation of energy becomes

$$-E_{out} = \Delta E$$

$$-Q_{out} = \Delta U = mC\Delta T$$

$$-Q_{out} = (2\ kg)(4.18\frac{kJ}{kg\cdot K})(10-35)K$$

$$-Q_{out} = -209.2\ kJ$$

$$Q_{out} = 209.2\ kJ$$

The heat transfer rate to cool the 10 bottles in one-half hour is

$$\dot{Q}_{out} = \frac{(10\,bottles)(209.2\,\frac{kJ}{bottle})}{0.5\,hr}\left(\frac{1hr}{3600s}\right)\left(\frac{kW}{\frac{kJ}{s}}\right)$$

$$= 1.162\,kW$$

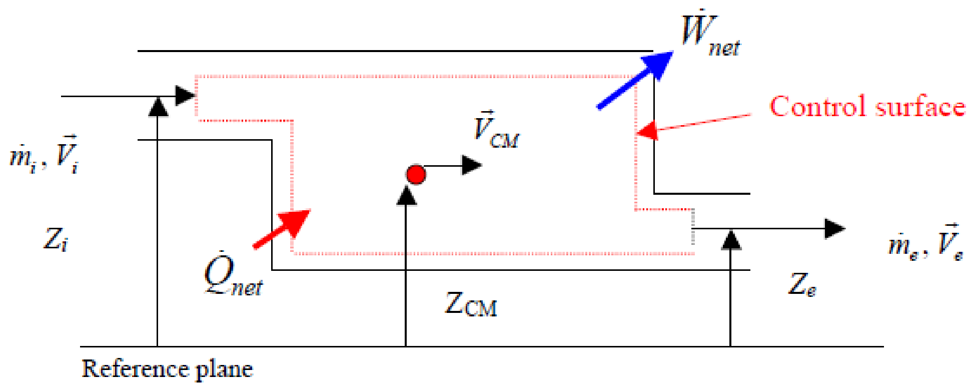
$$Cost = (1.162\,kW)(0.5\,hr)\frac{\$0.085}{kW-hr}$$

$$= \$0.05$$

First Law of Thermodynamics for a control volume

Conservation of Energy for Control volumes

The conservation of mass and the conservation of energy principles for open systems or control volumes apply to systems having mass crossing the system boundary or control surface. In addition to the heat transfer and work crossing the system boundaries, mass carries energy with it as it crosses the system boundaries. Thus, the mass and energy content of the open system may change when mass enters or leaves the control volume.



Typical control volume or open system

Thermodynamic processes involving control volumes can be considered in two groups: steady-flow processes and unsteady-flow processes. During a steady-flow process, the fluid flows through the control volume steadily, experiencing no change with time at a fixed position.

Mass Flow Rate

Mass flow through a cross-sectional area per unit time is called the mass flow rate $\dot{m}$. If the fluid density and velocity are constant over the flow cross-sectional area, the mass flow rate is

$$\dot{m} = \rho \vec{V}_{av} A = \frac{\vec{V}_{av} A}{v}$$

where ρ is the density, kg/m^3 (= 1/v), A is the cross-sectional area, m^2; and $\vec{V}_{av}$ is the average fluid velocity normal to the area, m/s.

The fluid volume flowing through a cross-section per unit time is called the volume flow rate $\dot{V}$.

$$\dot{V} = \vec{V} A \qquad (m^3 / s)$$

The mass and volume flow rate are related by

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v} \qquad (kg / s)$$

Conservation of Mass for General Control Volume

The conservation of mass principle for the open system or control volume is expressed as

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{into control volume}\end{bmatrix} - \begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{from control volume}\end{bmatrix} = \begin{bmatrix}\text{Time rate change}\\ \text{of mass inside}\\ \text{control volume}\end{bmatrix}$$

or

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \Delta \dot{m}_{system} \qquad (kg/s)$$

Conservation of Energy for General Control Volume

The conservation of energy principle for the control volume or open system has the same word definition as the first law for the closed system. Expressing the energy transfers on a rate basis, the control volume first law is

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{into control volume}\end{bmatrix} - \begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{from control volume}\end{bmatrix} = \begin{bmatrix}\text{Time rate change}\\ \text{of energy inside}\\ \text{control volume}\end{bmatrix}$$

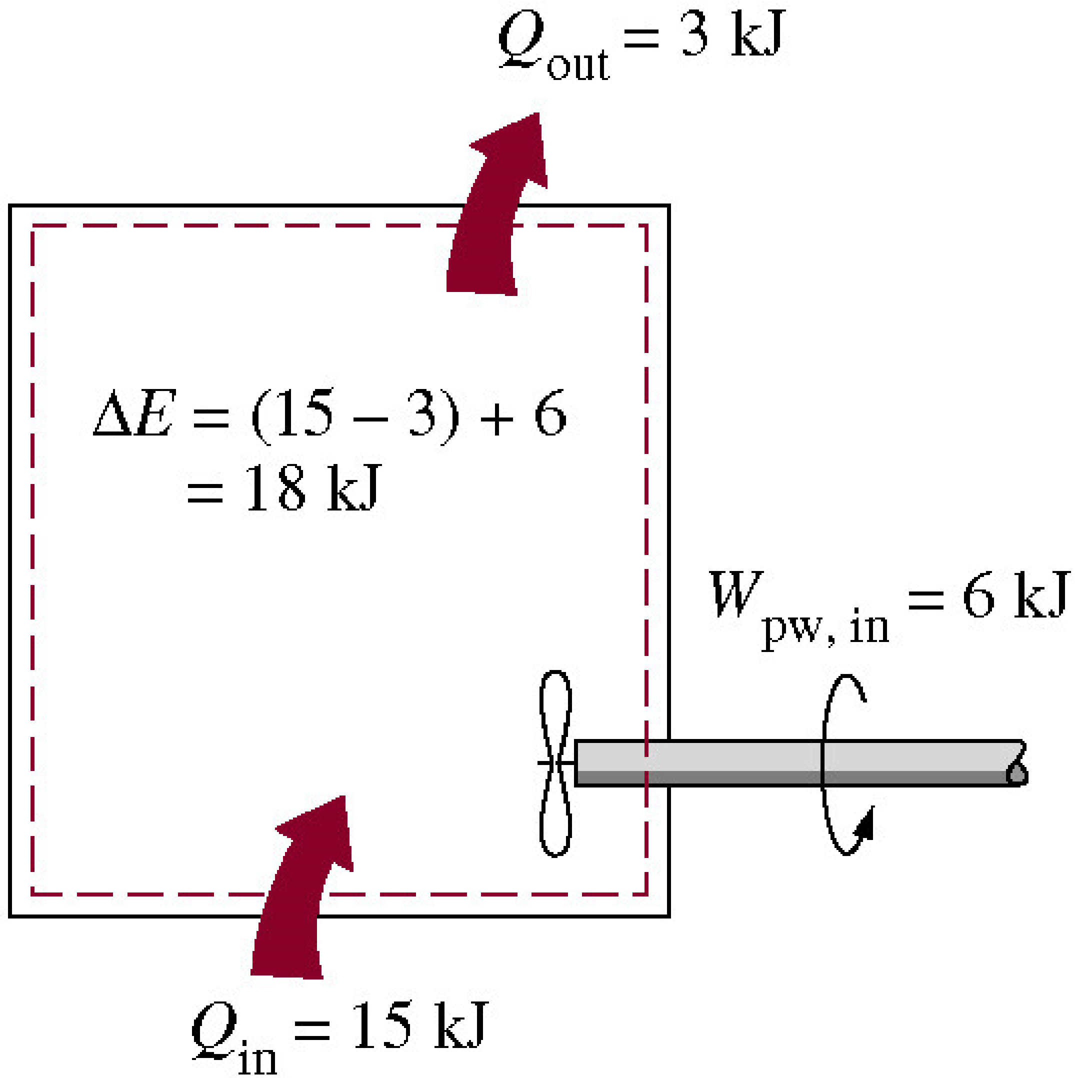
or

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}}_{\substack{\text{Rate change in internal, kinetic,}\\ \text{potential, etc., energies}}} \qquad (kW)$$

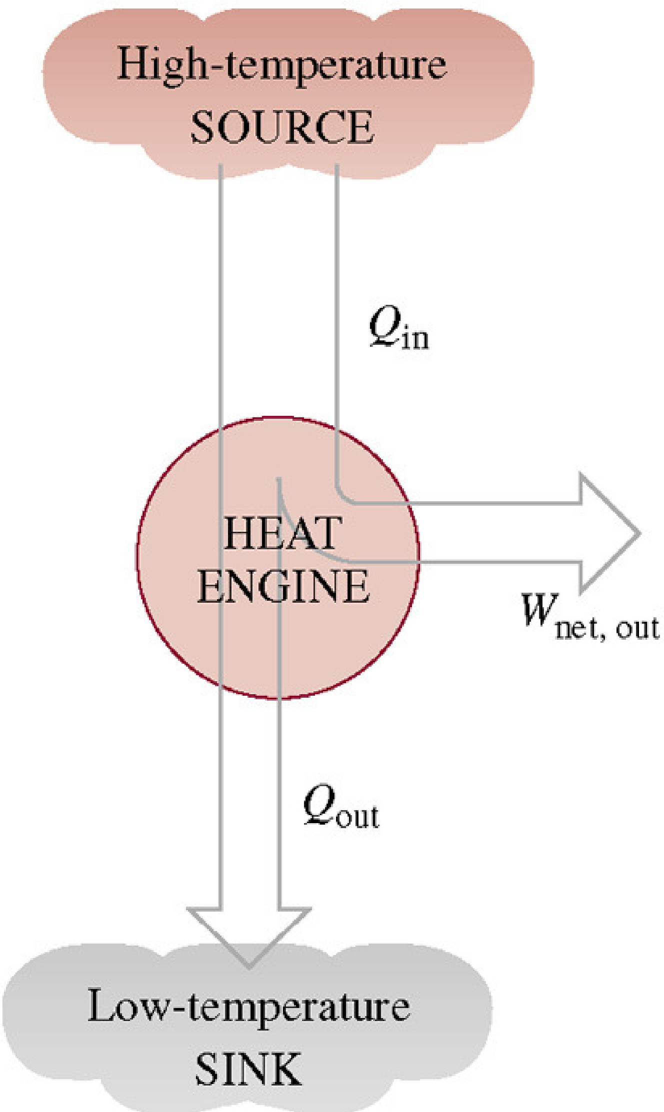
Considering that energy flows into and from the control volume with the mass, energy enters because heat is transferred to the control volume, and energy leaves because the control volume does work on its surroundings, the steady-state, steady-flow first law becomes

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \underbrace{\dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right)}_{\text{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \sum \underbrace{\dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + g z_e \right)}_{\text{for each exit}}$$

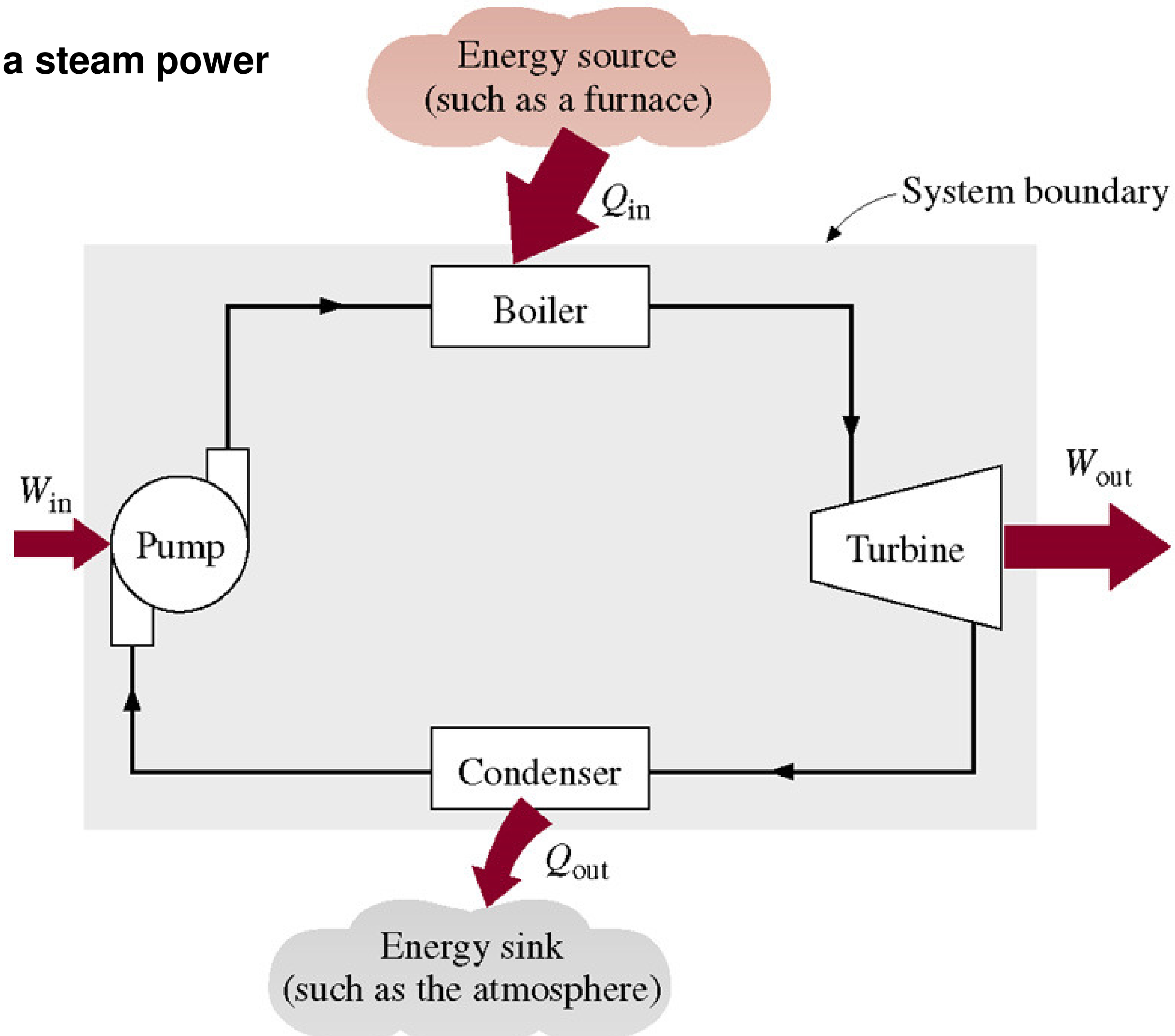
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.



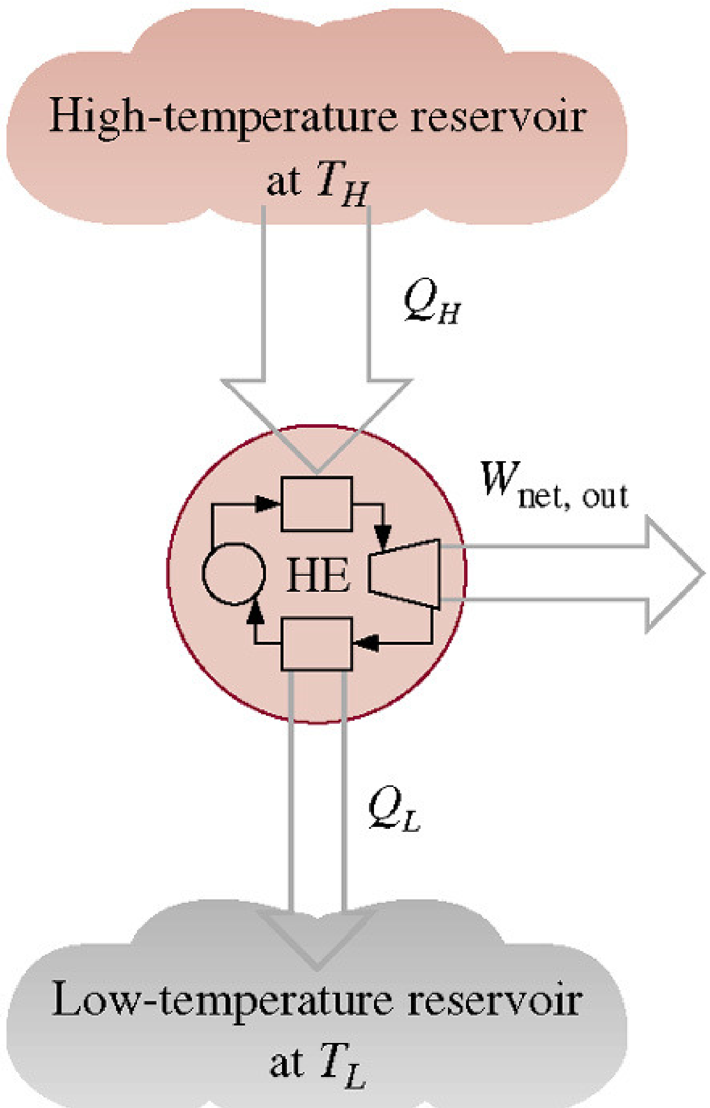
Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.



Schematic of a steam power plant.



Schematic of a heat engine.



Thermal Efficiency, η_{th}

The thermal efficiency is the index of performance of a work-producing device or a heat engine and is defined by the ratio of the net work output (the desired result) to the heat input (the costs to obtain the desired result).

$$\eta_{th} = \frac{\text{Desired Result}}{\text{Required Input}}$$

For a heat engine the desired result is the net work done and the input is the heat supplied to make the cycle operate. The thermal efficiency is always less than 1 or less than 100 percent.

$$\eta_{th} = \frac{W_{net,\,out}}{Q_{in}}$$

where

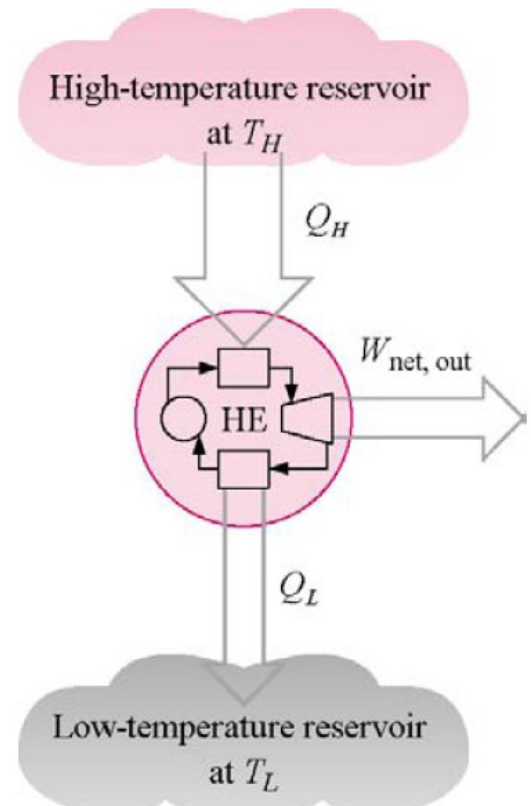
$$W_{net,\,out} = W_{out} - W_{in}$$

Now apply the first law to the cyclic heat engine.

$$Q_{net,in} - W_{net,out} = \Delta U^{\nearrow 0 \text{ (Cyclic)}}$$

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

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



The cycle thermal efficiency may be written as

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

$$= \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Cyclic devices such as heat engines, refrigerators, and heat pumps often operate between a high-temperature reservoir at temperature T_H and a low-temperature reservoir at temperature T_L.

Example

A steam power plant produces 50 MW of net work while burning fuel to produce 150 MW of heat energy at the high temperature. Determine the cycle thermal efficiency and the heat rejected by the cycle to the surroundings.

$$\eta_{th} = \frac{W_{net,\,out}}{Q_H}$$

$$= \frac{50\ MW}{150\ MW} = 0.333 \quad \text{or} \quad 33.3\%$$

$$W_{net,\,out} = Q_H - Q_L$$

$$Q_L = Q_H - W_{net,\,out}$$

$$= 150\ MW - 50\ MW$$

$$= 100\ MW$$

Thermal efficiency of a heat engine can **not** be greather than the efficiency of CARNOT engine

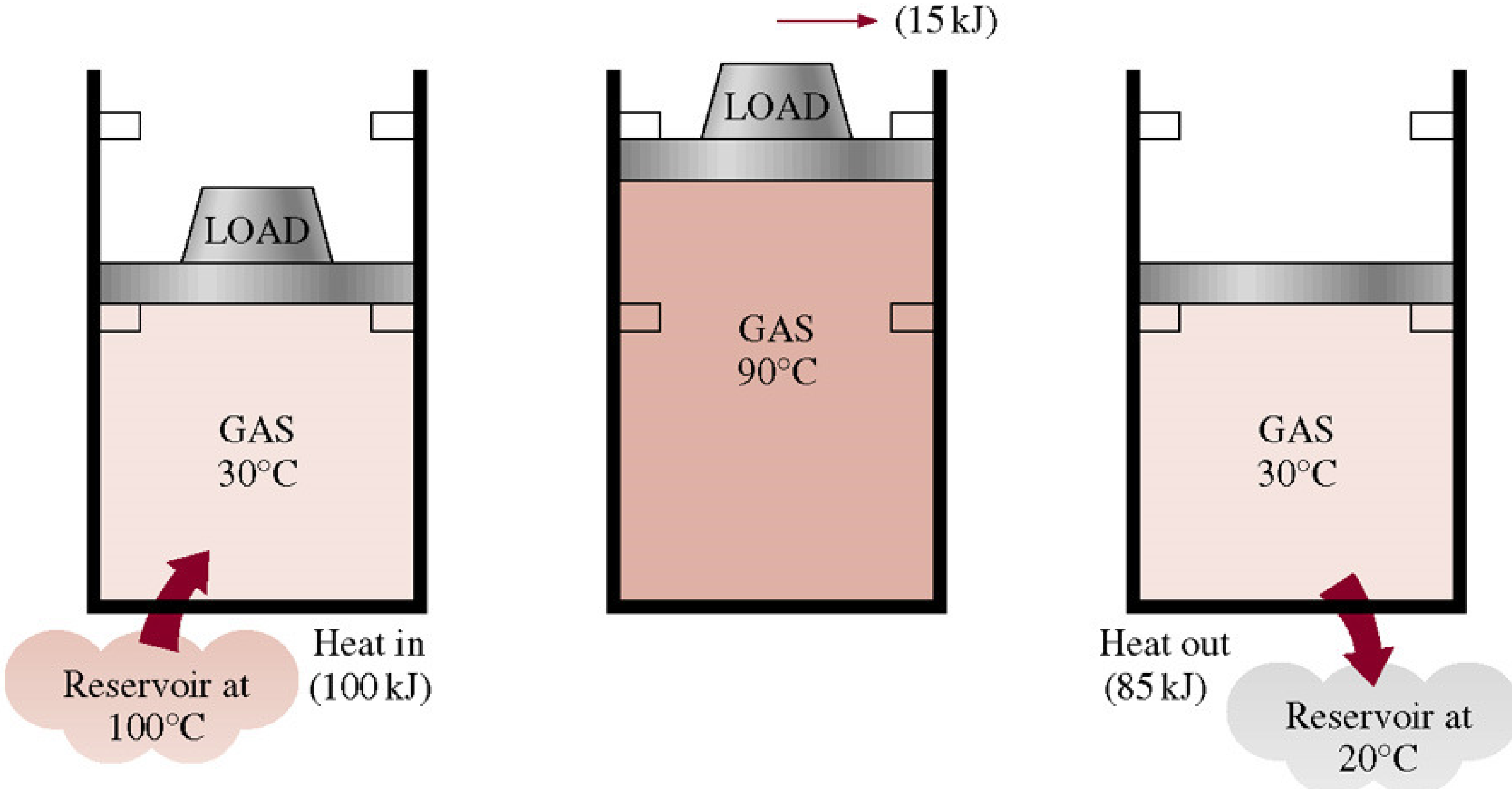
The Carnot thermal efficiency becomes

$$\eta_{th,\,rev} = 1 - \frac{T_L}{T_H}$$

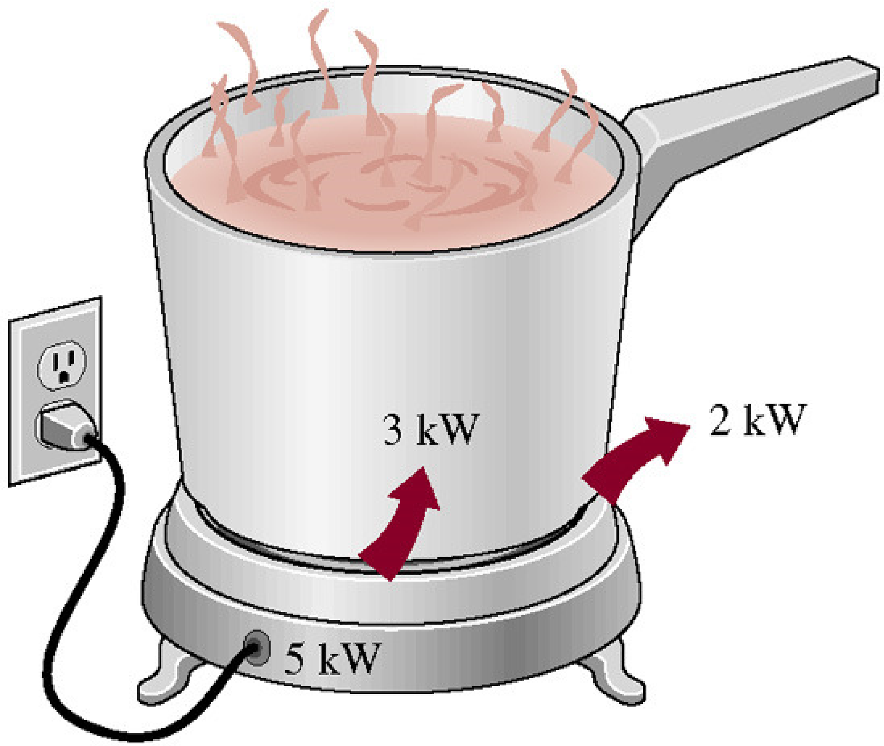
This is the maximum possible efficiency of a heat engine operating between two heat reservoirs at temperatures T_H and T_L. Note that the temperatures are absolute temperatures.

FIGURE 5-16

A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature



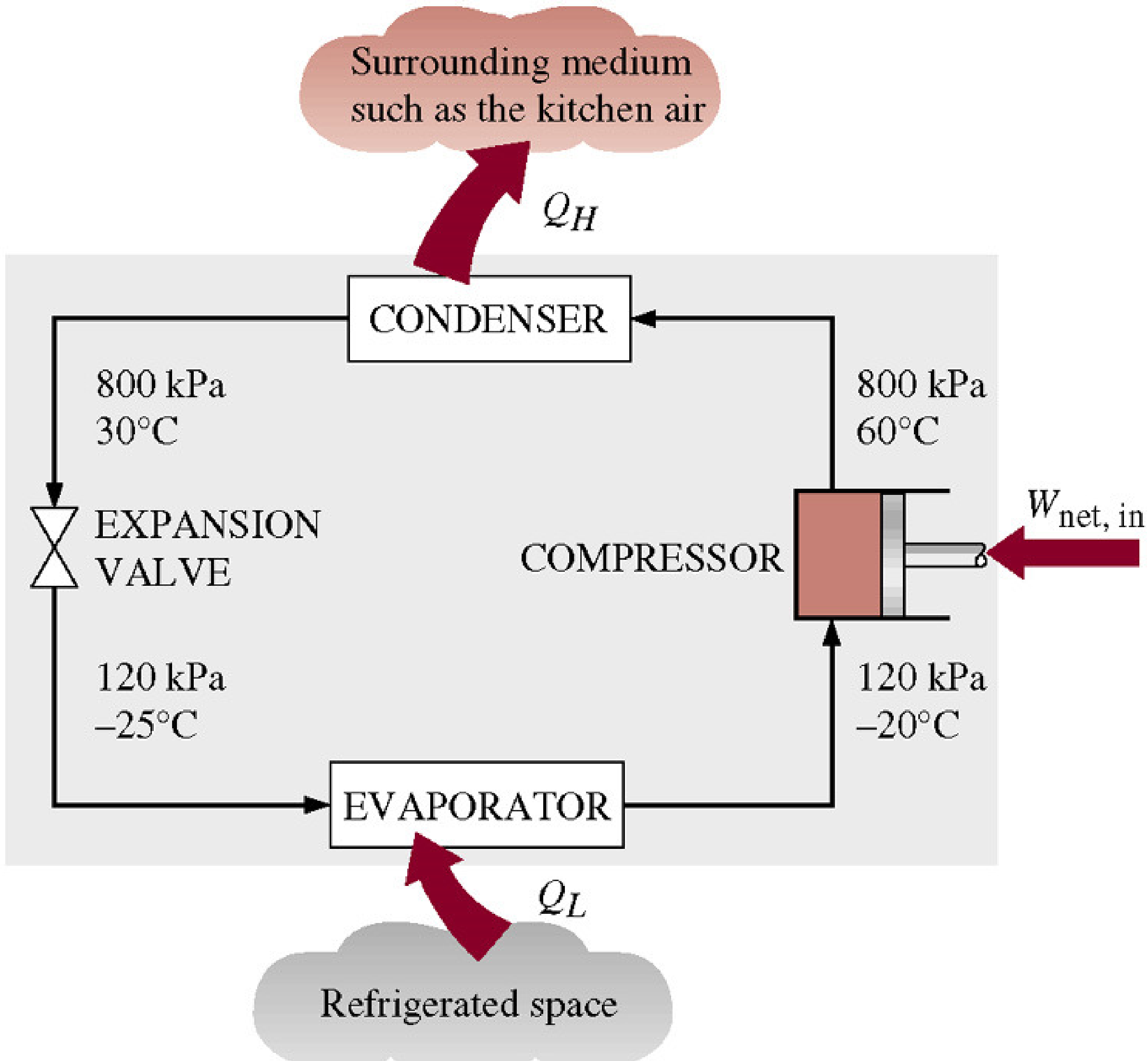
The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.



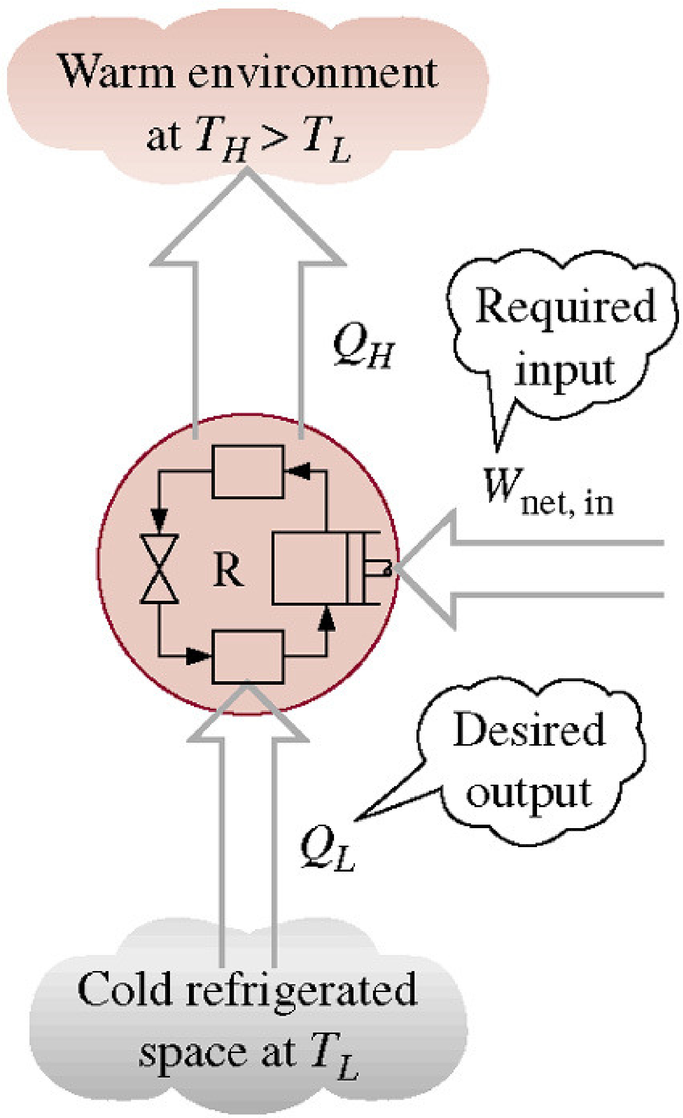
$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

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

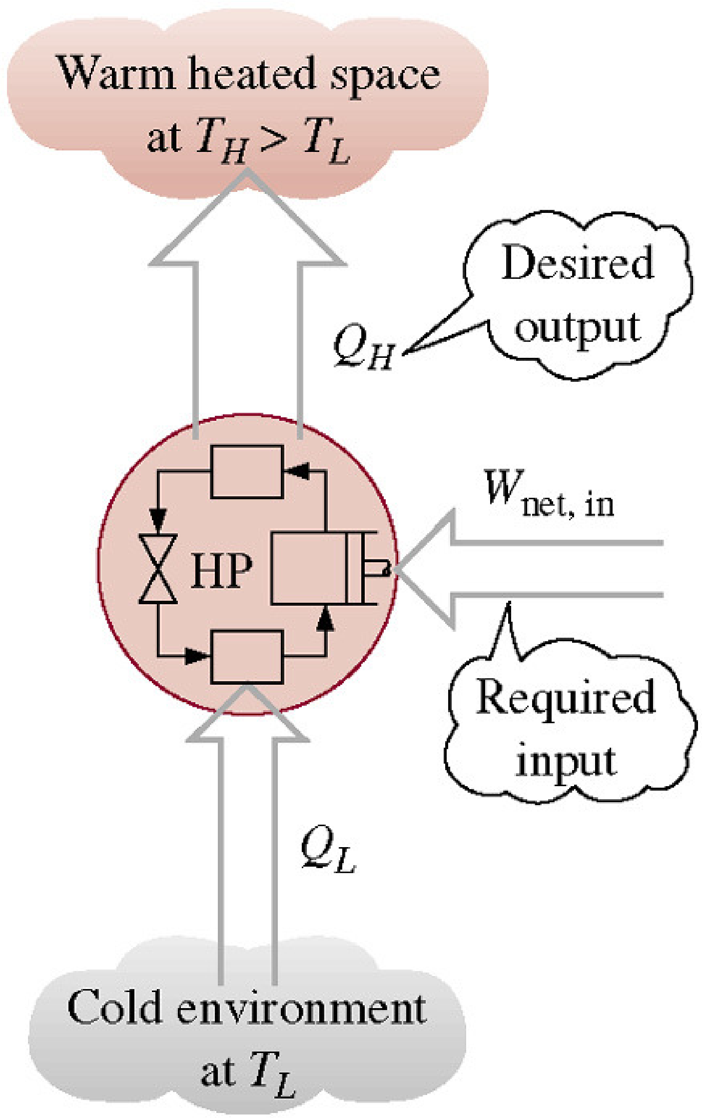
Basic components of a refrigeration system and typical operating conditions.



The objective of a refrigerator is to remove Q_L from the cooled space.



The objective of a heat pump is to supply heat Q_H into the warmer space.



HEAT TRANSFER

The science of thermodynamics deals with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference to *how long* the process will take. But in engineering, we are often interested in the *rate* of heat transfer, which is the topic of the science of *heat transfer.*

- *Heat is the form of energy that can be transferred from one system to another as a result of TEMPERATURE DIFFERENCE.*
- *The science that deals with the determination of the rates of such energy transfer is «Heat Transfer»*
- *Heat transfer equipment such as heat exchangers, boilers, condensers, radiators, heaters,furnaces, refrigerators, and solar collectors are designed on the basis of heat transfer analysis*

Heat can be transferred in three different modes: *conduction*, *convection*, and *radiation*. All modes of heat transfer require the existence of a temperature difference, and all modes are from the high-temperature medium to a lower-temperature one.

Fourier's law of heat conduction is

$$\dot{Q}_{cond} = -A\,k_t\,\frac{dT}{dx}$$

here

$\dot{Q}_{cond}$ = heat flow per unit time (W)

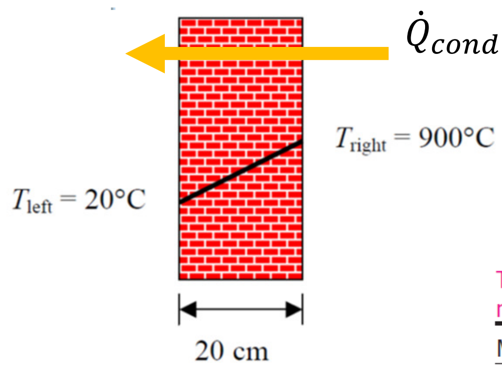
k_t = thermal conductivity (W/m·K)

A = area normal to heat flow (m^2)

$\frac{dT}{dx}$ = temperature gradient in the direction of heat flow (°C/m)

Integrating Fourier's law

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

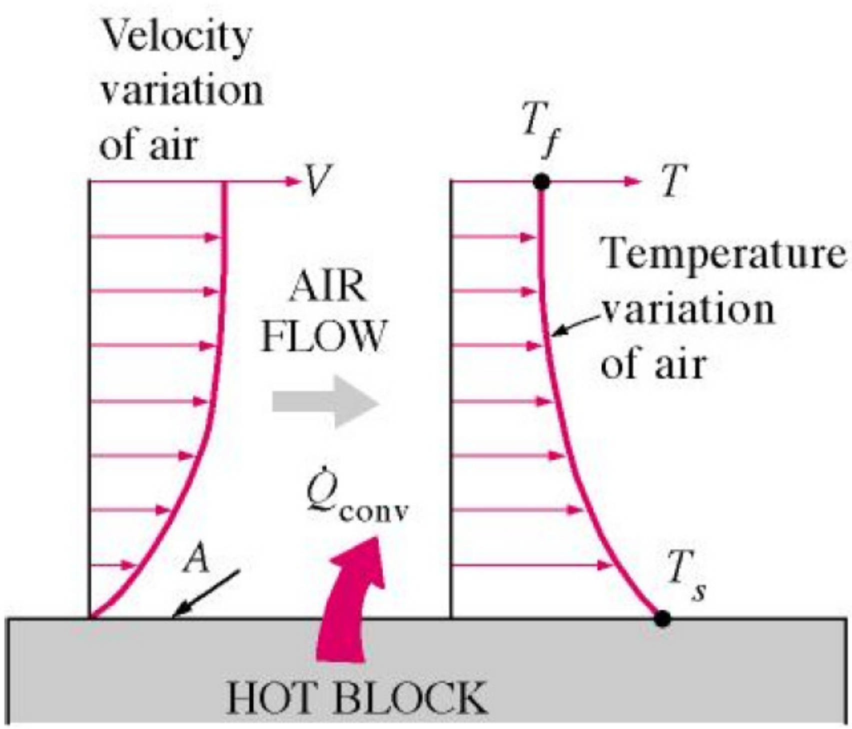


The thermal conductivities of some materials at room temperature

Material	k, W/m · °C*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.613
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

Convection Heat Transfer

Convection heat transfer is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion.



The rate of heat transfer by convection $\dot{Q}_{conv}$ is determined from Newton's law of cooling, expressed as

$$\dot{Q}_{conv} = h\,A\,(T_s - T_f)$$

here

$\dot{Q}_{conv}$ = heat transfer rate (W)

A = heat transfer area (m^2)

h = convective heat transfer coefficient ($W/m^2 \cdot K$)

T_s = surface temperature (K)

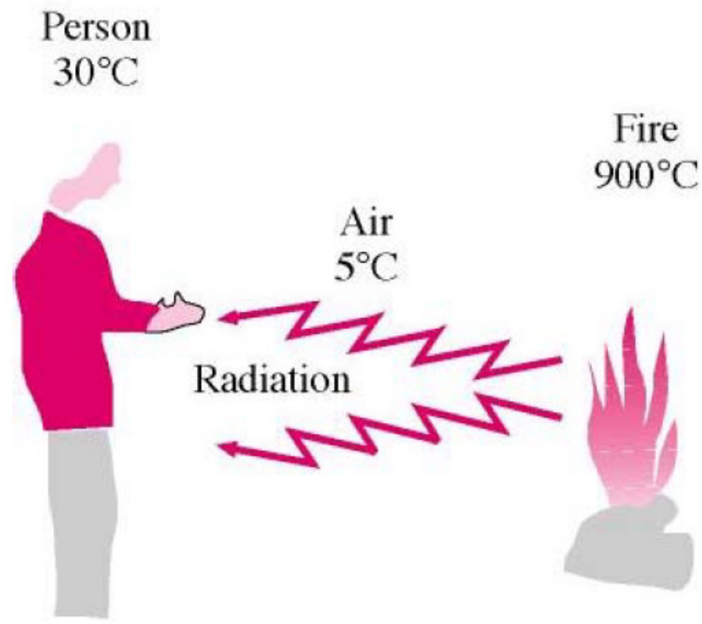
T_f = bulk fluid temperature away from the surface (K)

The convective heat transfer coefficient is an experimentally determined parameter that depends upon the surface geometry, the nature of the fluid motion, the properties of the fluid, and the bulk fluid velocity. Ranges of the convective heat transfer coefficient are given below.

	h W/m^2·K
free convection of gases	2-25
free convection of liquids	50-100
forced convection of gases	25-250
forced convection of liquids	50-20,000
convection in boiling and condensation	2500-100,000

Radiative Heat Transfer

Radiative heat transfer is energy in transition from the surface of one body to the surface of another due to electromagnetic radiation. The radiative energy transferred is proportional to the difference in the fourth power of the absolute temperatures of the bodies exchanging energy.



The net exchange of radiative heat transfer between a body surface and its surroundings is given by

$$\dot{Q}_{rad} = \varepsilon\,\sigma\,A\left(T_s^4 - T_{surr}^4\right)$$

here

$\dot{Q}_{rad}$	= heat transfer per unit time (W)
A	= surface area for heat transfer (m^2)
σ	= Stefan-Boltzmann constant, $5.67\text{x}10^{-8}$ W/m^2K^4 and $0.1713\text{x}10^{-8}$ $BTU/h\ ft^2\ R^4$
ε	= emissivity
T_s	= absolute temperature of surface (K)
T_{surr}	= absolute temperature of surroundings (K)