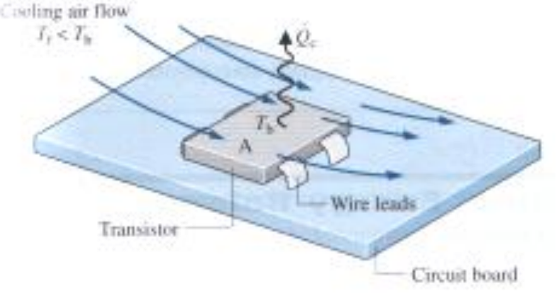
Convection Heat Transfer

Convection is energy transfer between a solid surface and an adjacent gas or liquid by the combined effects of conduction and bulk flow within the gas or liquid.

The rate of energy transfer by convection is quantified by *Newton's law of cooling*.

$$\dot{Q}_c = hA(T_b - T_f)$$



A : surface area (m^2)
h : heat transfer coefficient (W/m^2 K)

h is not a thermodynamic property.

NOTES:

- Both heat and work are recognized at the boundary of a system as they cross the boundaries. That is both heat and work are boundary phenomena.
- System possess energy, but not heat or work.
- Both heat and work are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.
- Both heat and work are path functions. Their magnitudes depend on the path followed during a process.

Path functions and point functions:

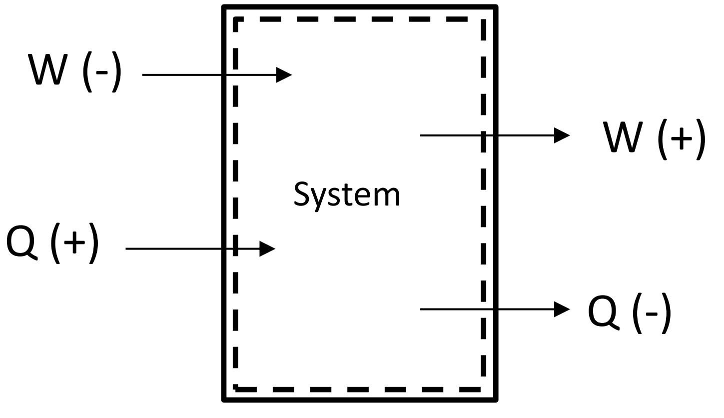
Path functions: Depend on process path as well as initial and final states.

Heat and work are path functions
They have inexact differentials, hence δQ and δW instead of dQ and dW symbols are used.

Point functions:
Depend on initial and final states, not on how a system reaches that state

Properties are point functions
They have exact differentials, hence dT, dP, dV, etc. Symbols are used.

SIGN CONVENTION



Thermodynamics frequently concerned with devices such as internal combustion engines and turbines. The purpose of such devices are to do work. Hence. Often it is convenient to consider work done by devices (system) as positive. That is,

$W>0$, if work done by the system
$W<0$, if work done on the system.

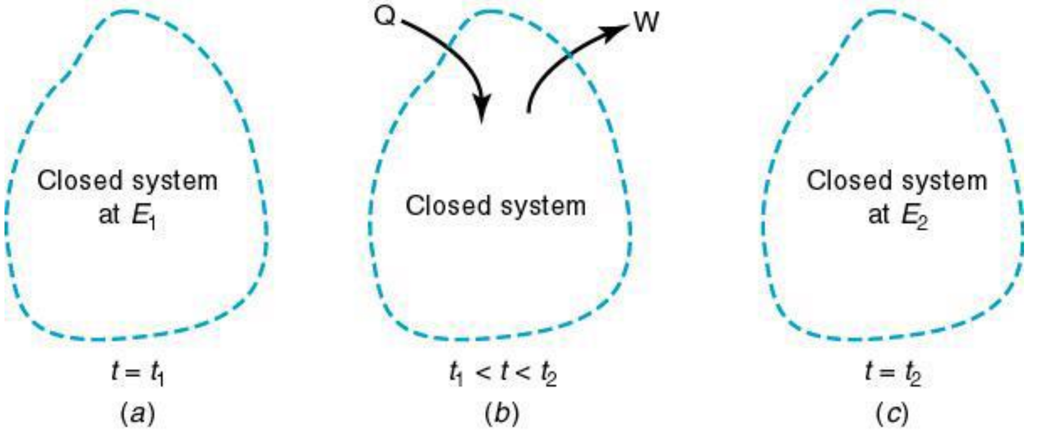
Heat transfer into a system is taken to be positive, and heat transfer from a system to surrounding is taken to be negative.

$Q>0$, if heat is transferred to the system
$Q<0$, if heat is transferred from the system.

ENRGY BALANCE AND THE FIRST LAW OF THERMODYNAMICS FOR CLOSED SYSTEMS

The first law of thermodynamics states that energy is conserved, it neither can be created nor destroyed.

Only ways the energy of a closed system can be changed are through transfer of energy by work and/or by heat. The first law of thermodynamics provides the basis for studying the relationships among the various forms of the energy and energy interactions.



$$\left\{\begin{array}{l}\text{change in amount}\\ \text{of energy contained}\\ \text{within the system}\\ \text{during some time}\\ \text{interval}\end{array}\right\} = \left\{\begin{array}{l}\text{net amount of energy}\\ \text{transferred in across}\\ \text{the system boundary}\\ \text{by heat transfer during}\\ \text{the time interval}\end{array}\right\} - \left\{\begin{array}{l}\text{net amount of energy}\\ \text{transferred out across}\\ \text{the system boundary}\\ \text{by work during}\\ \text{the time interval}\end{array}\right\}$$

Energy balance for a closed system can be expresses in symbols as

$$\Delta E = Q - W$$

$$E_2 - E_1 = Q - W$$

$$E = U + \frac{1}{2}mV^2 + mgz + ...$$

$$E = U + KE + PE$$

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

$$Q - W = (U_2 - U_1) + \frac{m}{2}\left(V_2^2 - V_1^2\right) + mg(z_2 - z_1)$$

In above equations, the algebraic signs before the heat and work terms are different. This is due to the sign convention adopted.

Other Forms of Energy Balance Equation
(Equation of the first law of thermodynamics)

Various special forms of energy balance can be written.

The energy balance in differential form:

$$dE = \delta Q - \delta W$$

dE is the differential of energy, a property. Since **Q** and **W** are not properties, their differentials are written as δQ and δW, respectively.

The instantaneous **time rate form of the energy balance** is:

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

$$\begin{Bmatrix} \text{time rate of} \\ \text{change of energy} \\ \text{contained within} \\ \text{the system} \\ \text{at time t} \end{Bmatrix} = \begin{Bmatrix} \text{net rate at which} \\ \text{energy is being transferred} \\ \text{by heat transfer} \\ \text{at time t} \end{Bmatrix} - \begin{Bmatrix} \text{net rate at which} \\ \text{energy is being} \\ \text{transferred} \\ \text{by work} \\ \text{at time t} \end{Bmatrix}$$

Since the time rate of change of energy is sum of the time rate of change of KE, PE and internal energy, the above equation can be written as,

$$\frac{dKE}{dt} + \frac{dPE}{dt} + \frac{dU}{dt} = \dot{Q} - \dot{W}$$

When applying the energy balance in any of its forms, it is important to be careful about signs and units and to distinguish carefully between rates and amounts.

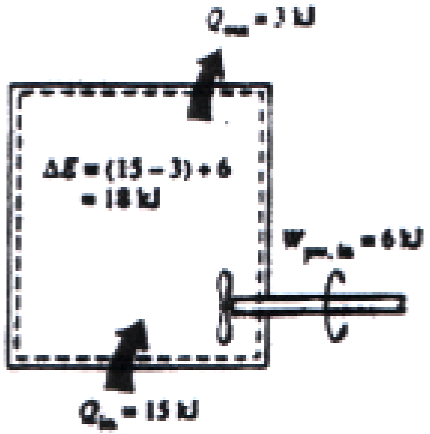
Note:

E: [kJ]   dE/dt: [kJ/s]

Q: [kJ] $\dot{Q} = \delta Q/dt$ [kJ/s]

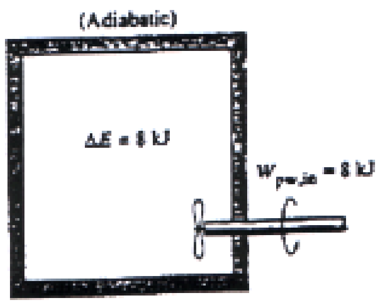
Q: [kJ] $\dot{W} = \delta W/dt$: [kJ/s]

Examples: Determine the total energy change of the systems below.

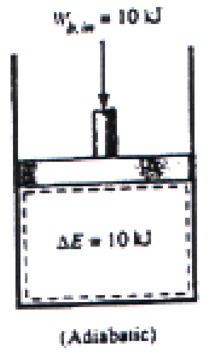


$$\Delta E = Q_{net} - W_{pw} = (15\,kJ - 3\,kJ) - (-6\,kJ) = 18\,kJ$$

Note: The increase in energy of the system is equal to the net energy transfer to the system.

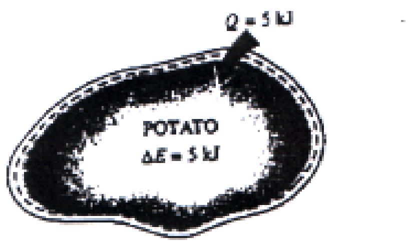


$$\Delta E = Q_{net} - W_{pw} = 0 - (-8\,kJ) = 8\,kJ$$

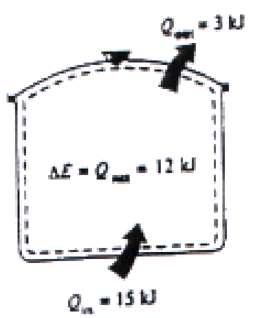


Note: The increase in energy of the system is equal to the work done on the system.

$$\Delta E = Q_{net} - W_{pw} = 0 - (-10\,kJ) = 10\,kJ$$



$$\Delta E = Q_{net} - W_{pw} = 5 - 0 = 5\,kJ$$



Note: The increase in energy of the system is equal to net heat transfer to the system.

$$\Delta E = Q_{net} - W_{pw} = (15 - 3) - (0) = 12\,kJ$$

Example:
Within a piston-cylinder assembly **4 kg** of a certain gas is contained . The gas undergoes a process for which the pressure-volume relationship is

$$pV^{1.5} = \text{constant}$$

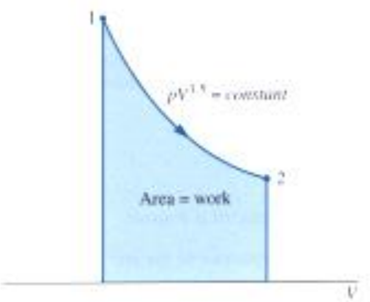
The initial pressure is **3 bar**, the initial volume is **0.1 m³**, and the final volume is **0.2 m³**. The change in specific internal energy of the gas in the process is $u_2 - u_1 = -4.6$ **kj/kg**. There are no significant changes in kinetic and potential energies. Determine the net heat transfer for the process, in **kJ**.

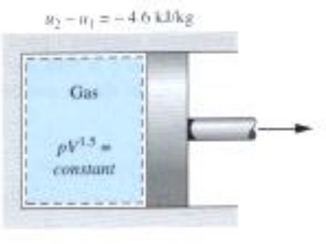
Solution:
Known: A gas in a piston-cylinder assembly undergoes an expansion for which the pressure-volume relation and the change in specific internal energy are specified

$$m = 4\text{ kg},\ p_1=3\text{ bar},\ V_1=0.1\text{ m}^3,\ V_2=0.2\text{ m}^3,\ u_2-u_1=-4.6\text{kJ/kg}$$

Find: Evaluate the net heat transfer for the process. **Q = ?**

Schematic and Given Data:





Assumptions:
1) The gas is a closed system.
2) The process is described by $pV^{1.5}$ = **constant**.
3) There is no change in the kinetic or potential energy of the system.

Analysis: An energy balance for the closed system can be written as

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

Kinetic and potential energy changes are negligible. Hence, $\Delta KE = 0$, $\Delta PE = 0$

Total internal change can be calculated as, $\Delta U = m\,\Delta u = m\,(u_2-u_1)$

During the process, a moving boundary work is done. In the above example, the moving boundary work is calculated as **W= +17.6 kJ.**

Now Q can be solved from the energy balance equation as follows:

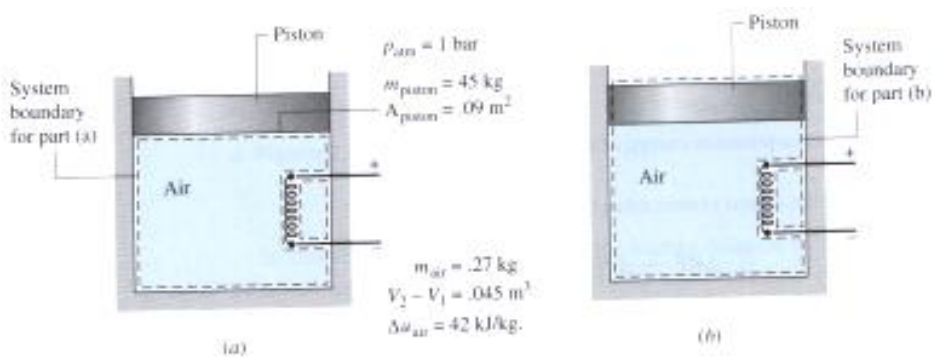
$$Q = m\,(u_2-u_1)+W = 4\text{ kg }(-4.6\text{ kJ/kg})+17.6\text{ kJ} = -18.4\text{ kJ} + 17.6\text{ kJ} = \mathbf{-0.8\ kJ}$$

Minus sign indicates that the heat is transferred from system to surrounding.

Example: Air is contained in a vertical piston-cylinder assembly fitted with an electrical resistor. The atmosphere exerts a pressure of **1 bar** on the top of the piston, which has a mass of **45 kg** and a face area of **0.09 m²**. Electric current passes through the resistor, and the volume of the air slowly increases by **0.045 m**³ while its pressure remains constant. The mass of the air is **0.27 kg**, and its specific internal energy increases by **42 kJ/kg**. The air and piston are at rest initially and finally. The piston-cylinder material is a ceramic composite and thus a **good insulator**. **Friction** between the piston and cylinder wall can be **ignored**, and the local acceleration of gravity is **g = 9.81 m/s²**. Determine the heat transfer from the resistor to the air, in **kJ**, for a system consisting of (a) the air alone, (b) the air and the piston.

Solution:
Known: Data are provided for air contained in a vertical piston-cylinder fitted with an electrical resistor.

Find: Considering each of two alternative systems, determine the heat transfer from the resistor to the air.
Schematic and Given Data:



Assumptions:
1) Two closed systems are under consideration, as shown in the schematic.
2) The only significant heat transfer is from the resistor to the air, during which the air expands slowly and its pressure remains constant.
3) There is **no net change in kinetic energy**; the change in potential energy of the air is negligible; and since the piston material is good insulator, the internal energy of the piston is not affected by the heat transfer.
4) **Friction** between the piston and cylinder wall is **negligible**.
5) The acceleration of gravity is constant; g = 9.81 m/s^2.

To be completed in class

Energy Analysis of Cycles

When a system at a given **initial state** goes through a sequence of processes and f**inally returns to that state,** the system has executed a thermodynamic cycle. The study of systems undergoing cycles has played an important role in the development of the subject of engineering thermodynamics. Both the first and second law of thermodynamics have roots in the study of cycles. In this section, cycles are considered from the perspective of the conservation of energy principle.

Cycle Energy Balance:
The energy balance for any system undergoing a **thermodynamic cycle** takes the form

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

Where
Q_{cyle}: Amount of energy transferred by heat transfer for cyle
W_{cyle}: Amount of energy transferred by work transfer for cyle

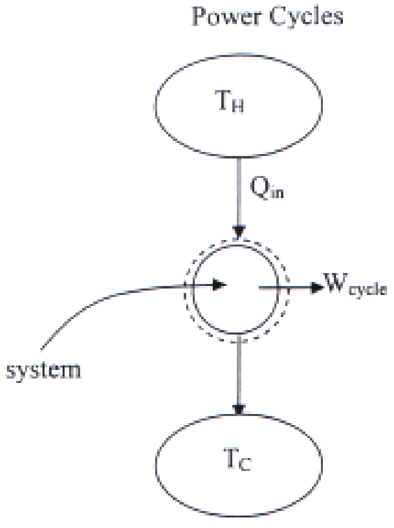
Since the system is returned to its initial state after the cycle, there is no net change in its energy. Therefore,

$$\Delta E_{cycle} = 0$$

Hence energy balance equation reduces to

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

Power Cycles:
Systems undergoing cycles of the type shown in the figure deliver a net work transfer of energy to their surroundings during each cycle. Any such cycle is called a **power cycle**.



System receives energy (heat), (Q_{in}), from a high temperature, (T_H), energy (heat) source (hot body), produces work, (W_{cyle}), and part of the heat, (Q_{out}), is rejected to a low temperature (T_C) body (surrounding).

The net work output equals the net heat transfer to the cycle, i.e.

$$\mathbf{W_{cyle} = Q_{in} - Q_{out}}$$

where
Q_{in}: the heat transfer into the system from the hot body
Q_{out}: heat transfer out of the system to the cold body

From conservation of energy, $Q_{in} > Q_{out}$

The **performance** of a system undergoing a power cycle can be described in terms of the extent to which the energy added by heat, Q_{in}, is converted to a net work output, $\mathbf{W_{cycle}}$. The extent of the energy conversion from heat to work is expressed by the following ratio, commonly called the **thermal efficiency** , η

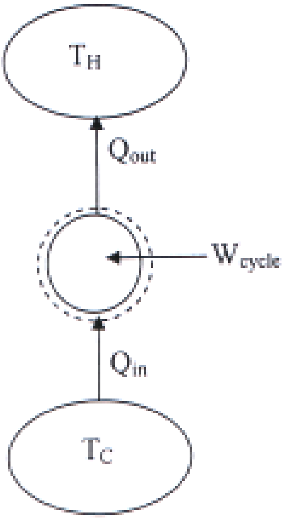
$$\eta = \frac{W_{cycle}}{Q_{in}}$$

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

The thermal efficiency can never be greater than unity (100%).

For an actual power cycle, $\mathbf{\eta < 1}$

Refrigeration Cycles:



Work is transferred to the system to extract heat from a low temperature body (i.e. inside of refrigerator) and transfer it to a high temperature body (surrounding).

Objective of a refrigerator is to further cool a low temperature body by transferring heat to a high temperature body.

NOTE: Heat always flow from a high temperature body to a low temperature body.

The performance of refrigeration cycles can be described as the ratio of the amount of energy received by the system undergoing the cycle from the cold body, $\mathbf{Q_{in}}$, to the net work into the system to accomplish this effect, $\mathbf{W_{cycle}}$. Thus, **the coefficient of performance**, β is

$$\beta = \frac{Q_{in}}{W_{cycle}}$$

Generally for a refrigerator, W_{cycle} is provided in the form of electricity.

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

Heat Pump Cycles:

Heat pumps work same as refrigerators. However, objective of refrigerator and heat pump are different.

Work is provided to the system, to extract heat from a low temperature body (i.e. surrounding, air, soil, water, etc.) and transfer it to a high temperature body (inside of a room, etc.).

Objective of a heat pump is to further heat a lhigh temperature body by transferring heat from a low temperature body.

The performance of heat pumps can be described as the ratio of the amount of energy discharged from the system undergoing the cycle to the hot body, Q_{out}, to the net work into the system to accomplish this effect, W_{cycle}. Thus, **the coefficient of performance, γ is**

$$\gamma = \frac{Q_{out}}{W_{cycle}} \qquad \gamma = \frac{Q_{out}}{Q_{out} - Q_{in}}$$