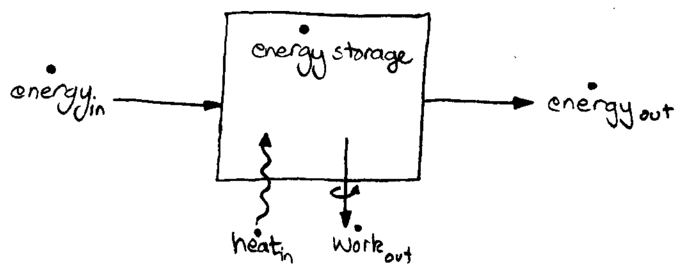
CIVE3331

<u>Materials Balance</u>

Energy balance is based on the conservation of energy (first law of thermodynamics) and the net growth of entropy (second law of thermodynamics)

Energy balance is used to track energy through a system. It is a little more complicated than the mass balance because the "transfer" term involves heat and work



The energy balance is usually written as an energy flow <u>rate</u> equation. Conservation of energy for a system says:

$$\left.\frac{dE}{dt}\right|_{system} = \underbrace{\frac{dQ}{dt}}_{\dot{heat}_{in}} - \underbrace{\frac{dW}{dt}}_{\dot{work}_{out}}$$

In words: rate of energy accumulated − rate entering + rate exiting = rate of heat entering − rate of work (done by system) out.

Using e as a symbol for energy, the balance can be arranged as

$$\underbrace{\dot{e}_{in} - \dot{e}_{out}}_{\text{usually associated with mass flows}} = \dot{e}_{storage} - \underbrace{\dot{q}_{in}}_{\text{heat flow into system}} + \underbrace{\dot{w}_{out}}_{\text{work done by system}}$$

An open system will usually have both mass & energy flows.

A closed system will have only heat (and possibly) work flows.

Energy is the ability to do work. There are different "kinds" of energy based on the kind of work performed

kinetic energy – momentum
potential energy – position in gravitational, electrical or magnetic field
internal energy – microscopic level associated with KE & PE and thermal energy of a molecule. Often expressed as pressure in gases & liquids – temperature in solids
chemical energy – energy associated with chemical bonds

Total energy is sum of all relevant types of energy for a fixed quantity of mass. $E = KE + PE + U$. Thus the energy in the balance expression includes all types of energy.

Adding energy to a system often raises its temperature (think of a teapot). The amount of heat added (thermal energy) to raise the temperature of a unit mass of a substance by 1 degree is called the specific heat of the substance.

Btu – energy to heat 1 lb water, 1°F @ 59°F.
kcal – energy to heat 1 kg water, 1°C @ 15°C
cal – " " 1 g water, 1°C @ 15°C

The preferred unit is kJ/kg. For water the specific heat is 4.184 kJ/kg. For substances that remain as liquids or solids during the entire heating event (no phase change), the specific heats are essentially constant.

Gasses expand during heating unless their volume is fixed. Specific heats are determined either at constant volume, constant pressure, or both c_v – constant volume sp. heat; c_p – constant pressure sp. heat

Enthalpy of a substance is the sum of its internal energy and its "state" ($p\forall$).
$$H = \underbrace{U}_{\text{internal energy}} + \underbrace{p\forall}_{\text{"compression" energy}}$$

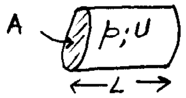
When heat is added to a substance, the change in enthalpy is given by
$$\frac{dH}{dT} = \frac{dU}{dT} + \frac{dp\forall}{dT} = \frac{dU}{dT} + p\frac{d\forall}{dT} + \forall\frac{dp}{dT}$$

For solids & liquids the $p\forall$ term is relatively constant ($\frac{dp\forall}{dT} \sim$ small) so that $\frac{dH}{dT} \approx \frac{dU}{dT}$.

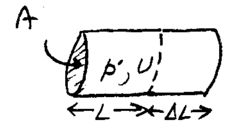
For a gas either $p = \text{const.}$ (balloon) or $\forall = \text{const.}$ (Gas cylinder)
$$H = U + p\forall = U + mRT$$
$$\left.\frac{dH}{dT}\right|_{\forall=\text{const.}} = \frac{dU}{dT} + \forall\frac{dp}{dT} = mc_v$$ ... (Although pressure changes, it cannot do any work; work = force * distance)
$$\left.\frac{dH}{dT}\right|_{p=\text{const}} = \frac{dU}{dT} + \underbrace{p\frac{d\forall}{dT}}_{\text{Work – some thermal energy is lost.}} = mc_p$$

In many systems of interest, the system is a fluid or solid – or behavior is isovolumetric so that the change in stored energy is mostly internal and can be represented as
$$\Delta e_{stored} = mC\Delta T$$

Constant pressure heating



$H_1 = U_1 + p_1 A L$ Now add heat



$H_2 = U_2 + p_2 A(L + \Delta L$

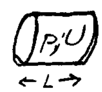
$\Delta H = H_2 - H_1 = U_2 - U_1 + p_2 A(L+\Delta L) - p_1 A L$ but $p_1 = p_2$ so

$= U_2 - U_1 + \underbrace{p_1 A \Delta L}_{\text{force * distance = Work}}$

$\therefore \quad \Delta H = \Delta U + \text{Work to expand}$

Constant volume heating

$H_1 = U_1 + p_1 A L$



$H_2 = U_2 + p_2 A L$

$\Delta H = H_2 - H_1 = U_2 - U_1 + (p_2 - p_1) A L$

$\Delta H = \Delta U + \underbrace{\Delta p \, A L}_{\text{No work because } \forall = \text{const.}}$

__Heat transfer__

Stored energy from heat transfer is $m C \Delta T$; the expression assumes $C \sim$ constant and that there is no phase change.

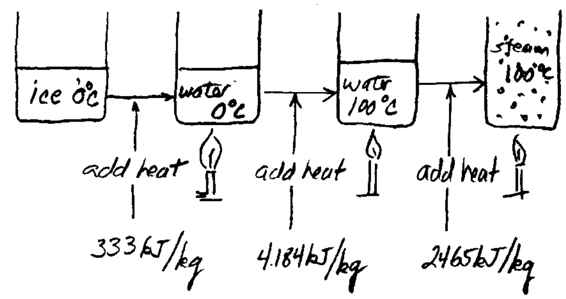
Phases: $\underbrace{\text{gas, liquid}}_{\text{fluids}}$, solid.

When a phase change occurs, energy is absorbed or released without a change in temperature ($\underbrace{\text{water freezes at } 0°C}_{\text{fusion}}$; $\underbrace{\text{ice melts at } 0°C}_{\text{fusion}}$)

($\underbrace{\text{water boils at } 100°C}_{\text{vaporization}}$; $\underbrace{\text{steam condenses at } 100°C}_{\text{vaporization}}$)

Constant pressure sp. ~~heat~~ energy required to change from solid to liquid (or reverse) is called the enthalpy of fusion (latent heat of fusion).

Constant pressure sp. energy required to change from liquid to gas (or reverse) is called the enthalpy of vaporization.



Total energy to convert 1 kg ice at 0°C to 1 kg steam 100°C is

333 kJ/kg (ice to water)
418 kJ/kg (water 0°C to water 100°C)
2465 kJ/kg (water 100°C to steam 100°C)
3216 kJ/kg

To reverse process remove energy in equal amounts

Phase change energies can be represented as $\Delta e_{\text{phase change}} = mL$

Many problems involve the flow of both mass and energy across the system boundary. In such cases we might write

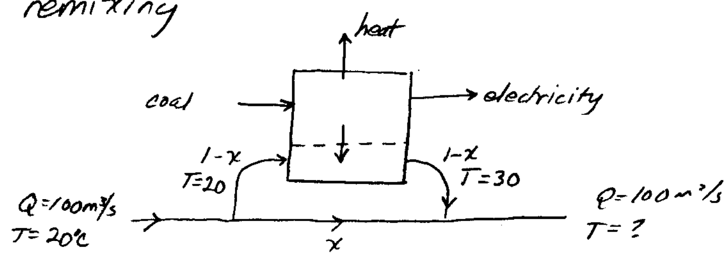
$\dot{e}_{stored} = \dot{m} c \Delta T$ $\quad \dot{m}$ is net mass flow rate.

$\dot{e}$ has units of power (kJ/sec; Btu/hr; $\frac{\text{work}}{\text{time}}$; $\frac{\text{force} \cdot \text{distance}}{\text{time}}$; force • velocity)

A typical integrated energy balance might be expressed as

$(U_{IN} + KE_{IN} + PE_{IN}) - (U_{OUT} + KE_{OUT} + PE_{OUT}) + HEAT_{IN} = \Delta E_{SYSTEM}$

Example: Coal fired 1000 MW power plant. 33% efficient. Remaining power lost as heat; 15% to atmosphere, 85% to cooling water. Cooling water from river $Q = 100\,m^3/s$, $T = 20°C$. How much flow is diverted from river if ΔT cooling water is 10°C? What is temp. of river after remixing



$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{1}{3} \quad \therefore \quad \text{coal } P_{IN} = \frac{P_{OUT}}{\frac{1}{3}} = 3P_{out} = 3000\,MW.$$

$$P_{lost} = P_{IN} - P_{out} = 2000\,MW$$

$$P_{ATM} = (0.15)(2000\,MW) = 300\,MW \quad ; \quad P_{RIVER} = (0.85)(2000\,MW) = 1700\,MW$$

Overall energy balance

$$\mathring{e}_{in} - \mathring{e}_{out} = \mathring{e}_{storage} - \mathring{q}_{in} + \mathring{w}_{out}$$

$$\mathring{e}_{in} = P_{IN_{coal}} + P_{IN_{cooling\ water}} \qquad \mathring{e}_{OUT} = P_{out_{elec}} + P_{out_{cooling\ water}}$$

$$\mathring{e}_{storage} = 0 \qquad \mathring{w}_{out} = 0$$

$$\mathring{q}_{in} = -P_{ATM}$$

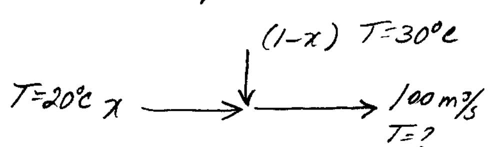
$$3000\,MW + \rho(1-x)c\,T_{IN} - 1000\,MW - \rho(1-x)c\,T_{OUT} = 300\,MW$$

$$2000\,MW - \rho(1-x)c\Delta T = 300\,MW$$

$$\rho(1-x)c\Delta T = 1700\,MW$$

$$(1-x) = \frac{1700 \cdot 10^6\ J/sec}{4184\,J/kg^\circ C \cdot 10^\circ C \cdot 1000\,kg/m^3} = 40.63\,m^3/sec$$

Downstream temperature



$$\mathring{e}_{in} - \mathring{e}_{out} = \cancel{\mathring{e}_{stor}}^{\,0} - \cancel{\mathring{q}_{in}}^{\,0} + \cancel{\mathring{w}_{out}}^{\,0}$$

$$\mathring{e}_{in} = \mathring{e}_{out}$$

$$\cancel{\rho} x \cancel{c}\, 20^\circ C + \cancel{\rho}(1-x)\cancel{c}\, 30^\circ C = \cancel{\rho}\, 100\,m^3/s\, \cancel{c}\, T^\circ C$$

$$\frac{59.47(20) + 40.63(30)}{100} = 24.1^\circ C$$

<u>Second law</u>

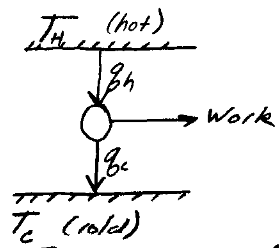
The second law of thermodynamics states that the rate of change of entropy in the system plus net rate of entropy flow out of the system is at least equal to overall heat transfer across the boundary and the internal heat production.

Entropy is roughly analagous to the reciprocal of "useful fuel".

As entropy decreases, a system can do more useful work. As entropy increases, a system does less useful work and generates more waste heat.

Carnot cycle heat engine

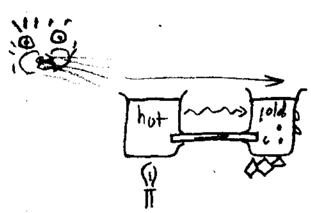
$$\eta = \frac{\text{Work out}}{\text{Work in}} = 1 - \frac{T_c}{T_h}$$



Maximum possible $\eta = 1$ when $T_C \to 0$ or $T_H \to \infty$. $\therefore$ All real systems have $\eta < 1$

- Component efficiencies can be very high, but overall η is what counts
- waste heat is wasted \$, but if a 1% increase in η costs more than the \$ saved, the efficiency will not be improved (economics)
- Waste is unavoidable – finding use for waste is beneficial and increases overall efficiency.

<u>Heat transfer concepts</u>



Two objects at different T. Heat will transfer from hot to cold object.

conduction – transfer by direct physical contact

convection – transfer by host fluid that carries heat

radiation – transfer by heat acting as e-m wave.