Chapter 2

Energy, Energy Transfer, and General Energy Analysis

Study Guide in PowerPoint

to accompany

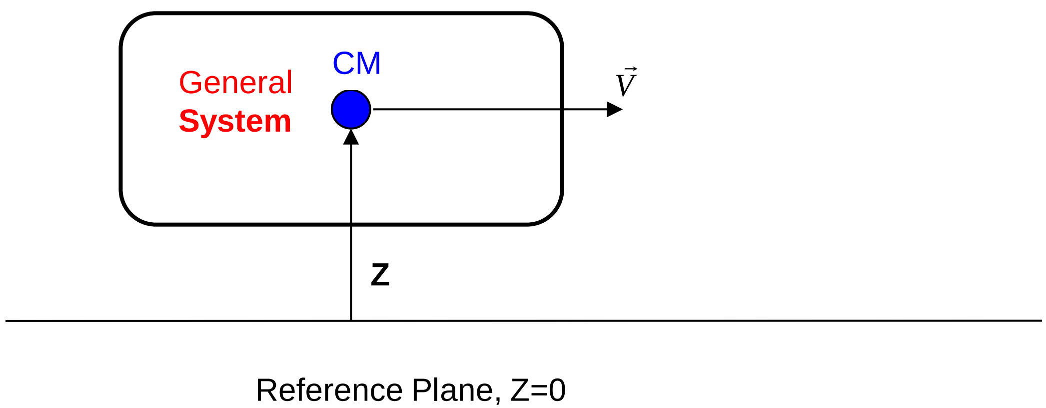
<u>Thermodynamics: An Engineering Approach</u>, 7th edition
by Yunus A. Çengel and Michael A. Boles

We will soon learn how to apply the first law of thermodynamics as the expression of the conservation of energy principle. But, first we study the ways in which energy may be transported across the boundary of a general thermodynamic system. For closed systems (fixed mass systems) energy can cross the boundaries of a closed system only in the form of heat or work. For open systems or control volumes energy can cross the control surface in the form of heat, work, and energy transported by the mass streams crossing the control surface. We now consider each of these modes of energy transport across the boundaries of the general thermodynamic system.

For more information and animations illustrating this topic visit the Animation Library developed by Professor S. Bhattacharjee, San Diego State University, at this link.
test.sdsu.edu/testhome/vtAnimations/index.html

Energy

Consider the system shown below moving with a velocity, $\vec{V}$ at an elevation *Z* relative to the reference plane.



The total energy *E* of a system is the sum of all forms of energy that can exist within the system such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear. The total energy of the system is normally thought of as the sum of the internal energy, kinetic energy, and potential energy. The internal energy *U* is that energy associated with the molecular structure of a system and the degree of the molecular activity (see Section 2-1 of text for more detail). The kinetic energy *KE* exists as a result of the system's motion relative to an external reference frame. When the system moves with velocity $\vec{V}$ the kinetic energy is expressed as

$$KE = m\frac{\vec{V}^2}{2} \qquad (kJ)$$

The energy that a system possesses as a result of its elevation in a gravitational field relative to the external reference frame is called potential energy *PE* and is expressed as

$$PE = mgZ \qquad (kJ)$$

where *g* is the gravitational acceleration and *z* is the elevation of the center of gravity of a system relative to the reference frame. The total energy of the system is expressed as

$$E = U + KE + PE \qquad (kJ)$$

or, on a unit mass basis,

$$e = \frac{E}{m} = \frac{U}{m} + \frac{KE}{m} + \frac{PE}{m} \qquad (\frac{kJ}{kg})$$

$$= u + \frac{\vec{V}^2}{2} + gZ$$

where $e = E/m$ is the specific stored energy, and $u = U/m$ is the specific internal energy. The change in stored energy of a system is given by

$$\Delta E = \Delta U + \Delta KE + \Delta PE \qquad (kJ)$$

Most closed systems remain stationary during a process and, thus, experience no change in their kinetic and potential energies. The change in the stored energy is identical to the change in internal energy for stationary systems.

If $\Delta KE = \Delta PE = 0$,

$$\Delta E = \Delta U \qquad (kJ)$$

Energy Transport by Heat and Work and the Classical Sign Convention

Energy may cross the boundary of a closed system only by heat or work.

Energy transfer across a system boundary due solely to the temperature difference between a system and its surroundings is called heat.

Energy transferred across a system boundary that can be thought of as the energy expended to lift a weight is called work.

Heat and work are energy transport mechanisms between a system and its surroundings. The similarities between heat and work are as follows:

1. Both are recognized at the boundaries of a system as they cross the boundaries. They are both boundary phenomena.

2. Systems possess energy, but not heat or work.

3. Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.

4. Both are path functions (i.e., their magnitudes depends on the path followed during a process as well as the end states.

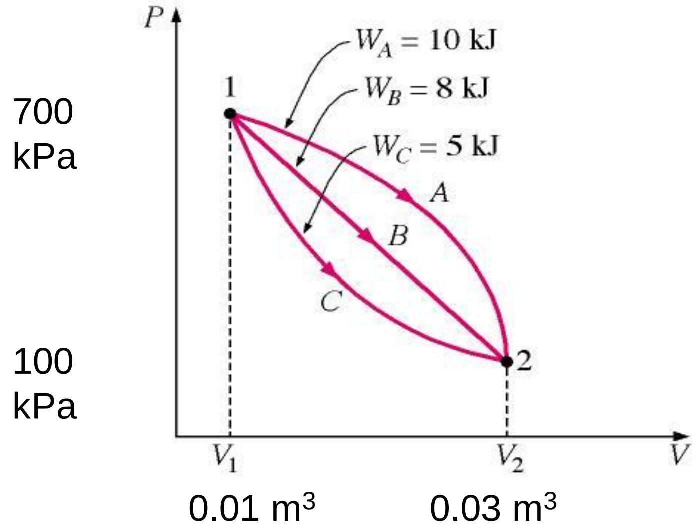
Since heat and work are path dependent functions, they have inexact differentials designated by the symbol δ. The differentials of heat and work are expressed as δQ and δW. The integral of the differentials of heat and work over the process path gives the amount of heat or work transfer that occurred at the system boundary during a process.

$$\int_{1,\,along\ path}^{2} \delta Q = Q_{12} \qquad \text{(not } \Delta Q\text{)}$$

$$\int_{1,\,along\ path}^{2} \delta W = W_{12} \qquad \text{(not } \Delta W\text{)}$$

That is, the total heat transfer or work is obtained by following the process path and adding the differential amounts of heat (δQ) or work (δW) along the way. The integrals of δQ and δW are not $Q_2 - Q_1$ and $W_2 - W_1$, respectively, which are meaningless since both heat and work are not properties and systems do not possess heat or work at a state.

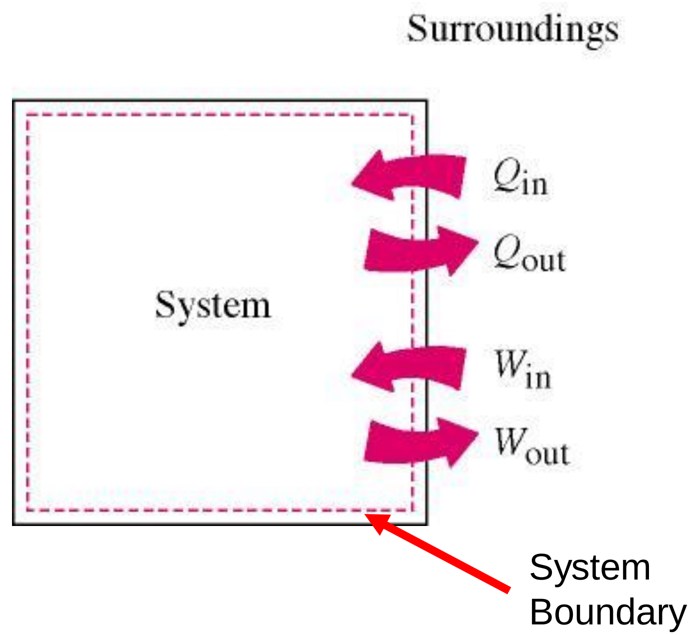
The following figure illustrates that properties (P, T, v, u, etc.) are point functions, that is, they depend only on the states. However, heat and work are path functions, that is, their magnitudes depend on the path followed.



A sign convention is required for heat and work energy transfers, and the classical thermodynamic sign convention is selected for these notes. According to the classical sign convention, heat transfer ***to*** a system and work ***done by*** a system are positive; heat transfer ***from*** a system and work a system are negative. The system shown below has heat supplied to it and work done by it.

In this study guide we will use the concept of net heat and net work.

A discussion of the global energy balance for the earth may be found at http://earthguide.ucsd.edu/earthguide/diagrams/energybalance/index.html



Energy Transport by Heat

Recall that heat is energy in transition across the system boundary solely due to the temperature difference between the system and its surroundings. The net heat transferred to a system is defined as

$$Q_{net} = \sum Q_{in} - \sum Q_{out}$$

Here, Q_{in} and Q_{out} are the magnitudes of the heat transfer values. In most thermodynamics texts, the quantity Q is meant to be the net heat transferred to the system, Q_{net}. Since heat transfer is process dependent, the differential of heat transfer δQ is called inexact. We often think about the heat transfer per unit mass of the system, q.

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

Heat transfer has the units of energy measured in joules (we will use kilojoules, kJ) or the units of energy per unit mass, kJ/kg.

Since heat transfer is energy in transition across the system boundary due to a temperature difference, there are three modes of heat transfer at the boundary that depend on the temperature difference between the boundary surface and the surroundings. These are conduction, convection, and radiation. However, when solving problems in thermodynamics involving heat transfer to a system, the heat transfer is usually given or is calculated by applying the first law, or the conservation of energy, to the system.

An **adiabatic** process is one in which the system is perfectly insulated and the heat transfer is zero.

Introduction to the Basic Heat Transfer Mechanisms

For those of us who do not have the opportunity to have a complete course in heat transfer theory and applications, the following is a short introduction to the basic mechanisms of heat transfer. Those of us who have a complete course in heat transfer theory may elect to omit this material at this time.

Heat transfer is energy in transition due to a temperature difference. The three modes of heat transfer are conduction, convection, and radiation.

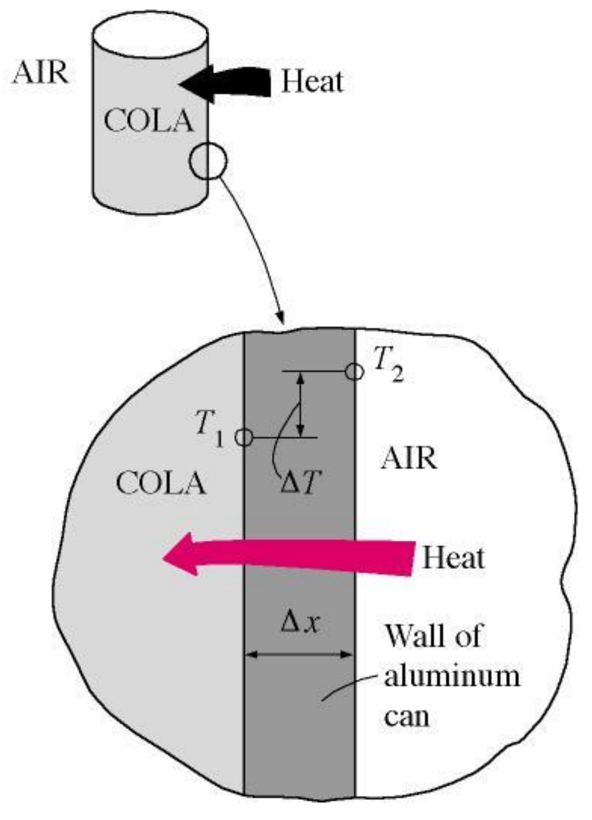
A discussion of these topics may be found at

http://www.school-for-champions.com/Science/heat_transfer.htm

http://www.wisc-online.com/objects/index_tj.asp?objID=SCE304

Conduction through Plane Walls

Conduction heat transfer is a progressive exchange of energy between the molecules of a substance.



Fourier's law of heat conduction is

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

here $\dot{Q}_{cond}$

$\frac{dT}{dx}$ = heat flow per unit time (W)

k_t = thermal conductivity (W/m·K)

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

= temperature gradient in the direction of heat flow (°C/m)

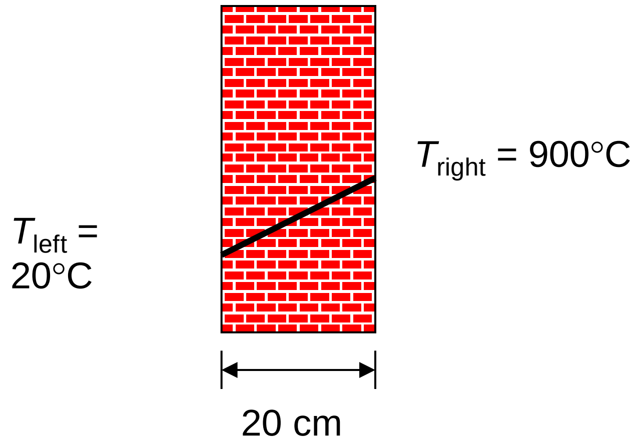
Integrating Fourier's law

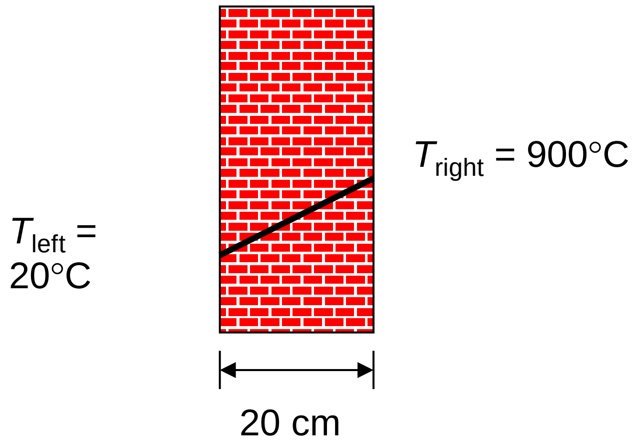
$$\dot{Q}_{cond} = k_t A \frac{\Delta T}{\Delta x}$$

Since $T_2 > T_1$, the heat flows from right to left in the above figure.

Example 2-1

A flat wall is composed of 20 cm of brick having a thermal conductivity k_t = 0.72 W/m·K. The right face temperature of the brick is 900°C, and the left face temperature of the brick is 20°C. Determine the rate of heat conduction through the wall per unit area of wall.





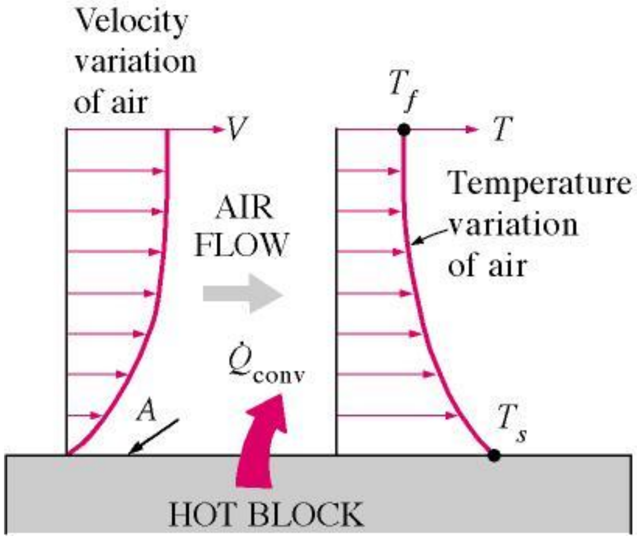
$$\dot{Q}_{cond} = k_t A \frac{\Delta T}{\Delta x}$$

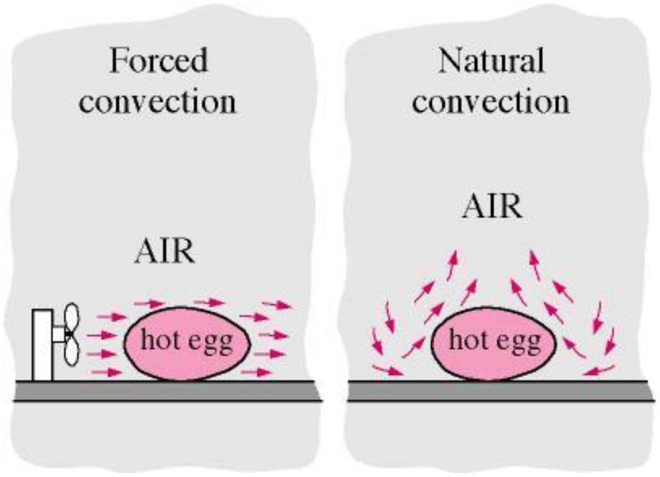
$$\frac{\dot{Q}_{cond}}{A} = k_t \frac{\Delta T}{\Delta x} = 0.72 \frac{W}{m \cdot K} \frac{(900-20)K}{0.2m}$$

$$= 3168 \frac{W}{m^2}$$

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.

Newton's law of cooling is expressed as

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

here

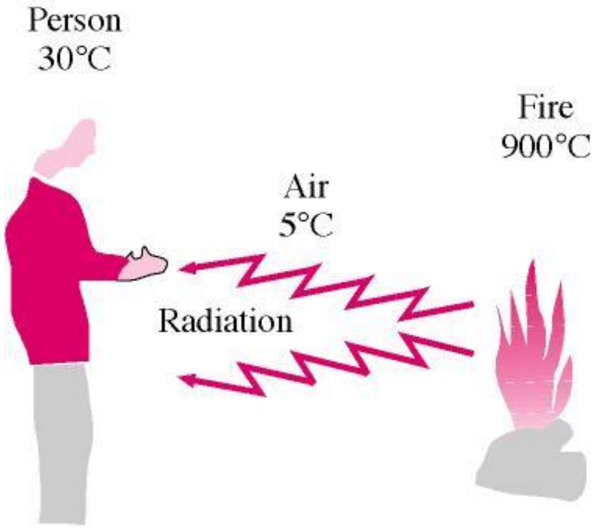
$\dot{Q}_{conv}$	= heat transfer rate (W)
A	= heat transfer area (m^2)
h	= convective heat transfer coefficient ($W/m^2 \cdot K$)
T_s	= surface temperature (K)
T_f	= bulk fluid temperature away from the surface (K)

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/m²·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 Stefan-Boltzmann law states that the maximum radiative heat transfer per unit surface area that may be emitted by a surface is given by product of the Stefan-Boltzmann constant and the fourth power of the absolute temperature of the surface. The radiative energy transferred is proportional to the difference in the fourth power of the absolute temperatures of the bodies exchanging energy.



For a small surface exchanging net radiative energy with its larger surroundings, the rate of radiative heat transfer exchange between the two surfaces is given by

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

here

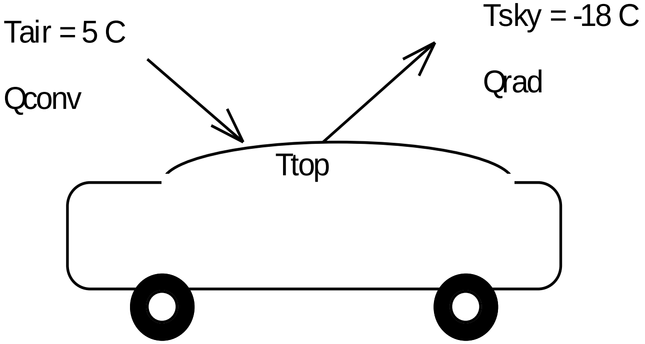
$\dot{Q}_{rad}$ = heat transfer per unit time (W)
A = surface area for heat transfer (m^2)
σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2K^4 and 0.1713×10^{-8} BTU/h ft^2 R^4
ε = emissivity
T_s = absolute temperature of surface (K)
T_{surr} = absolute temperature of surroundings (K)

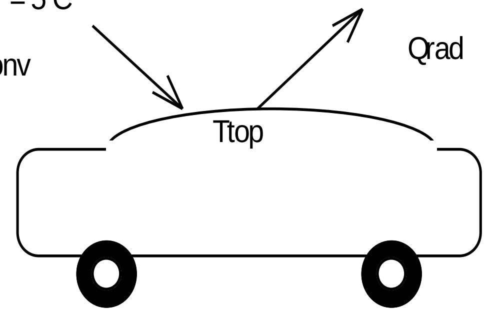
Example 2-2

A vehicle is to be parked overnight in the open away from large surrounding objects. It is desired to know if dew or frost may form on the vehicle top. Assume the following:

- Convection coefficient *h* from ambient air to vehicle top is 6.0 $W/m^2 \cdot {}^\circ C$.
- Equivalent sky temperature is -18°C.
- Emissivity of vehicle top is 0.84.
- Negligible conduction from inside vehicle to top of vehicle.

Determine the temperature of the vehicle top when the air temperature is 5°F. State which formation (dew or frost) occurs.





Under steady-state conditions, the energy convected to the vehicle top is equal to the energy radiated to the sky.

$$\dot{Q}_{conv} = \dot{Q}_{rad}$$

The energy convected from the ambient air to the vehicle top is

$$\dot{Q}_{conv} = A_{top}\, h\,(T_{air} - T_{top})$$

The energy radiated from the top to the night sky is

$$\dot{Q}_{rad} = \varepsilon\sigma A_{top}\left(T_{top}^4 - T_{sky}^4\right)$$

Setting these two heat transfers equal gives

$$A_{top} h\left(T_{air} - T_{top}\right) = \varepsilon\sigma A_{top}\left(T_{top}^4 - T_{sky}^4\right)$$

$$h\left(T_{air} - T_{top}\right) = \varepsilon\sigma\left(T_{top}^4 - T_{sky}^4\right)$$

$$6.0\frac{W}{m^2K}\left[\left(5+273\right) - T_{top}\right]K$$

$$= \left(0.84\right)\left(5.67x10^{-8}\frac{W}{m^2K^4}\right)\left[T_{top}^4 - \left(-18+273\right)^4\right]K^4$$

Write the equation for T_{top} in C (T K = TC + 273)

$$\left(5 - T_{top}\right) = \frac{\left(0.84\right)\left(5.67\right)}{6.0}\left[\left(\frac{T_{top}+273}{100}\right)^4 - \left(2.55\right)^4\right]$$

Using the EES software package

$$T_{top} = -3.38\,^\circ\mathrm{C}$$

Since T_{top} is below the triple point of water, 0.01°C, the water vapor in the air will form frost on the car top (see Chapter 14).

Extra Problem

Explore what happens to T_{top} as you vary the convective heat transfer coefficient. On a night when the atmosphere is particularly still and cold and has a clear sky, why do fruit growers use fans to increase the air velocity in their fruit groves?

Energy Transfer by Work

Electrical Work

The rate of electrical work done by electrons crossing a system boundary is called electrical power and is given by the product of the voltage drop in volts and the current in amps.

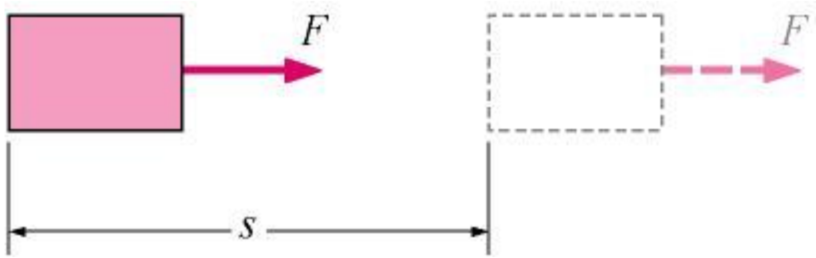
$$\dot{W}_e = V\,I \qquad \text{(W)}$$

The amount of electrical work done in a time period is found by integrating the rate of electrical work over the time period.

$$W_e = \int_1^2 V\,I\,dt \qquad \text{(kJ)}$$

Mechanical Forms of Work

Work is energy expended by a force acting through a distance. Thermodynamic work is defined as energy in transition across the system boundary and is done by a system if the sole effect external to the boundaries could have been the raising of a weight.



Mathematically, the differential of work is expressed as

$$\delta W = \vec{F} \cdot d\vec{s} = F\, ds \cos\Theta$$

here Θ is the angle between the force vector and the displacement vector.
As with the heat transfer, the Greek symbol δ means that work is a path-dependent function and has an inexact differential. If the angle between the force and the displacement is zero, the work done between two states is

$$W_{12} = \int_1^2 \delta W = \int_1^2 F ds$$

Work has the units of energy and is defined as force times displacement or newton times meter or joule (we will use kilojoules). Work per unit mass of a system is measured in kJ/kg.

Common Types of Mechanical Work Energy (See text for discussion of these topics)

- Shaft Work
- Spring Work
- Work done of Elastic Solid Bars
- Work Associated with the Stretching of a Liquid Film
- Work Done to Raise or to Accelerate a Body

Net Work Done By A System

The net work done by a system may be in two forms other work and boundary work. First, work may cross a system boundary in the form of a rotating shaft work, electrical work or other the work forms listed above. We will call these work forms "other" work, that is, work not associated with a moving boundary. In thermodynamics electrical energy is normally considered to be work energy rather than heat energy; however, the placement of the system boundary dictates whether to include electrical energy as work or heat. Second, the system may do work on its surroundings because of moving boundaries due to expansion or compression processes that a fluid may experience in a piston-cylinder device.

The net work done by a closed system is defined by

$$W_{net} = \left(\sum W_{out} - \sum W_{in}\right)_{other} + W_b$$

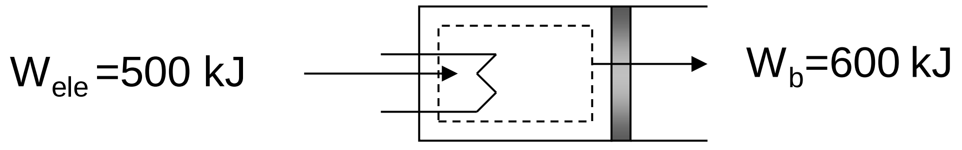
Here, W_{out} and *W*in are the magnitudes of the other work forms crossing the boundary. W_b is the work due to the moving boundary as would occur when a gas contained in a piston cylinder device expands and does work to move the piston. The boundary work will be positive or negative depending upon the process. Boundary work is discussed in detail in Chapter 4.

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

Several types of “other” work (shaft work, electrical work, etc.) are discussed in the text.

Example 2-3

A fluid contained in a piston-cylinder device receives 500 kJ of electrical work as the gas expands against the piston and does 600 kJ of boundary work on the piston. What is the net work done by the fluid?



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

$$W_{net} = \left(W_{out} - W_{in,ele}\right)_{other} + W_b$$

$$W_{net} = \left(0 - 500\,kJ\right) + 600\,kJ$$

$$W_{net} = 100\,kJ$$

The First Law of Thermodynamics

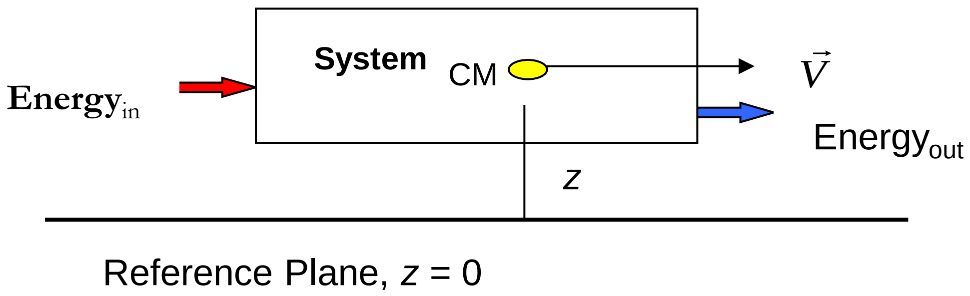
The first law of thermodynamics is known as the conservation of energy principle. It states that energy can be neither created nor destroyed; it can only change forms. Joule's experiments lead to the conclusion: For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process. A major consequence of the first law is the existence and definition of the property total energy E introduced earlier.

The First Law and the Conservation of Energy

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 may cross a system boundary (control surface) of an open system by heat, work and mass transfer.

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

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

or

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

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**, $\boldsymbol{E}_{\mathbf{system}}$, is given as

$$E = Internal\ energy\ +\ Kinetic\ energy\ +\ Potential\ energy$$

$$E = U + KE + PE$$

Recall that *U* is the sum of the energy contained within the molecules of the system other than the kinetic and potential energies of the system as a whole and is called the internal energy. The internal energy *U* is dependent on the state of the system and the mass of the system.

For a system moving relative to a reference plane, the kinetic energy *KE* and the potential energy *PE* are given by

$$KE = \int_{\vec{V}=0}^{\vec{V}} m\vec{V}\,d\vec{V} = \frac{m\vec{V}^2}{2}$$

$$PE = \int_{z=0}^{z} mg\,dz = mgz$$

The change in stored energy for the system is

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

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

$$E_{in} - E_{out} = \Delta U + \Delta KE + \Delta PE$$

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

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

Mechanisms of Energy Transfer, Ein and Eout

The mechanisms of energy transfer at a system boundary are: Heat, Work, mass flow. Only heat and work energy transfers occur at the boundary of a closed (fixed mass) system. Open systems or control volumes have energy transfer across the control surfaces by mass flow as well as heat and work.

1. Heat Transfer, Q: Heat is energy transfer caused by a temperature difference between the system and its surroundings. When added to a system heat transfer causes the energy of a system to increase and heat transfer from a system causes the energy to decrease. Q is zero for adiabatic systems.

2. Work, W: Work is energy transfer at a system boundary could have caused a weight to be raised. When added to a system, the energy of the system increases; and when done by a system, the energy of the system decreases. W is zero for systems having no work interactions at its boundaries.

3. Mass flow, m: As mass flows into a system, the energy of the system increases by the amount of energy carried with the mass into the system. Mass leaving the system carries energy with it, and the energy of the system decreases. Since no mass transfer occurs at the boundary of a closed system, energy transfer by mass is zero for closed systems.

The energy balance for a general system is

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

Expressed more compactly, the energy balance is

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \qquad (kJ)$$

or on a rate form, as

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

For constant rates, the total quantities during the time interval Δt are related to the quantities per unit time as

$$Q = \dot{Q}\,\Delta t, \quad W = \dot{W}\,\Delta t, \quad \text{and} \quad \Delta E = \Delta \dot{E}\,\Delta t \quad (kJ)$$

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

$$e_{in} - e_{out} = \Delta e_{system} \qquad (kJ/kg)$$

and in the differential forms as

$$\delta E_{in} - \delta E_{out} = \delta E_{system} \qquad (kJ)$$

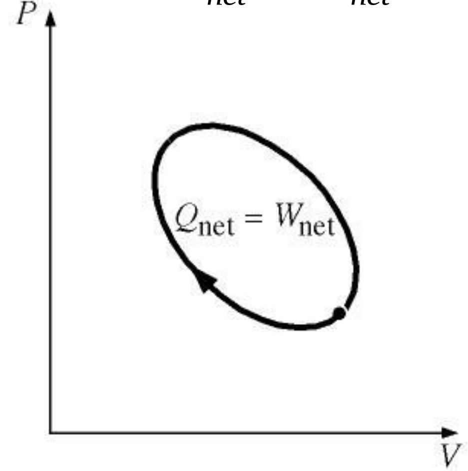
$$\delta e_{in} - \delta e_{out} = \delta e_{system} \qquad (kJ/kg)$$

First Law for a Cycle

A thermodynamic cycle is composed of processes that cause the working fluid to undergo a series of state changes through a process or a series of processes. These processes occur such that the final and initial states are identical and the change in internal energy of the working fluid is zero for whole numbers of cycles. Since thermodynamic cycles can be viewed as having heat and work (but not mass) crossing the cycle system boundary, the first law for a closed system operating in a thermodynamic cycle becomes

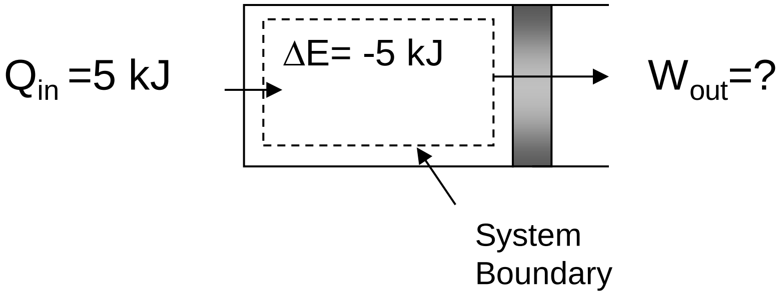
$$Q_{net} - W_{net} = \Delta E_{cycle}$$

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



Example 2-4

A system receives 5 kJ of heat transfer and experiences a decrease in energy in the amount of 5 kJ. Determine the amount of work done by the system.



We apply the first law as

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

$$E_{in} = Q_{in} = 5\,kJ$$

$$E_{out} = W_{out}$$

$$\Delta E_{system} = -5\,kJ$$

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

$$W_{out} = \left[5 - (-5)\right] kJ$$

$$W_{out} = 10\,kJ$$

The work done by the system equals the energy input by heat plus the decrease in the energy of the working fluid.

Example 2-5

A steam power plant operates on a thermodynamic cycle in which water circulates through a boiler, turbine, condenser, pump, and back to the boiler. For each kilogram of steam (water) flowing through the cycle, the cycle receives 2000 kJ of heat in the boiler, rejects 1500 kJ of heat to the environment in the condenser, and receives 5 kJ of work in the cycle pump. Determine the work done by the steam in the turbine, in kJ/kg.

For a thermodynamic cycle, the first law becomes

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

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

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

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

$$\text{Let} \quad w = \frac{W}{m} \quad \text{and} \quad q = \frac{Q}{m}$$

$$w_{out} = q_{in} - q_{out} + w_{in}$$

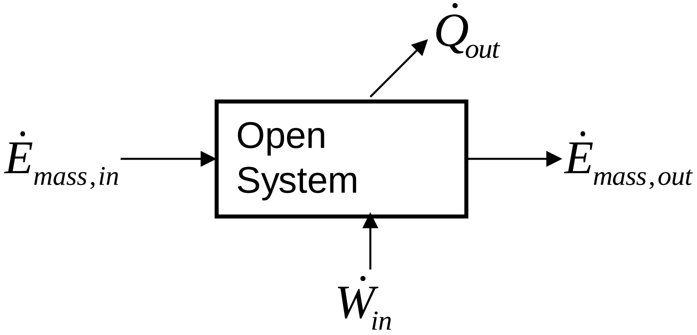
$$w_{out} = \left(2000 - 1500 + 5\right) \frac{kJ}{kg}$$

$$w_{out} = 505 \frac{kJ}{kg}$$

Example 2-6

Air flows into an open system and carries energy at the rate of 300 kW. As the air flows through the system it receives 600 kW of work and loses 100 kW of energy by heat transfer to the surroundings. If the system experiences no energy change as the air flows through it, how much energy does the air carry as it leaves the system, in kW?

System sketch:



Conservation of Energy:

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

$$\dot{E}_{mass,in} + \dot{W}_{in} - \dot{E}_{mass,out} - \dot{Q}_{out} = \Delta\dot{E}_{system} = 0$$

$$\dot{E}_{mass,out} = \dot{E}_{mass,in} + \dot{W}_{in} - \dot{Q}_{out}$$

$$\dot{E}_{mass,out} = \left(300 + 600 - 100\right) kW = 800\, kW$$

Energy Conversion Efficiencies

A measure of performance for a device is its efficiency and is often given the symbol η. Efficiencies are expressed as follows:

$$\eta = \frac{\text{Desired Result}}{\text{Required Input}}$$

How will you measure your efficiency in this thermodynamics course?

Efficiency as the Measure of Performance of a Thermodynamic cycle

A system has completed a thermodynamic cycle when the working fluid undergoes a series of processes and then returns to its original state, so that the properties of the system at the end of the cycle are the same as at its beginning.

Thus, for whole numbers of cycles

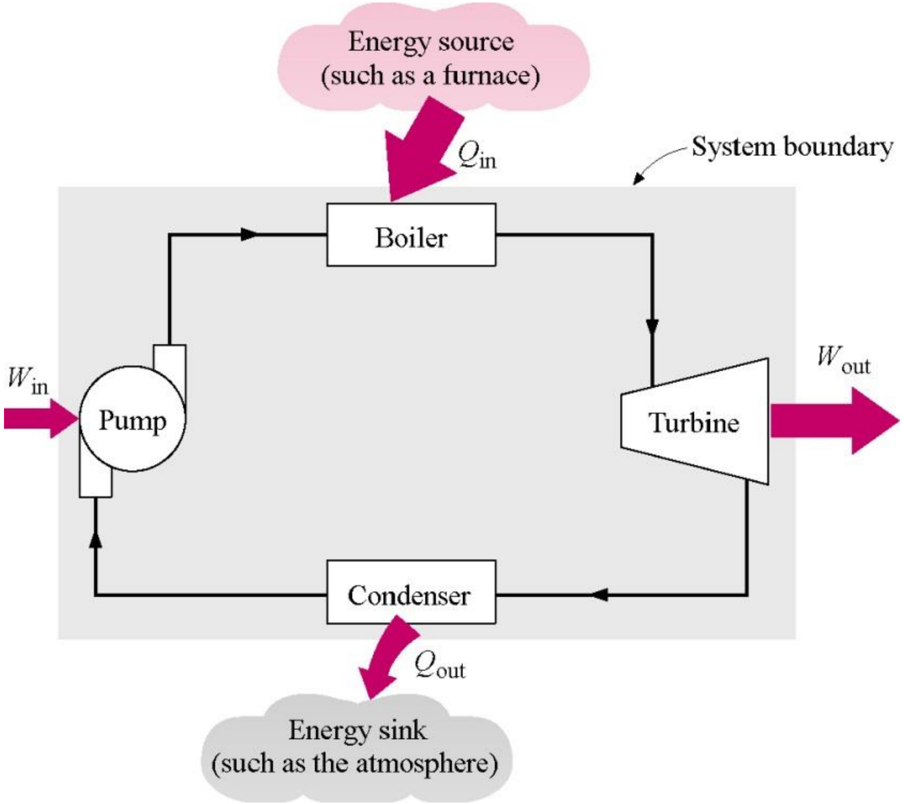
$$P_f = P_i,\; T_f = T_i,\, u_f = u_i,\, v_f = v_i,\, etc.$$

Heat Engine

A heat engine is a thermodynamic system operating in a thermodynamic cycle to which net heat is transferred and from which net work is delivered.

The system, or working fluid, undergoes a series of processes that constitute the heat engine cycle.

The following figure illustrates a steam power plant as a heat engine operating in a thermodynamic cycle.



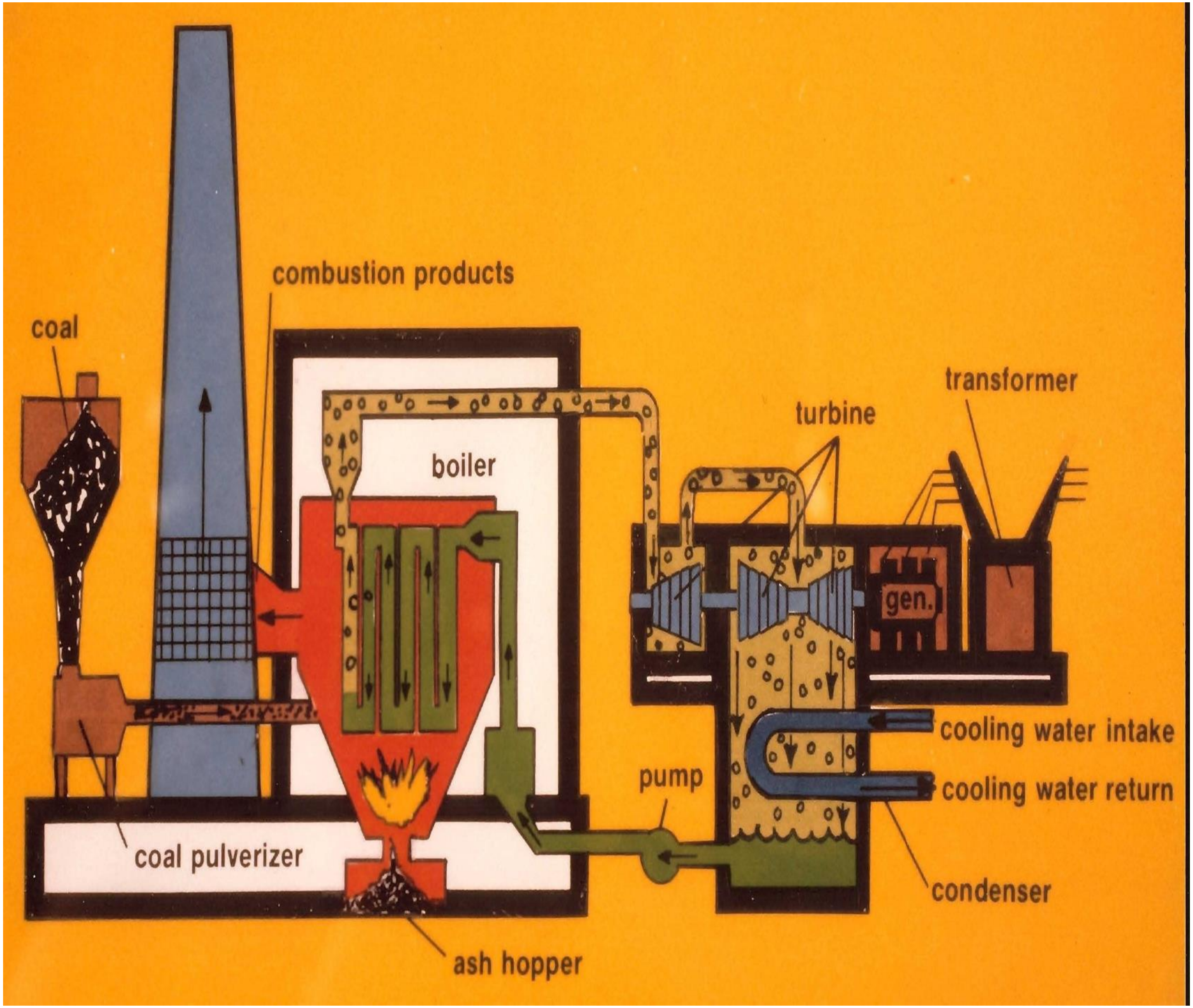


Photo courtesy of Progress Energy Carolinas, Inc.

Thermal Efficiency, ηth

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 cost or required input 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 (W_{out} – W_{in}) and the input is the heat supplied to make the cycle operate Q_{in}. The thermal efficiency is always less than 1 or less than 100 percent.

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

where

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

$$Q_{in} \neq Q_{net}$$

Here, the use of the *in* and *out* subscripts means to use the magnitude (take the positive value) of either the work or heat transfer and let the minus sign in the net expression take care of the direction.

Example 2-7

In example 2-5 the steam power plant received 2000 kJ/kg of heat, 5 kJ/kg of pump work, and produced 505 kJ/kg of turbine work. Determine the thermal efficiency for this cycle.

We can write the thermal efficiency on a per unit mass basis as:

$$\eta_{th} = \frac{w_{net,\,out}}{q_{in}}$$

$$= \frac{w_{out} - w_{in}}{q_{in}} = \frac{(505-5)\dfrac{kJ}{kg}}{2000\dfrac{kJ}{kg}}$$

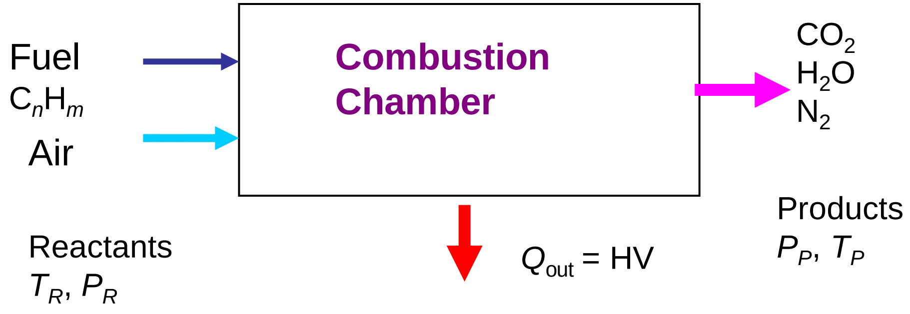
$$= 0.25 \quad \text{or} \quad 25\%$$

Combustion Efficiency

Consider the combustion of a fuel-air mixture as shown below.

Combustion Efficiency

Consider the combustion of a fuel-air mixture as shown below.



Fuels are usually composed of a compound or mixture containing carbon, C, and hydrogen, H_2. During a complete combustion process all of the carbon is converted to carbon dioxide and all of the hydrogen is converted to water. For stoichiometric combustion (theoretically correct amount of air is supplied for complete combustion) where both the reactants (fuel plus air) and the products (compounds formed during the combustion process) have the same temperatures, the heat transfer from the combustion process is called the heating value of the fuel.

The **lower heating value, LHV**, is the heating value when water appears as a gas in the products.

$$LHV = Q_{out} \;\; with \; H_2O_{vapor} \;\; in \;\; products$$

The lower heating value is often used as the measure of energy per kg of fuel supplied to the gas turbine engine because the exhaust gases have such a high temperature that the water formed is a vapor as it leaves the engine with other products of combustion.

The **higher heating value, HHV**, is the heating value when water appears as a liquid in the products.

$$HHV = Q_{out} \;\; with \; H_2O_{liquid} \;\; in \;\; products$$

The higher heating value is often used as the measure of energy per kg of fuel supplied to the steam power cycle because there are heat transfer processes within the cycle that absorb enough energy from the products of combustion that some of the water vapor formed during combustion will condense.

Combustion efficiency is the ratio of the actual heat transfer from the combustion process to the heating value of the fuel.

$$\eta_{combustion} = \frac{Q_{out}}{HV}$$

Combustion Efficiency

Combustion efficiency is the ratio of the actual heat transfer from the combustion process to the heating value of the fuel.

$$\eta_{combustion} = \frac{Q_{out}}{HV}$$

Example 2-8

A steam power plant receives 2000 kJ of heat per unit mass of steam flowing through the steam generator when the steam flow rate is 100 kg/s. If the fuel supplied to the combustion chamber of the steam generator has a higher heating value of 40,000 kJ/kg of fuel and the combustion efficiency is 85%, determine the required fuel flow rate, in kg/s.

$$\eta_{combustion} = \frac{Q_{out}}{HV} = \frac{\dot{m}_{steam} q_{out\,to\,steam}}{\dot{m}_{fuel} HHV}$$

$$\dot{m}_{fuel} = \frac{\dot{m}_{steam} q_{out\,to\,steam}}{\eta_{combustion} HHV}$$

$$\dot{m}_{fuel} = \frac{\left(100 \frac{kg_{steam}}{s}\right)\left(2000 \frac{kJ}{kg_{steam}}\right)}{(0.85)\left(40000 \frac{kJ}{kg_{fuel}}\right)}$$

$$\dot{m}_{fuel} = 5.88 \frac{kg_{fuel}}{s}$$

Generator Efficiency:

$$\eta_{generator} = \frac{\dot{W}_{electrical\,output}}{\dot{W}_{mechanical\,input}}$$

Power Plant Overall Efficiency:

$$\eta_{overall} = \left(\frac{\dot{Q}_{in,cycle}}{\dot{m}_{fuel} HHV_{fuel}} \right) \left(\frac{\dot{W}_{net,cycle}}{\dot{Q}_{in,cycle}} \right) \left(\frac{\dot{W}_{net,electrical\,output}}{\dot{W}_{net,cycle}} \right)$$

$$\eta_{overall} = \eta_{combustion} \eta_{thermal} \eta_{generator}$$

$$\eta_{overall} = \frac{\dot{W}_{net,electrical\,output}}{\dot{m}_{fuel} HHV_{fuel}}$$

Motor Efficiency:

$$\eta_{motor} = \frac{\dot{W}_{mechanical\,output}}{\dot{W}_{electrical\,input}}$$

Lighting Efficacy:

$$Lighting\ \ Efficacy = \frac{\text{Amount of Light in Lumens}}{\text{Watts of Electricity Consumed}}$$

Type of lighting	Efficacy, lumens/W
Ordinary Incandescent	6 - 20
Ordinary Fluorescent	40 - 60

Effectiveness of Conversion of Electrical or chemical Energy to Heat for Cooking, Called Efficacy of a Cooking Appliance:

$$Cooking\ \ Efficacy = \frac{\text{Useful Energy Transferred to Food}}{\text{Energy Consumed by Appliance}}$$