Spring Semester, 2011
Energy Engineering
에너지공학

Thermal Energy

Ref. Textbook (AJ), Ch. 2

1. Heat & temperature

Temperature: a characteristic of the thermal energy of a body due to the internal motion of molecules.

Thermal equilibrium: both at the same temperature

Heat ΔQ required to raise T of unit mass of a material by an amount of ΔT

$$\Delta Q = c\,\Delta T$$

c: specific heat (independent of T)

-Units of thermal energy: 1 cal ~ 4.2 J

Change of phase of a material: heat is absorbed & T remains constant

$$\Delta Q = L \quad \text{(L: latent heat)}$$

latent heat of evaporation (from liquid to gas) is one or two order larger than latent heat of fusion (from solid to liquid)

2. Heat transfer: conduction, convection, radiation

(1) Conduction (열전도): transfer of thermal energy within a body due to the random motion of molecules

A bar: length d, cross-sectional area A, one end T_1, the other end T_2 ($T_1 > T_2$)

Fourier's law of heat conduction (In the steady-state, the rate of flow of heat is constant along the length of the bar.)

$$Q = kA[(T_1 - T_2)/d]$$

k: thermal conductivity

(e.g. 2.1)

In practice, it takes time to establish a steady-state T distribution → For unsteady heat conduction, the characteristic time (t) to establish a steady-state for an isotherm to diffuse a distance x

$$t \sim x^2/\kappa$$

thermal diffusivity $\kappa = k/\rho c$ ($m^2 s^{-1}$)

(e.g. 2.2)

(2) Convection(열대류): transport of heat due to the bulk motion of a fluid

A fluid of density ρ and T moving with velocity u → mass flow per unit area per second = ρu & the thermal energy per unit mass = cT

The rate of flow of heat per unit area by convection

$$Q/A = (\rho u)(cT) = \rho u cT$$

In forced convection (cold fluid flows over a hot surface) → higher rate of heat transfer than that in stationary fluid (열전도보다 훨씬 큼 (Nu 배만큼))

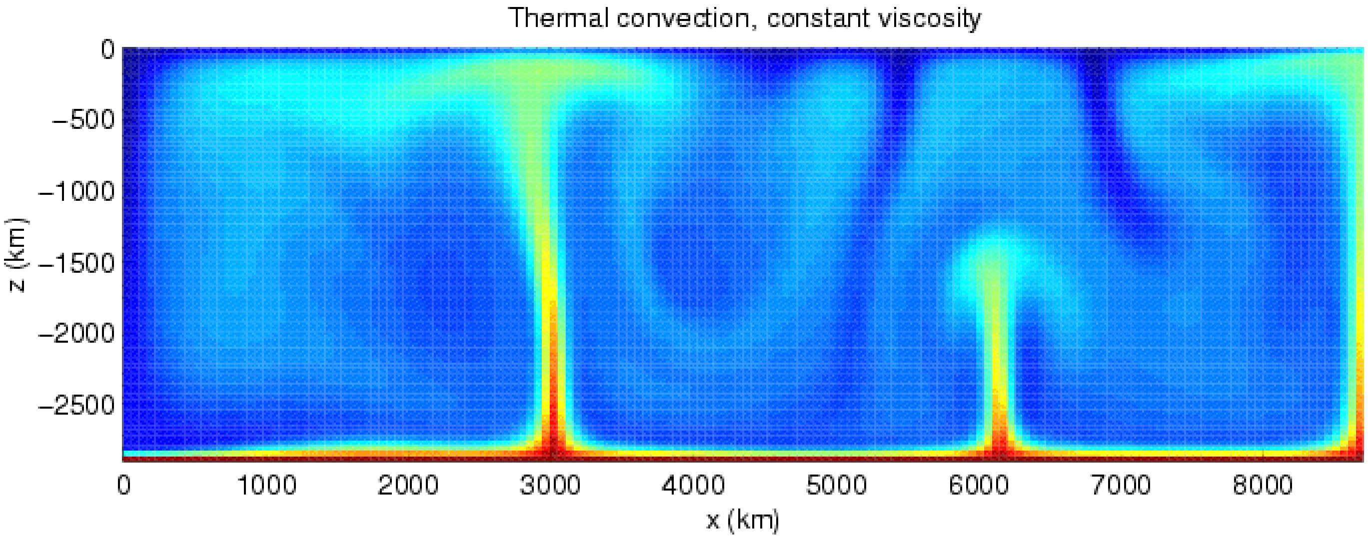
$$Q/A = \mathrm{N}u[k(T_s - T_\infty)/L]$$

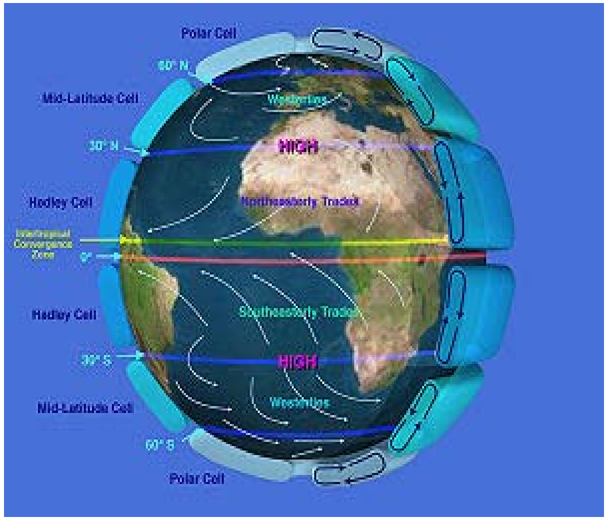
T_s : T of surface, T_∞: T of fluid, L: a characteristic length, Nu: Nusselt number (dimensionless parameter)

Nu = f(Pr, Re), Pr = $c\mu/k$ (Prandtl number), Re = $\rho u L/\mu$ (reynolds number)
μ : coefficient of dynamic viscosity

Prandtl number: depends only on the properties of material
Reynolds number : depends on the velocity of the fluid

(e.g. 2.3) pipe의 turbulent flow에서 단순 열전도보다 40배 더 높은 열전달!


Thermal convection, constant viscosity
0
−500
−1000
−1500
−2000
−2500
z (km)
0
1000
2000
3000
4000
5000
6000
7000
8000
x (km)


Polar Cell
60° N
Mid-Latitude Cell
Westerlies
30° N
HIGH
Hadley Cell
Northeasterly Trades
Intertropical Convergence Zone
0°
Hadley Cell
Southeasterly Trades
30° S
HIGH
Mid-Latitude Cell
Westerlies
60° S
Polar Cell

맨틀의 운동, 기류, 조류..

(3)Radiation(복사): transport of energy by electromagnetic wave

A fluid of The energy radiated per unit area per second (i.e., power per unit area) from a surface at T (Stefan-Boltzmann law)

$$P_e = \varepsilon\sigma T^4$$

ε: emissivity of the surface, dimensionless, 0 ~ 1 depending the nature of the surface

$\sigma \sim 5.67 \times 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$ (Stefan-Boltzmann constant)

Net rate of emission per unit area per second

$$P = P_e - P_a = \varepsilon\sigma(T^4 - T_o^4)$$

P_a: rate of adsorption

Black body: a surface that absorbs *all* incident radiation

Examples of radiation: sun radiation, dominant heat transfer in the furnace

(e.g. 2.4) 지표상의 총태양에너지 $P_s \sim 3.9 \times 10^{26}$ W

적도 상의 단위면적당 에너지 ~1.37 kW/m^2 (solar constant)

(한국 ~1 kW/m^2)

Greenhouse effect: 대기권의 복사 → 지표면 온도에 영향

Incident solar radiation : 1.37 kW/m^2 (solar constant))
Fraction of incident radiation (“albedo”): reflected by clouds & earth surface into outer space → albedo ~ 30%
The radiation is absorbed by an area πR^2 (cross-section facing the Sun, R: radius of Earth)
(i) 대기가 incident solar radiation과 지표면으로부터 열(IR)을 흡수 안할 경우
Albedo: A, incident solar intensity: S,
assume emissivity ~ 1 (like a black body), equilibrium at T on Earth surface

$$(1 - A)S\,\pi R^2 = 4\pi R^2 \sigma T^4$$

(radiation is emitted by the whole of the Earth’s surface (area = $4\pi R^2$))

$A = 0.3$, $S = 1.37$ kWm-2 → $T = 255\ \mathrm{K} = -18^\circ\mathrm{C}$

(ii) 대기가 incident light은 흡수 안하면서 지표면으로부터 열은 흡수할 경우
→ 대기는 온도 T_a까지 증가

$$(1 - A)S\,\pi R^2 = 4\pi R^2 \sigma T_a^4$$

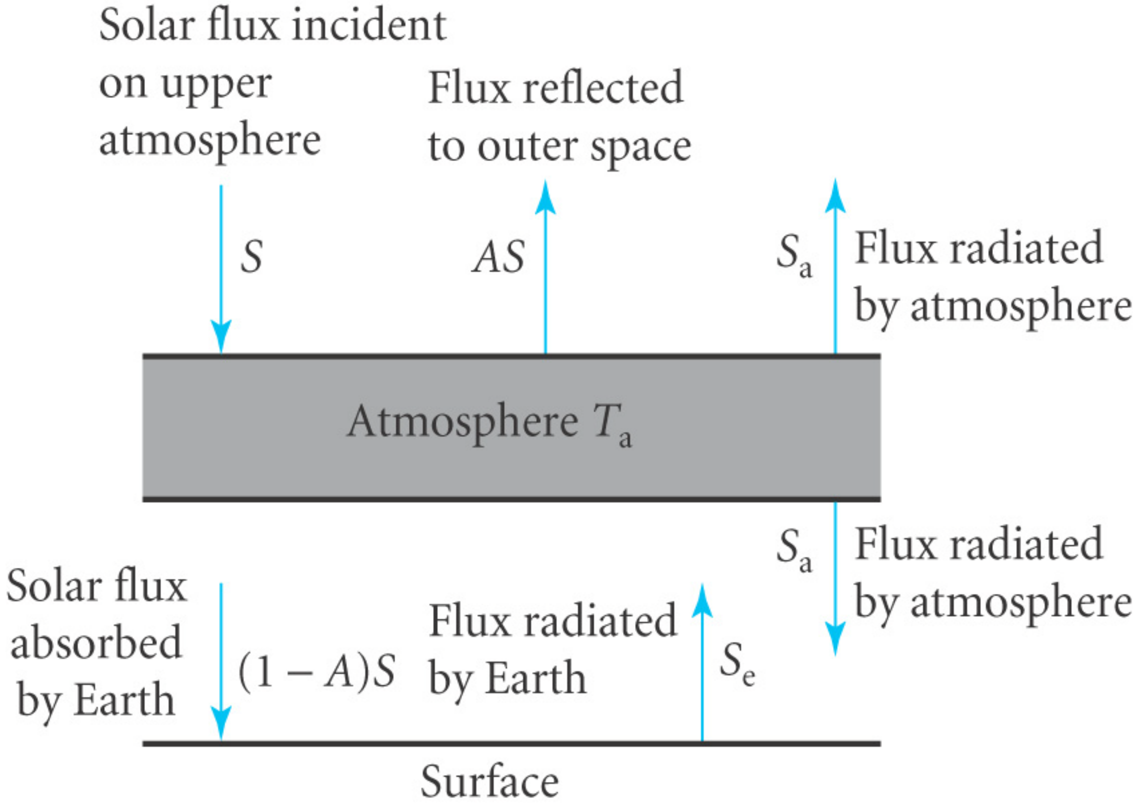
→ T_a = T(지표면 온도) = 255 K
대기가 지구표면과 지구 밖으로 동일한 양을 복사하게 됨 → 지표면 온도는 이 대기로부터 열을 받아 T_E로 올라감

$$(1 - A)S\,\pi R^2 + 4\pi R^2 \sigma T_a^4 = 4\pi R^2 \sigma T_E^4$$

$4\pi R^2 \sigma T_a^4$ 에 대해 앞쪽 마지막 식을 대입하면,

$T_E^4 = 2T^4 \rightarrow T_E = 303\text{ K} = 30\ ^\circ\text{C}$

Rise in surface temperature due to IR(열) 복사 흡수 → **“greenhouse effect”(온실 효과)**



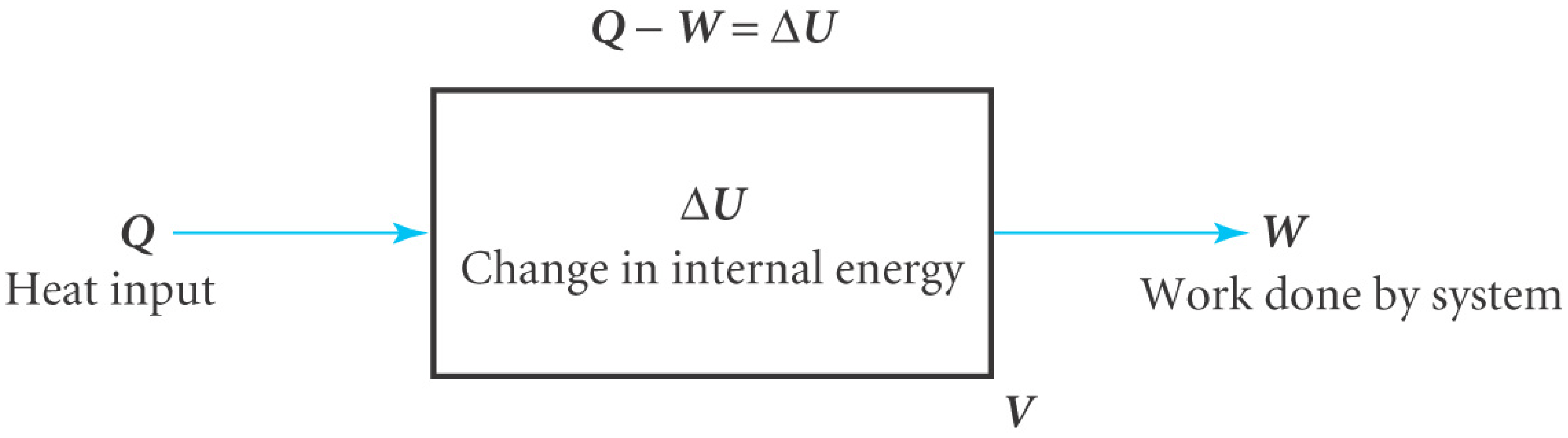
3. 1^{st} law of thermodynamics & the efficiency of a thermal power plant

1^{st} law of thermodynamics: energy conservation

$$Q - W = \Delta U$$

(Q & W are positive if heat flows into the system and work is done by the system)

The maximum possible efficiency of a thermal power plant can be obtained from this law



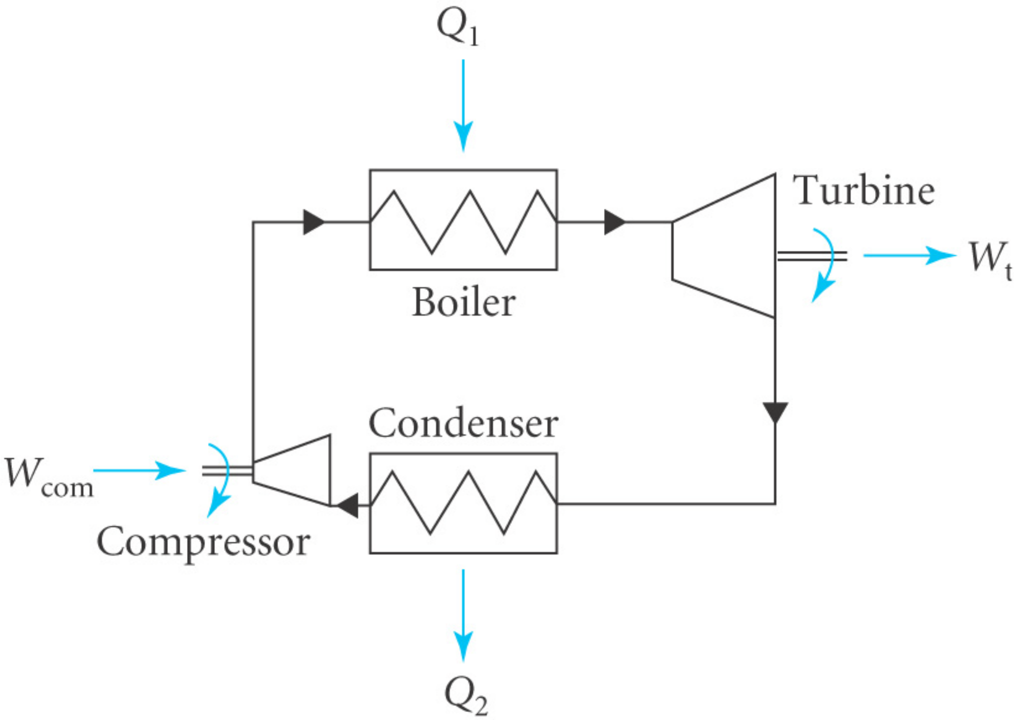
4. Closed cycle for a steam power plant

(1) compressor (boiler feed pump): work W_{com} done on the system to compress cold water from subatmospheric pressure to high pressure

(2) Boiler: heat Q_1 added to the system to convert cold water into system

(3) Turbine: work W_t done by the system (i.e. by steam) on the turbine blades

(4) Condenser: heat Q_2 lost from the system to the environment in converting steam back to cold water



After each complete cycle, the working fluid has the same internal energy, U → net change in internal energy is zero, $\Delta U = 0$

$$(Q_1 - Q_2) - (W_t - W_{com}) = 0$$

The efficiency of the process

η = [net work output]/[heat input] = $(W_t - W_{com})/Q_1 = (Q_1 - Q_2)/Q_1 = 1 - (Q_2/Q_1)$

$Q_2 > 0 \rightarrow \eta < 1$: system is less than 100% efficient

→ "2nd law of thermodynamics": heat increases the disorder (entropy), no system operating in a closed cycle can convert all the heat absorbed from a heat reservoir into the same amount of work

Carnot: maximum possible efficiency of a heat engine operating in a closed cycle between two heat reservoirs depends only on the ratio of the absolute temperatures of the reservoirs

$$\eta_C = 1 - (T_2/T_1)$$

T_1, T_2 are the absolute temperatures (K) of the upper & lower reservoirs

Efficiency of a Carnot cycle

Consider ideal gas ($pV = nRT$) operating in the closed cycle *abcda*
ab & *cd* are isotherms at T_1 & T_2; *bc* & *da* are reversible adiabatics (i.e, no heat transfer with the surroundings)

By the 1st law of thermodynamics,

$$dQ = dU + pdV = C_V dT + pdV$$

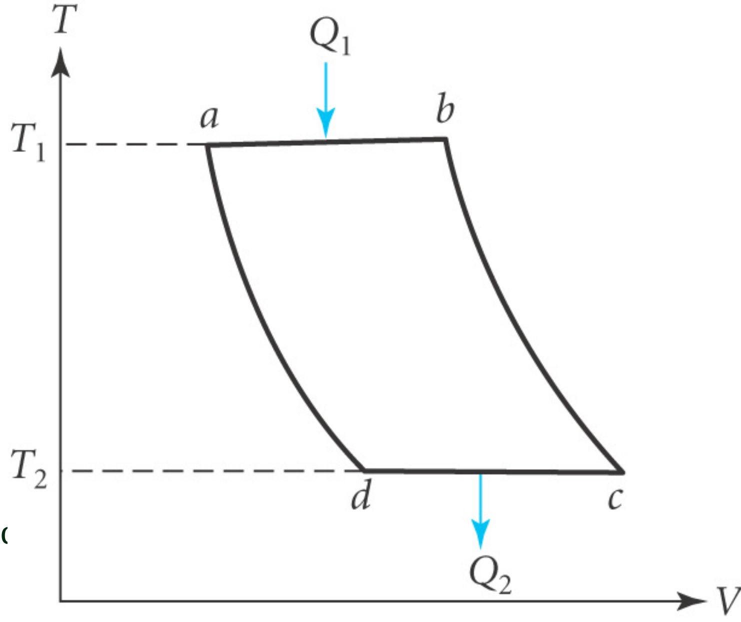
(C_V: heat capacity at constant volume)

Along isotherm *ab*, $dT = 0 \rightarrow dQ = pdV$
$Q_1 = \int \; pdV = nRT_1 \int \; (dV/V) = nRT_1 \ln(V_b/V_a)$

Along *cd*, $Q_2 = nRT_2 \ln(V_c/V_d)$

$Q_2/Q_1 = [T_2 \ln(V_c/V_d)]/ \, [T_1 \ln(V_b/V_a)]$

Along adiabatic *da*, $dQ = 0 \rightarrow C_V dT = -pdV$
$C_V(dT/T) = -nR(dV/V) \rightarrow C_V \ln(T_1/T_2) = -nR\ln(V_a/V$
Along adiabatic *da*, $C_V \ln(T_1/T_2) = -nR\ln(V_b/V_c)$
$\rightarrow (V_a/V_d) = (V_b/V_c)$ or $(V_c/V_d) = (V_b/V_a)$



$$Q_2/Q_1 = T_2/T_1$$

$$\eta = 1 - (Q_2/Q_1) = \mathbf{1 - (T_2/T_1)}$$

5. Useful thermodynamic quantities

Six key thermodynamics quantities of a thermal power plant: T, p, specific volume v (volume per unit mass, i.e., reciprocal of density), specific internal energy u, specific enthalpy h, specific entropy s

Enthalpy, $h = u + pv$

1. Heat transfer at constant pressure (e.g., in boilers & condensers)

$h_1 – h_2 = Q$ (enthalphy change = heat input)

2. Adiabatic ($Q = 0$) compression or expansion (e.g., in compressors & turbines)

$W = h_1 – h_2$ (net work done on the shaft = enthalpy change)

Entropy: a measure of the degree of disorder (2nd law of thermodynamics)

1. Reversible process: both system & surroundings can recover their original states
2. Irreversible process

$$\Delta s = \Delta Q_{rev}/T$$

Expansion of a gas at constant pressure

dQ is required to expand the volume from v to v + dv

Work done by the gas to the surroundings: $dW = pdv$

1st law of thermodynamics: $du = dQ - pdv$

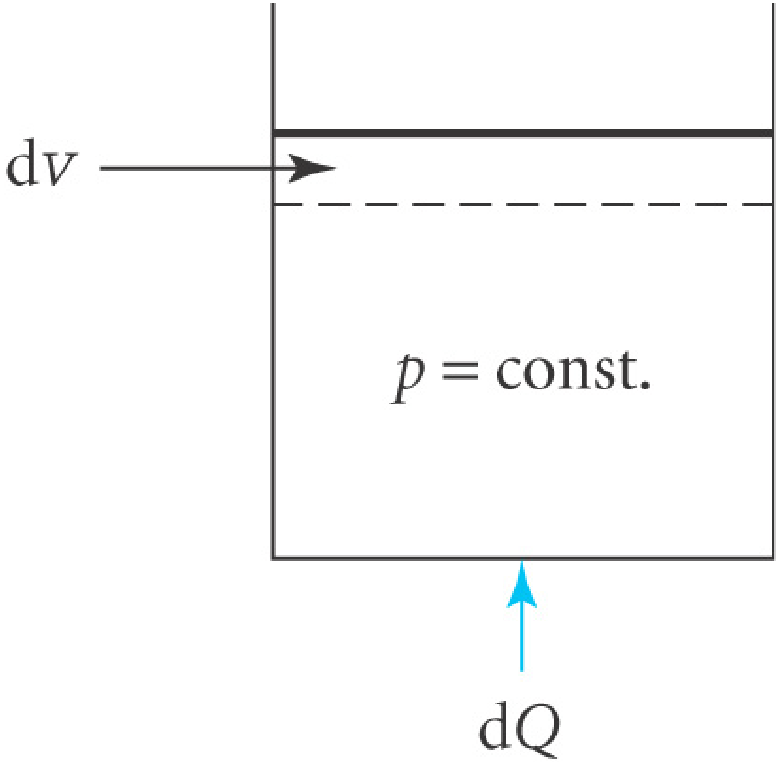
For constant p, $pdv = d(pv) \rightarrow du = dQ - d(pv)$

Total change in internal energy,

$$u_2 - u_1 = Q - (p_2v_2 - p_1v_1)$$

$$\rightarrow \qquad (u_2 + p_2v_2) - (u_1 + p_1v_1) = Q$$

or $$h_2 - h_1 = Q$$

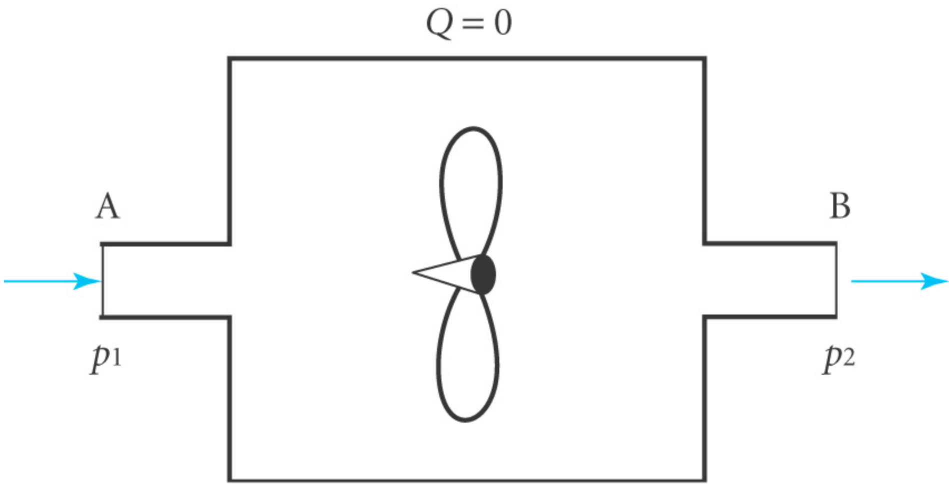


Adiabatic compression or expansion (Q = 0)

The work done in moving unit mass of fluid through a volume v_1 at A: p_1v_1

The work through volume v_2 at B: $-p_2v_2$

→ net work done by the fluid : $p_2v_2 - p_1v_1$



Work done by the shaft : W_s

The total work done by the system

$W = W_s + (p_2v_2 - p_1v_1)$

1st law of thermodynamics: $Q - W = \Delta u$

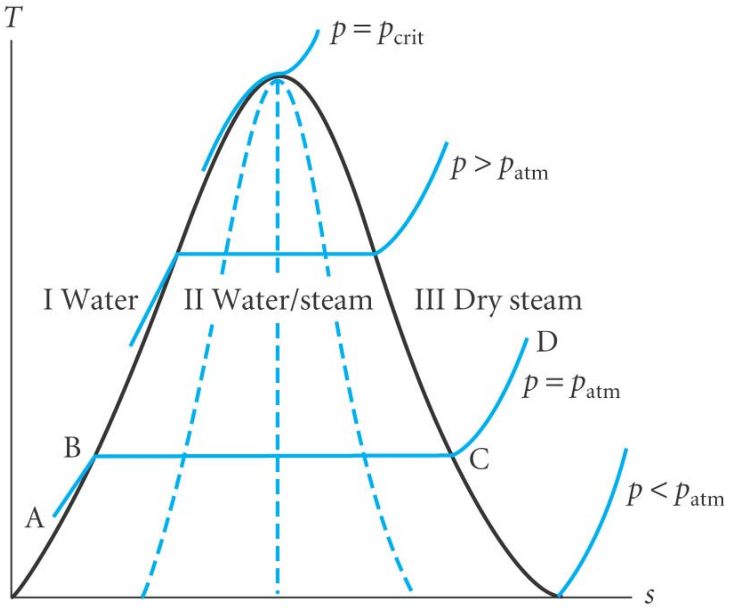
$Q = 0 \rightarrow -W_s - (p_2v_2 - p_1v_1) = u_2 - u_1$

$W_s = (u_1 + p_2v_2) - (u_2 + p_1v_1)$

or $W_s = h_1 - h_2$

6. Thermal properties of water and steam

Temperature T – entropy s diagram for water & steam (thermal power plant)



Bell-shaped curve: phase boundary
Solid lines: isobars (constant pressure)
Dashed lines in region II: constant steam quality, x (i.e., fraction by mass of steam in the two-phase mixture)

In isobar BC, $m = m_f + m_g$ (water mass + steam(gas) mass)

If v_f is the specific volume of liquid water at B & v_g the specific volume of dry steam at C → total volume of the mixture, $V = V_f + V_g = m_f v_f + v_g m_g$

Specific volume,
$v = V/m = (m_f v_f + m_g v_g)/m = (m - m_g)v_f/m + m_g v_g/m = (1 - m_g/m)v_f + (m_g/m)v_g$

The ratio, $x = m_g/m$ (steam quality)

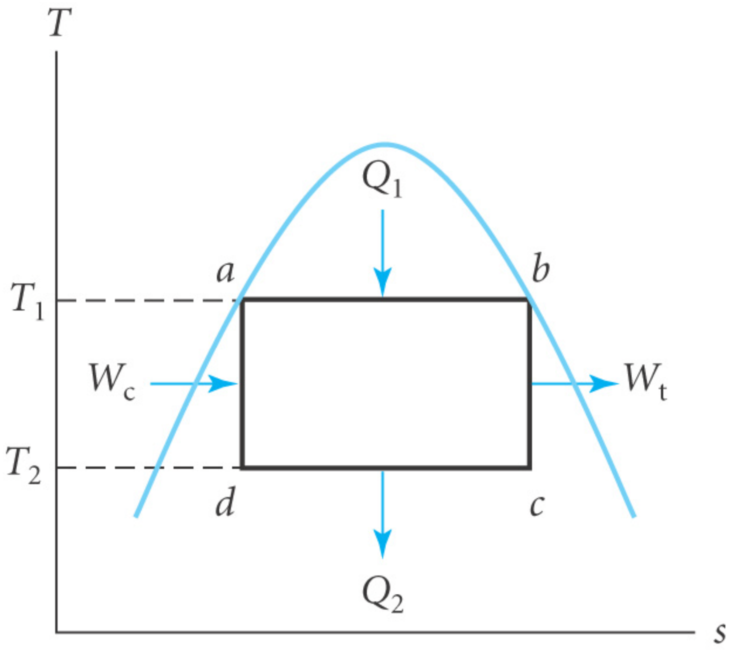
Steam quality at B, $x = 0$ (all water), at C, $x = 1$ (all steam)

$v = (1 - x)v_f + xv_g$

동일하게,

$u = (1 - x)u_f + xu_g$
$h = (1 - x)h_f + xh_g$
$s = (1 - x)s_f + xs_g$

(e.g. 2.5) steam power plant in the Carnot cycle



7. Disadvantages of a Carnot cycle for a steam power plant

T_1 of the upper reservoir to be constant → only achieved along an isobar in region II → not possible to operate the boiler in the dry steam region (III) since T rises → upper temperature of the cycle, T_1, is constrained by the maximum temperature of the two-phase boundary

Another problem arises in the turbine: turbine operates with a two-phase mixture of water and steam (region II) → momentum of fast moving water droplets in the mixture damages the turbine blades and shortens the life of the turbines

Same in compressor: damage the blades of the compressor. Volume of steam in the mixture is very large → large compressor needed so expensive

Carnot cycle: impractical for a steam power plant

8. Rankine cycle for steam power plants

- Carnot cycle의 문제점을 해결하려는 thermodynamic cycle

(1) Rankine cycle without reheat

de: condenser에서 steam이 전부 물로 바뀜
(Carnot cycle과 다름)

ef: compressor가 물의 압력을 adiabatically 높임

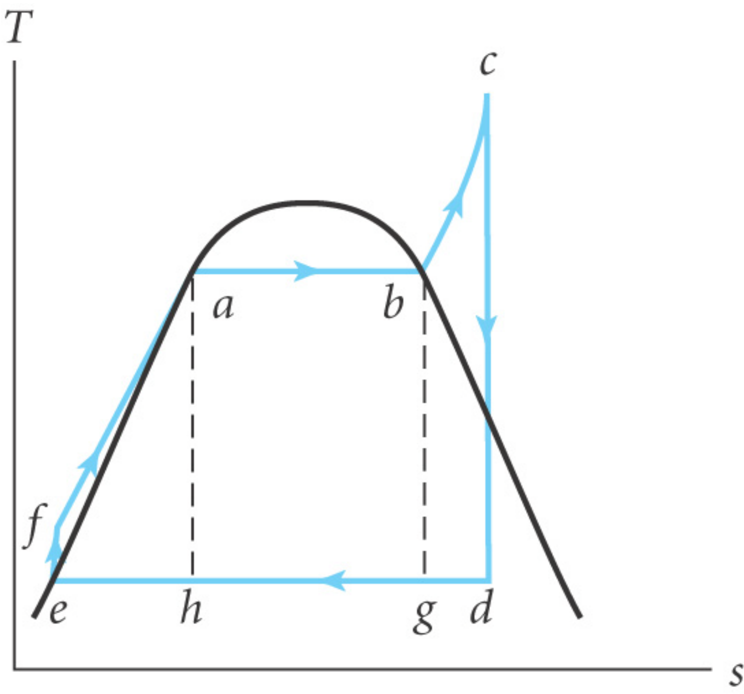
현재 steam power plant의 boiler는 세부분:

fa (economizer): 물이 끓을 때까지 고압에서 가열

ab (evaporator): 등압에서 two-phase mixture의 물이 dry steam으로 바뀌도록 가열

bc (superheater): 등압에서 dry steam의 가열

cd: 고압에서 dry steam이 turbine에 들어가 turbine blades에 일을 함



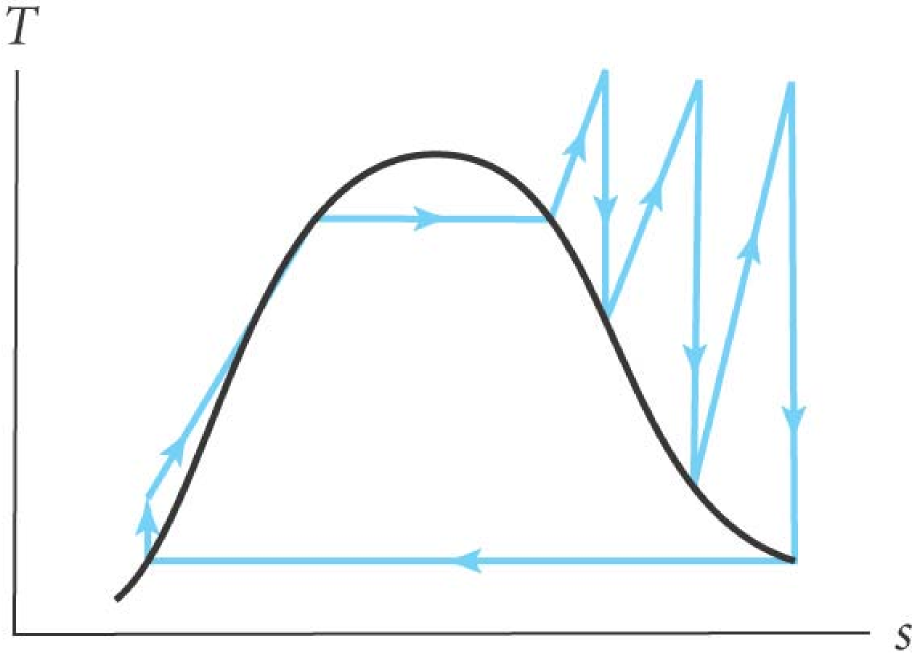
효율 계산: Carnot법을 적용하기 어려움 (upper T가 constant하지 않음) → economizer와 superheater의 평균온도 적용

(e.g. 2.6) steam power plant in a Rankine cycle without reheat

(2) Rankine cycle with reheat

Rankine cycle withour reheat: turbine blades를 마모시키는 높은 momentum의 물방울 생성을 완전히 제거하지 못함 → “with reheat” 도입 → steam is reheated several times before entering the condenser → 효율 증대 및 물방울 생성 억제

Maximum operating temperature in the superheater: 650°C (손상방지를 위해)
현재 효율은 40~45% 정도 도달



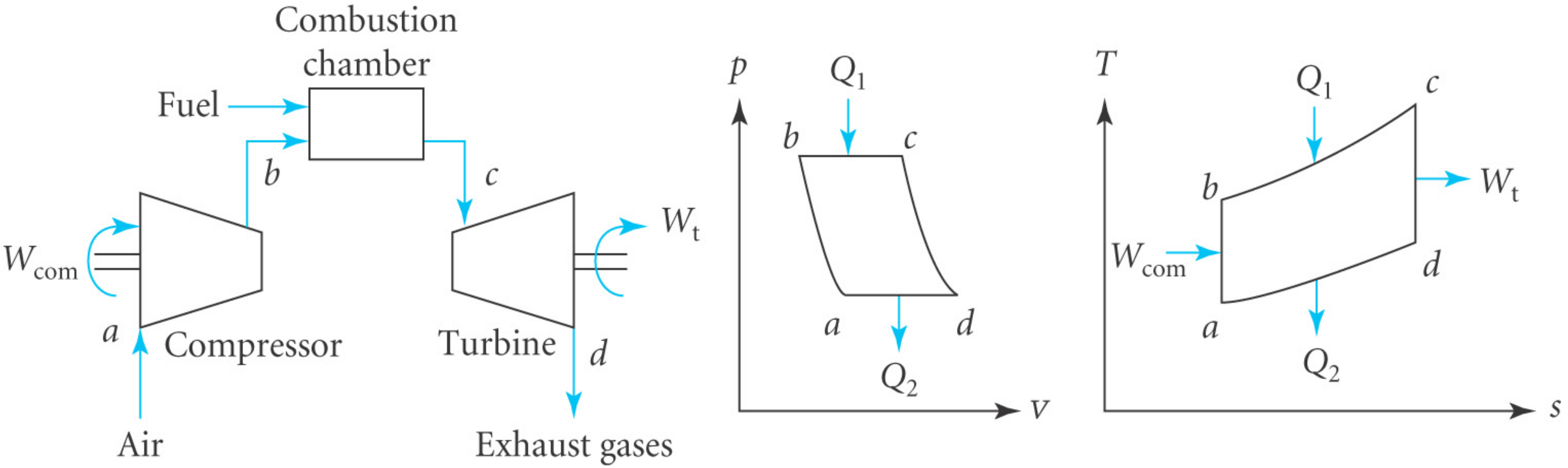
9. Gas turbines & the Brayton (or Joule) cycle

Gas turbine: gaseous products of combustion온도가 1300°C에 달함 (ceramic coating on turbine blades)

전기생성을 위한 gas turbine은 jet turbine engine에서 시작

Jet engine: combustion of gaseous fuel & expansion of exhaust gases → same gas phase, no condenser, steam engine보다 작고 저가

Gas turbine은 Brayton (or Joule) cycle: atmosphere가 heat exchanger역할을 하기 때문에 closed cycle (combustion chamber에 들어가는 공기 냉각)



대기압의 공기가 compressor로 들어가(a) 10~20 bar로 압축(b) → combustion chamber에서 연료와 혼합됨 → turbine에 일을 하는 뜨거운 combustion gas들 생성 (c) → exhause gas들 대기로 배출 (d)

Compressor와 turbine에서 adiabatic process ($Q = 0$)를 가정하면,
열역학제1법칙은 $-W_c = \Delta U$.
Compressor에서 행해진 일 = 엔탈피 증가, $W_{com} = h_b - h_a = c_p(T_b - T_a)$
(c_p: specific heat at constant pressure)
Turbine에 행해진 일, $W_t = h_c - h_d = c_p(T_c - T_d)$
Net heat supplied, $Q = h_c - h_b = c_p(T_c - T_b)$

Efficiency of the cycle, $\eta = (W_t - W_{com})/Q = [(T_c - T_d) - (T_b - T_a)]/(T_c - T_b)$

More useful expression for efficiency of gas turbine, $\boldsymbol{\eta = 1 - r^{-[(\gamma-1)/\gamma]}}$
$r = p_b/p_a = p_c/p_d$ (pressure ratio) & $\gamma = c_p/c_v$ (ratio of specific heats)

Gas turbine: relatively low cost, start up quickly. Efficiency ~ 40%

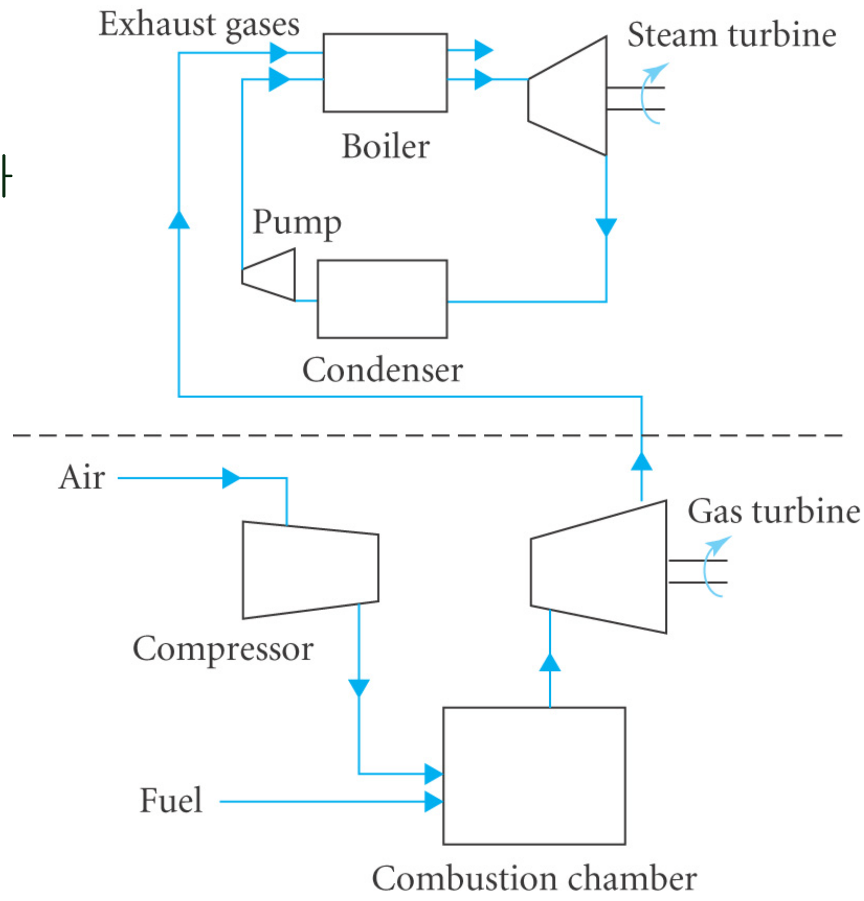
$\eta = 1 - r^{-[(\gamma-1)/\gamma]}$ 유도 (37쪽)

(e.g. 2.7)

10. Combined cycle gas turbine (CCGT)

Exhaust gases를 steam power plant 에 공급 gas turbine의 효율 증대: CCGT → 효율 ~60%

이보다 더 큰 효율은 combined heat and power cycle (CHP)로 확보 가능: 일반적 steam power plant 보다 더 높은 온도에서 condenser 작동. Waste Heat은 주변지역 난방으로 활용: 종효율 ~80%
(단점: 설치비용 고가 → 산업단지나 인구밀접지역 가능)



11. Fossil fuels and combustion

천연가스: CH_4 연소 → 발열반응

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ 55MJ/kg CH_4

16 kg CH_4 → 44 kg CO_2

Oil: example pentane

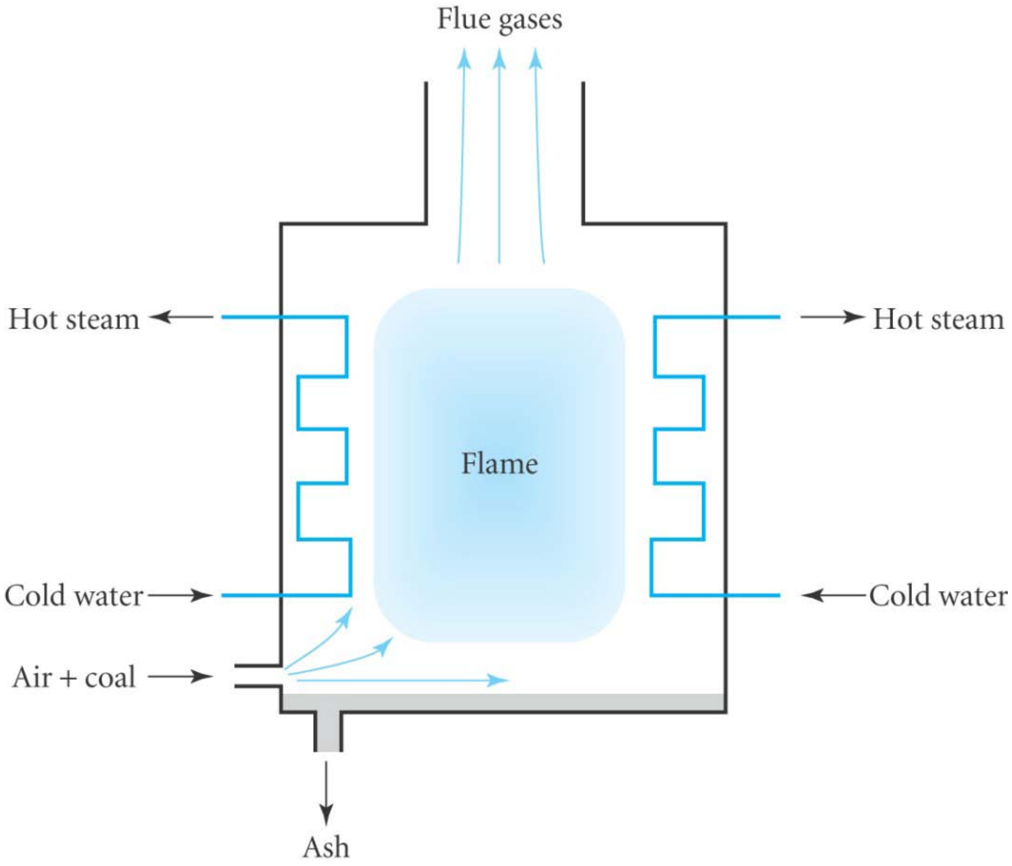
$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$

72 kg pentane → 220 kg CO_2

500 MW coal-fired plant consumes
250 ton coal per hour

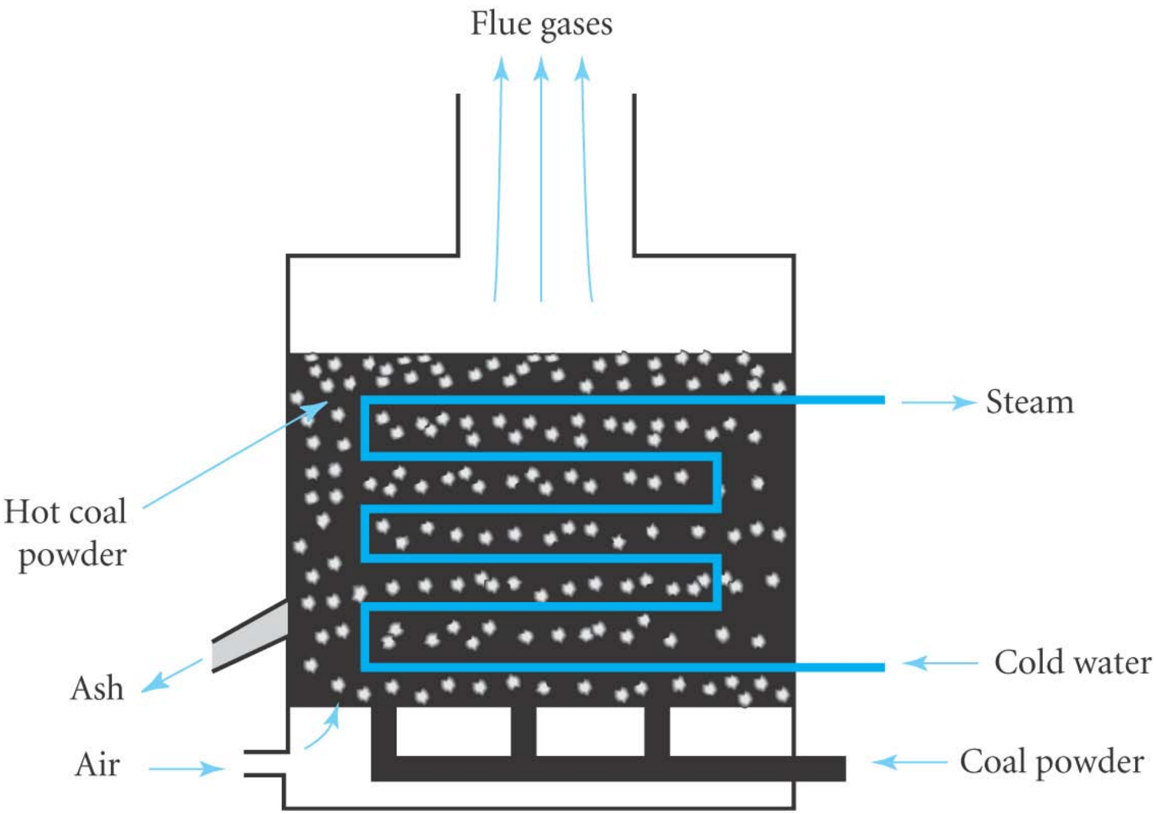
$C + O_2 \rightarrow CO_2$

$2C + O_2 \rightarrow 2CO$ (incomplete)



12. Fluidized beds

환경유해 배출가스 감소



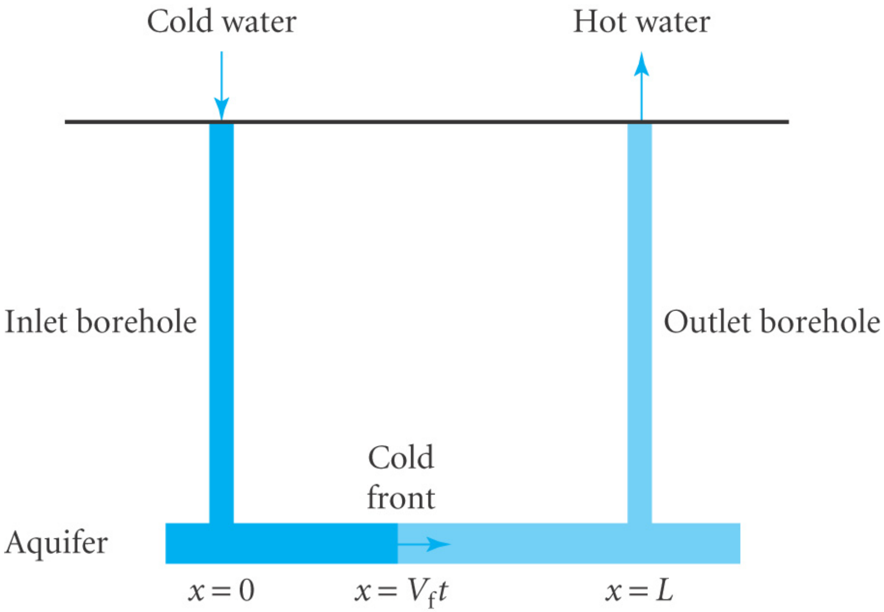
13. Carbon sequestration (carbon capture)

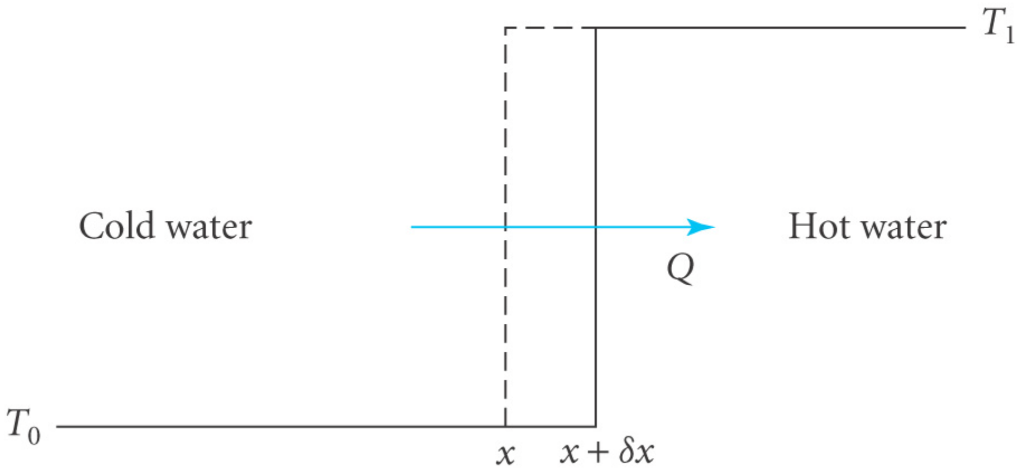
온실가스 감축방안

14. Geothermal energy

지구핵 온도: 4000°C → temperature gradient at Earth's surface: 30°C/km
활발한 지열활동: Iceland, California, Italy, New Zealand..
지열활동이 활발하지 않아도 지하 수 km의 지열이용 가능: >150°C (electric power plant에 water heating에 주입), <150°C(난방)

(1) Aquifer(대수층[帶水層])로부터 heat extraction

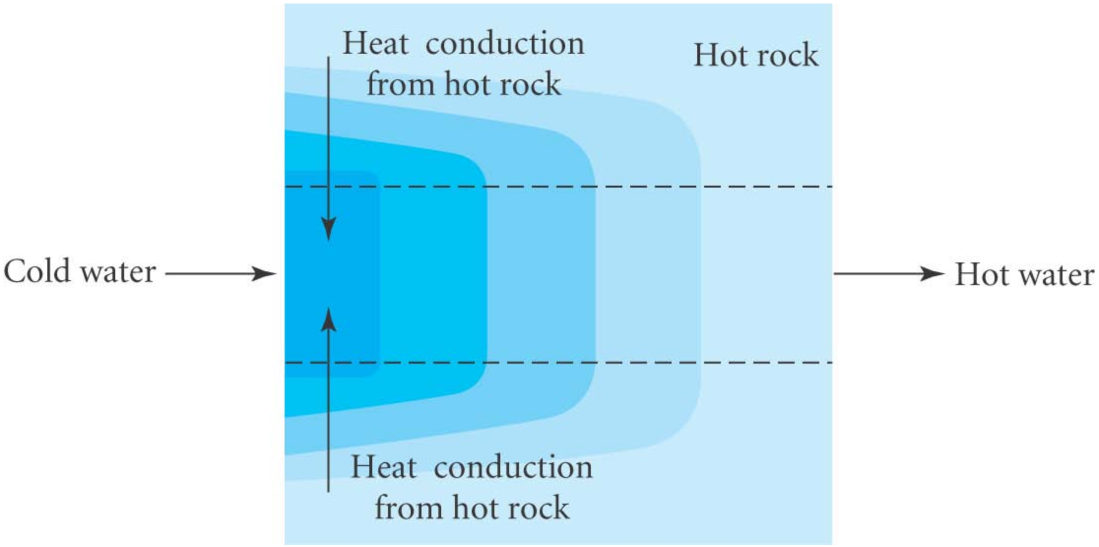




(e.g. 2.8)

(2) Hot dry rock으로부터 heat extraction

Enhanced geothermal systems (EGS)



(3) Geothermal heat pumps

(4) Economics and potential of geothermal power