First Law of Thermodynamics

Reading: Chapter 18, Sections 18-7 to 18-11

Heat and Work

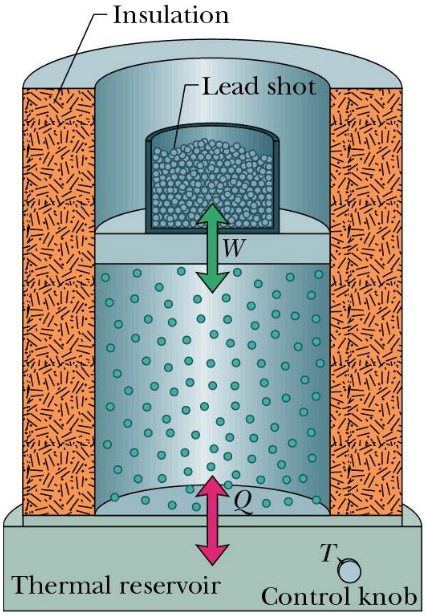


FIG. 18-13 A gas is confined to a cylinder with a movable piston. Heat Q can be added to or withdrawn from the gas by regulating the temperature T of the adjustable thermal reservoir. Work W can be done by the gas by raising or lowering the piston.

When the piston is displaced by $d\vec{s}$,
force exerted by the gas = $F = pA$,
work done by the gas:

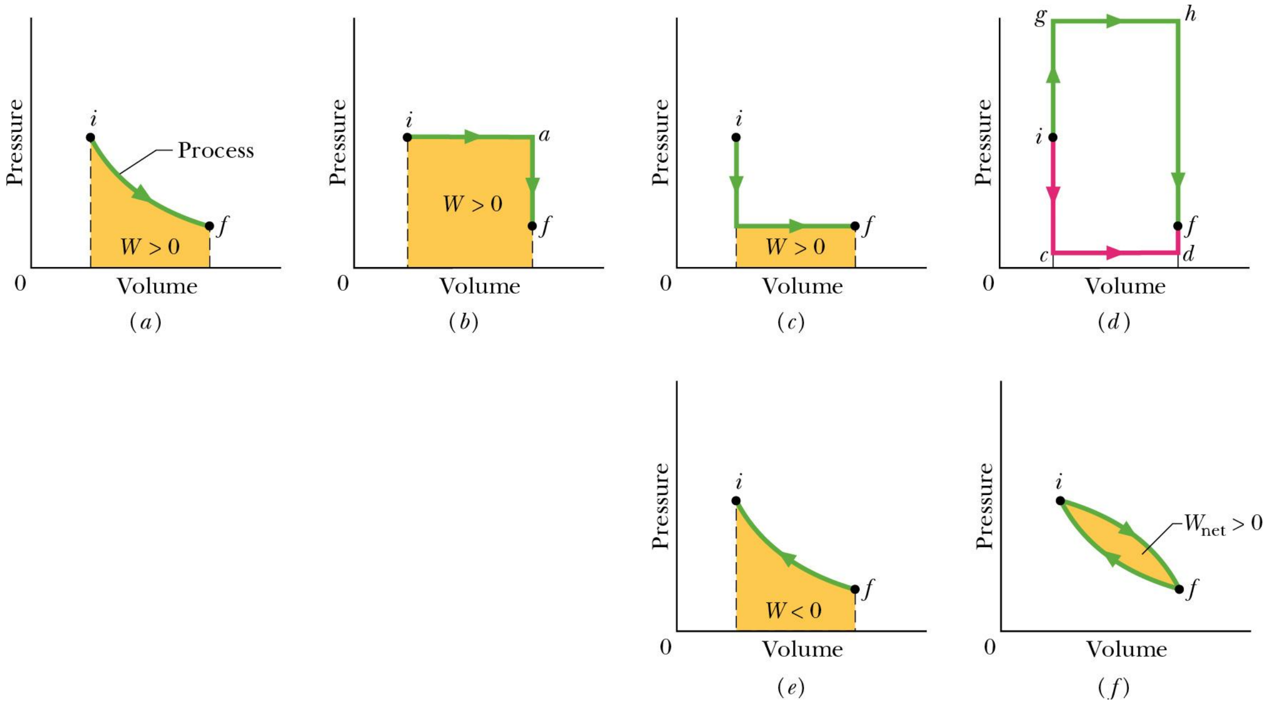
$$dW = \vec{F} \cdot d\vec{s} = (pA)(ds) = p(A\,ds) = p\,dV.$$

When the volume of the gas changes from V_i to V_f, total work done:

$$\boxed{W = \int dW \;\; = \int_{V_i}^{V_f} p\,dV \;\; .}$$

This work done is represented by the area under the *p*-*V* curve in the *p*-*V* diagram between points *i* and *f*.

When the work is done in a thermodynamic cycle, the net work done by the system is equal to the area of the cycle enclosed by the cycle.



(a) The work *W* done by a system as it goes from an initial state *i* to a final state *f*. Work *W* is positive when the system's volume increases.
(b) *W* is still positive, but now greater.
(c) *W* is still positive, but now smaller.
(d) *W* can be even smaller (path *icdf*) or larger (path *ighf*).
(e) The system goes from state *f* to state *i* as the gas is compressed to less volume by an external force.
(f) The net work W_{net} done by the system during a complete cycle is represented by the enclosed area.

The First Law of Thermodynamics

$$\boxed{\Delta E_{\text{int}} = Q - W,}$$

where ΔE_{int} = change in internal energy of the system,
Q = heat absorbed *by* the system,
W = work done *by* the system.

For a differential change,

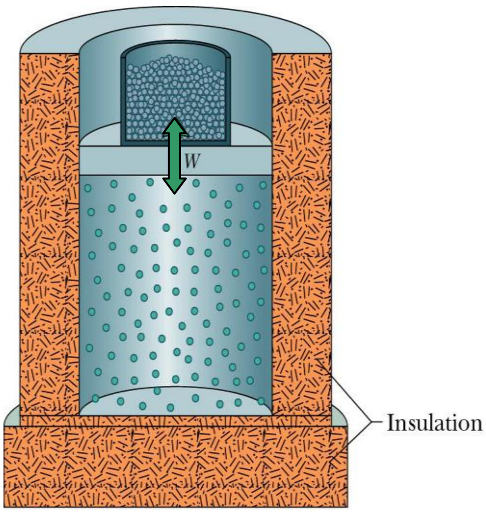
$$\boxed{dE_{\text{int}} = dQ - dW.}$$

The first law of thermodynamics is an extension of the conservation of energy.
See Youtube "Rubber Band Heat Engine"

Special Cases

Adiabatic processes: No transfer of heat e.g. the process occurs too rapidly, the system is thermally insulated. Then $Q = 0$, leading to

$$\Delta E_{\text{int}} = -W.$$



If the gas is allowed to expand, its internal energy decreases.
If the gas is compressed, its internal energy increases.

Constant-volume processes: No work is done. Then W = 0, leading to

$$\Delta E_{\text{int}} = Q.$$

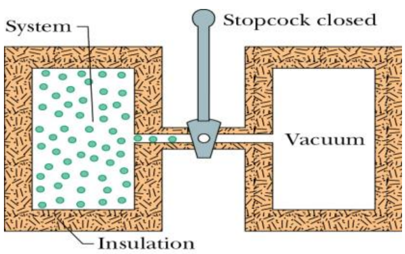
If heat is added to the system, its internal energy increases.
If heat is removed, its internal energy decreases.

Cyclical Processes: When a cycle is complete, it forms a closed loop in the p-V diagram. Since the internal energy is an intrinsic property of the system, it returns to the initial state. Then $\Delta E_{\text{int}} = 0$, leading to

$$Q = W.$$

Free Expansion: Since the system is insulated, Q = 0. Since the gas expands freely into vacuum, no work is done, W = 0. This leads to

$$\Delta E_{\text{int}} = 0.$$



Examples

18-5 Let 1.00 kg of liquid water at 100°C be converted to steam at 100°C by boiling at standard atmospheric pressure (1.00 atm or 1.01 × 10^5 Pa). The volume changes from an initial value of 1.00 × 10^{-3} m^3 as a liquid to 1.671 m^3 as steam.

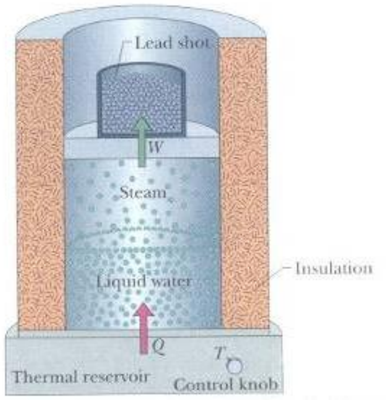
(a) How much work is done by the system during this process?

(b) How much heat must be added to the system during the process?

(c) What is the change in the internal energy of the system during the boiling process?

(The latent heat of vaporization of water is 2256 $kJkg^{-1}$.)

(a) $W = \int_{V_i}^{V_f} p\,dV = p\int_{V_i}^{V_f} dV$



$= p(V_f - V_i)$

$= (1.01\times10^5)(1.671 - 1\times10^{-3})$

$= 1.69\times10^5\text{ J} = 169\text{ kJ}$ (ans)

(b) $Q = L_V m$

$= (2256\text{kJkg}^{-1})(1\text{ kg})$

$= 2256\text{ kJ} \approx 2260\text{ kJ}$ (ans)

(c) Using the first law of thermodynamics,

$\Delta E_{\text{int}} = Q - W$

$= 2256 - 169 = 2090\text{ kJ}$ (ans)

Problem 82. A cylinder contains gas and is closed by a movable piston. The cylinder is kept submerged in an ice-water mixture. The piston is *quickly* pushed down from position 1 to position 2 and then held at position 2 until the gas is again at the temperature of the ice-water mixture; it then is *slowly* raised back to position 1. If 100 g of ice is melted during the cycle, how much work has been done *on* the gas? (L_F = 333 kJ kg^{-1})