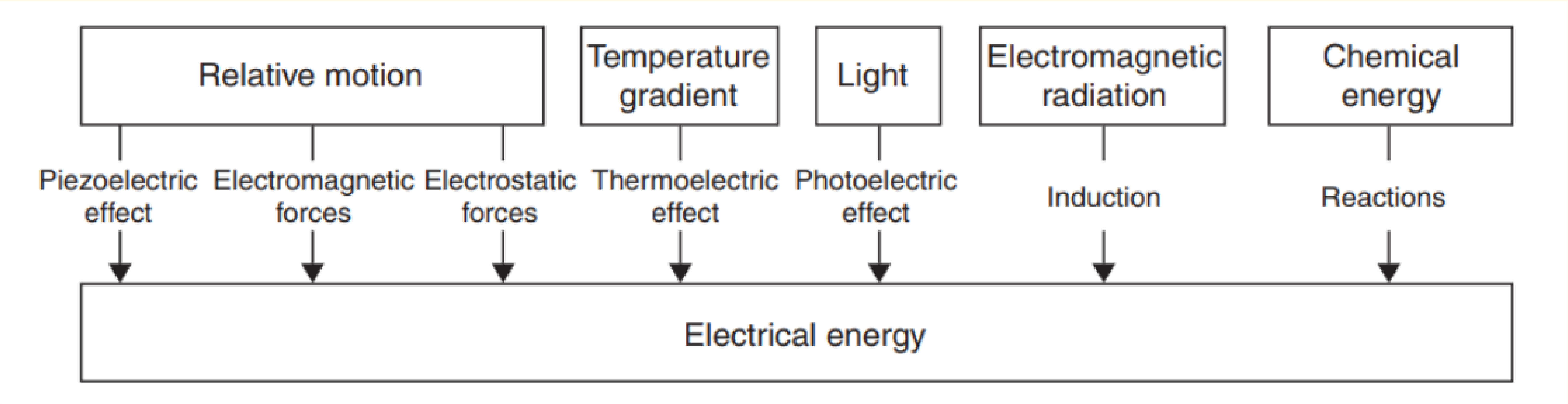
- ME (Mechanical-to elec) -> turbine → Piezo, electro
- CE (Chemical..) -> battery, fuel cell
- SE (Solar..) -> PV/SH
- RFE (Radio Frequency..) -> ambient electromagnetic energy to elec → Rectena
- TE (Thermal..) -> TEG

- Direct force
- Inertial force

- Seebeck : $\Delta T \to e^-$
- Peltier : $e^- \to \Delta T$

- Resonant
- Non-resonant

- Battery
- Fuel cell



$$\underbrace{U}_{\text{internal energy}} = \underbrace{\bar{Q}}_{\text{heat}} + \underbrace{\bar{W}}_{\text{work}}$$

$Q = \int C\, dT \to c \cdot \Delta T$

$W = P \cdot \Delta V$

$\Delta V = 0 \to$ no work

Avogadro $\frac{V_1}{n_1} = \frac{V_2}{n_2}$

Gas Law Formula		
Gas Law	**Formula**	**Description**
Boyle's Law	$P_1V_1 = P_2V_2$	At constant *T*, as pressure increases, volume decreases.
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Ideal Gas Law	$PV = nRT$	$\rho = PM/RT$ → molar mass $\frac{m}{n}$
V = volume in dm^3 (litre) T = temperature in K	P = pressure in kPa n = number of moles	R = ideal gas constant $0.0821\ \frac{L \cdot atm}{mol K}$

TEG

$$ZT = \left(S^2\sigma/\kappa_e + \kappa_L\right) T$$

$$\eta = \frac{P}{Q} = \frac{\Delta T}{T_H}\left(\frac{\sqrt{1+\overline{ZT}}-1}{\sqrt{1+\overline{ZT}}+\frac{T_C}{T_H}}\right)$$

$$P_{max} = \frac{(S\Delta T)^2}{4R} = \frac{(S\Delta T)^2}{4\rho}\frac{A}{L}$$

$$P_{max} = \frac{{V_{oc}}^2}{4R} = \frac{\left(n(|S_p|+|S_n|)\Delta T\right)^2}{4R}$$

The output power of the device (P_L) can be expressed as:

$$P_L = P = \frac{{V_L}^2}{R_L} = \frac{\left(\frac{R_L V_{oc}}{R+R_L}\right)^2}{R_L}$$

$$P_{max} = \frac{{V_{oc}}^2}{4R} = \frac{\left(n(|S_p|+|S_n|)\Delta T\right)^2}{4R}$$

Waste heat

Carnot eff

$$\eta_c = \frac{T_h - T_c}{T_h}. T_c$$

Thermal eff

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

Wind

$$\text{Power} = \frac{1}{2}\rho A U^3 = \frac{1}{2}\rho\pi R^2 U^3$$

$$C_p = \frac{P_{aero}}{P_{wind}} = \frac{P_{aero}}{1/2\,\rho A U^3} = \frac{P_{aero}}{1/2\,\rho\pi R^2 U^3}$$

U relative

C_p Betz limit (max) = 0.59

Solar collector

absorbed solar radiation (S) using:

$$S = G_T \times (\tau\alpha)_{av}$$

useful energy gain ($\dot{Q}_u$) using:

$$\dot{Q}_u = A_c \times F_R \times [S - U_L(T_{in} - T_{amb})]$$

e outlet temperature (T_{out}) of the working fluid using:

$$T_{out} = T_{in} + \frac{\dot{Q}_u}{\dot{m}c_p}$$

thermal efficiency (η) of the collector:

$$\eta = \frac{\dot{Q}_u}{A_c G_T}$$

$$C_{geo} = \frac{A_a}{A_r}$$

$$U_L = \dot{Q}_s = \eta_0 \times A_a \times I_0 \times \text{heat transfer efficiency}$$

Friis Eq

$$P_R = P_T \cdot G_T \cdot G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

T : Transmitted
R : received
P : power (W)
G : Antenna gains
d : distance

Thermodynamic

- Thermal energy: Total energy of particle molecules – vibration / rotational / move / transational
- Temperature: avg kinetic E per particle
- Heat E: amount of thermal E transferred

Thermodynamic laws

- 0th : temp
- 1st :

$$U = \bar{Q} + \bar{W}$$

internal energy — heat — work

$Q = \int C\, dT \rightarrow C \cdot \Delta T$

$W = P \cdot \Delta V$

$\Delta V = 0 \rightarrow$ no work

- 2nd : phases vs chaos (solid -> liquid-> gas)
  terature — chaotic
- 3rd : T = 0 K -> absolute zero energy

System — homogeneous / heterogeneous

- Open : mass & E transfer
- Closed : only E transfer
- Isolated : no transfer

between syst & surrounding

Approach:

- Macro : few properties
- Micro : detailed properties

intensive dependent to m

extensive independent to m

state

$V = f(n, p, T)$ or $p = g(n, V, T)$

3 H_2 (g, 1 bar, 100 °C)

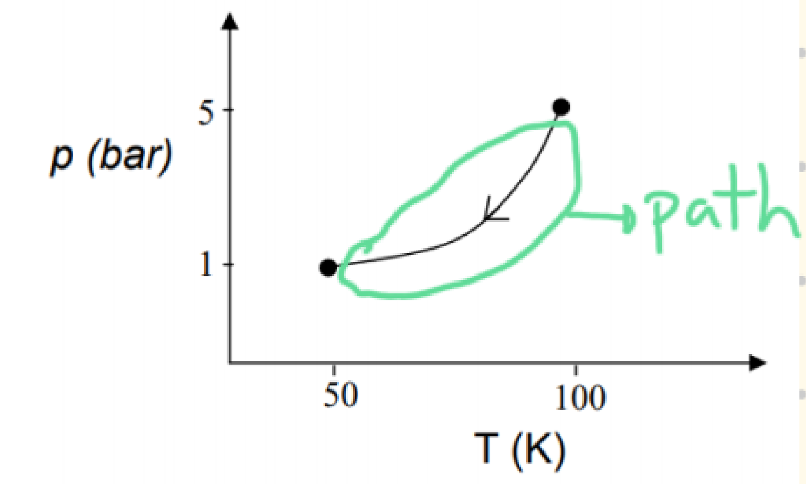
3 moles (n=3) — gas — p=1 bar — T=100 °C

Change of state or Transformation

❖Notation:

$$\underbrace{3\ H_2\ (g,\ 5\ \text{bar},\ 100\ °C)}_{\textit{initial state}} = \underbrace{3\ H_2\ (g,\ 1\ \text{bar},\ 50\ °C)}_{\textit{final state}}$$

❖Path: Sequence of intermediate states



Process: Describes the Path

❖Reversible (always in Equilibrium) water ←→ ice

❖Irreversible (defines direction of time) wood → ash

❖Adiabatic (no heat transfer between system and surroundings) → Q=0

❖Isobaric (constant pressure) → W+Q

❖Isothermal (constant temperature) ΔT=0 → Q=0

❖Isochoric (constant volume) → ΔV=0 → W=0

path dependent properties?

Avogadro $\frac{V_1}{n_1} = \frac{V_2}{n_2}$

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TEH

- Material: Bi2Te3, PbTe

Parameter:

- Figure of Merit (ZT)

$$ZT = (S^2\sigma / \kappa_e + \kappa_L)\,T$$

Power factor — in Kelvin — no unit — seebeck coef — electrical — Latice

- Efficiency

$$\eta = \frac{P}{Q} = \frac{\Delta T}{T_H}\left(\frac{\sqrt{1+\overline{ZT}}-1}{\sqrt{1+\overline{ZT}}+\frac{T_C}{T_H}}\right)$$

$$Q_H = \alpha I T_H - \tfrac{1}{2} I^2 R + K \Delta T$$
$$P = I^2 R_L$$
$$I = V_{oc} / (R + R_L)$$
$$\Delta T = T_H - T_C$$
$$V_{oc} = \alpha \Delta T$$
$$R = \rho L / A$$
$$K = \kappa A / L$$
$$Q_H = P + Q_C$$
$$Z = \alpha^2 / \rho / \kappa$$

Q_H = heat input to the thermoelectric generator
Q_C = waste heat
α = Seebeck coefficient
Z = figure-of-merit
κ = thermal conductivity
ρ = electrical resistivity
T_H = hot side temperature
I = current
P = output power
T_C = cold side temperature
V_{OC} = open circuit voltage
R_L = load resistance
L = length of pellet
A = cross sectional area of pellet

$$P_{max} = \frac{(S\Delta T)^2}{4R} = \frac{(S\Delta T)^2}{4\rho}\frac{A}{L}$$

$$P_{max} = \frac{V_{oc}^{\,2}}{4R} = \frac{\left(n(|S_p| + |S_n|)\Delta T\right)^2}{4R}$$

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$$P_{max} = \frac{V_{oc}^{\,2}}{4R} = \frac{\left(n(|S_p| + |S_n|)\Delta T\right)^2}{4R}$$

$\frac{P_p L}{A}$, $\frac{P_n L}{A}$

Design a small thermoelectric generator to power a wearable health monitoring device using the temperature difference between the human body and the ambient environment.

Example calculation: Assume the body temperature is 37°C and the ambient temperature is 20°C. Design a TEG with a footprint of 5 cm^2 and a thickness of 5 mm to generate sufficient power to run the wearable device.

1. To design the TEG, we need to consider the following factors: Temperature difference: ΔT = 37°C - 20°C = 17°C
2. Thermoelectric material properties: Seebeck coefficient, electrical resistivity, thermal conductivity
3. Geometric dimensions: cross-sectional area and length of the thermoelectric elements.
4. Using the power output formula and typical thermoelectric material properties, we can calculate the expected power output for the given temperature difference and device size.

Sample calculation: Consider a TEG with a temperature difference of 200°C, a cross-sectional area of 10 cm^2, and a length of 2 cm. Assume the thermoelectric material has a Seebeck coefficient of 200 µV/K, an electrical resistivity of 1 × 10^-5 Ω·m, and a thermal conductivity of 1.5 W/m·K. Calculate the power output of the TEG (Bell, 2008) (Yazawa & Shakouri, 2011).

S	0.0002	P	2
T	200		
A	0.001		
L	0.02		
elec rest	0.00001		
k	1.5		

```
=(B22*B23)^2*B24/(4*B26*B25)
```

Determine the conversion efficiency of a thermoelectric generator given the material's figure of merit and the temperature difference between the hot and cold sides.

Consider a thermoelectric material with a figure of merit, *ZT*, of 1.0. The hot-side temperature is 600 K, and the cold-side temperature is 300 K. Calculate the maximum theoretical efficiency of a thermoelectric generator using this material.

$$\eta = \frac{P}{Q} = \frac{\Delta T}{T_H}\left(\frac{\sqrt{1+\overline{ZT}}-1}{\sqrt{1+\overline{ZT}}+\frac{T_C}{T_H}}\right)$$

Group Session

Thursday, 20th February 2025

A **GPS tracking sensor** requires **100 mW (0.1 W)** of continuous power. A thermoelectric generator (TEG) will be used, utilizing a **hot surface at 150°C** and a **cold side at 50°C**.

Design a thermoelectric generator (TEG) to meet this requirement, considering:

1. **Material selection** (using Bismuth Telluride, Bi_2Te_3).
2. **Number of thermocouples** needed.
3. **Leg sizing** (length L and cross-section A).
4. **Required heat input**.

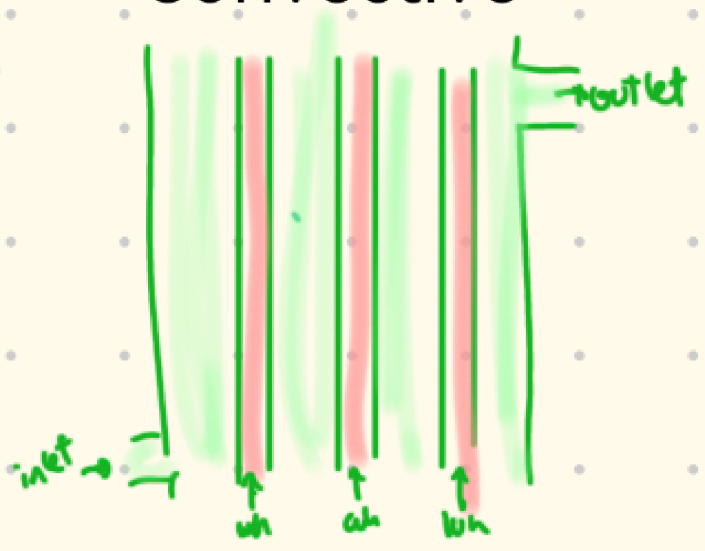
Waste Heat

Type: Low (<230C), Medium (230-650C), High (>650C)

- Heat Exchangers: Heat exchangers are widely used to transfer heat from combustion exhaust gases to the incoming combustion air in furnaces. By preheating the combustion air, the furnace requires less fuel to reach the desired temperature. Common air preheating technologies include **recuperators, furnace regenerators, burner regenerators, rotary regenerators, and passive air preheaters**.
- Thermoelectric Generators: These solid-state devices convert temperature differences directly into electricity, making them suitable for low-grade waste heat recovery
- Organic Rankine Cycle: This is a type of heat engine that uses an organic, high-molecular-mass fluid with a low boiling point for its working fluid, allowing it to efficiently generate electricity from low-grade waste heat.
- Thermophotovoltaic Systems: These convert thermal radiation from a hot surface into electricity, and they can be used to harvest waste heat from high-temperature sources
- Piezoelectric Generators: These devices convert mechanical strain induced by temperature changes into electrical energy, making them suitable for harvesting waste heat from vibrating or oscillating sources.

Recuperator (Area & Time)

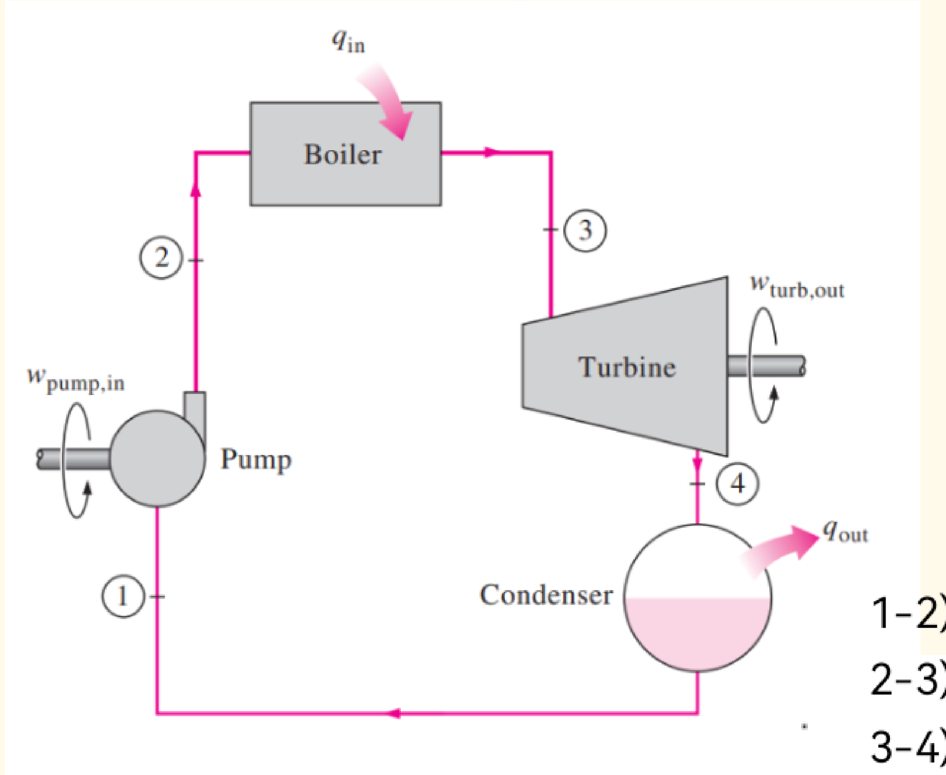
- Radiation
- Convective



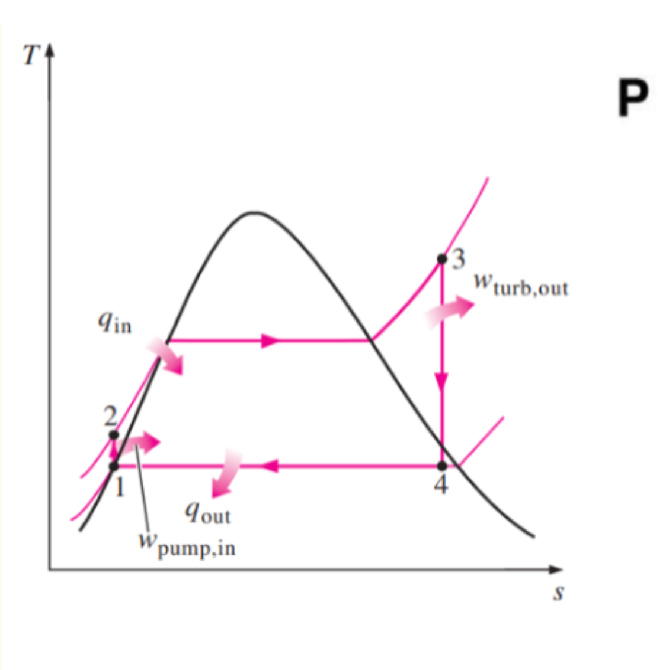
Carnot eff

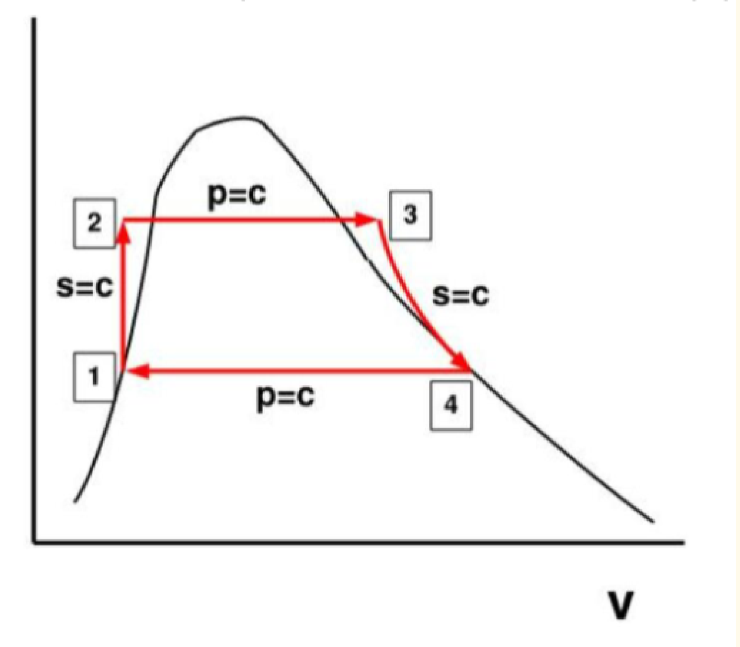
$$\eta_c = \frac{T_h - T_c}{T_h}. T_c$$

Ideal Rankine Cycle



1-2) Isentropic compression (Q)
2-3) Isobaric heat add (P)
3-4) Isentropic expension (Q)
4-1) Isobaric heat release (P)





heat?

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

Pump $(q = 0)$: $\quad w_{pump,in} = h_2 - h_1$

or,

$$w_{pump,in} = v(P_2 - P_1)$$

where

$$h_1 = h_{f @ P_1} \quad \text{and} \quad v \cong v_1 = v_{f @ P_1}$$

Boiler $(w = 0)$: $\quad q_{in} = h_3 - h_2$

Turbine $(q = 0)$: $\quad w_{turb,out} = h_3 - h_4$

Condenser $(w = 0)$: $\quad q_{out} = h_4 - h_1$

Thermal eff

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

Design:

- Ketahananan thd mechanical & temp stress
- Develoopment of high thermal conductivity composites and **phase-change material** (molten salt, parafin)

Solar Thermal

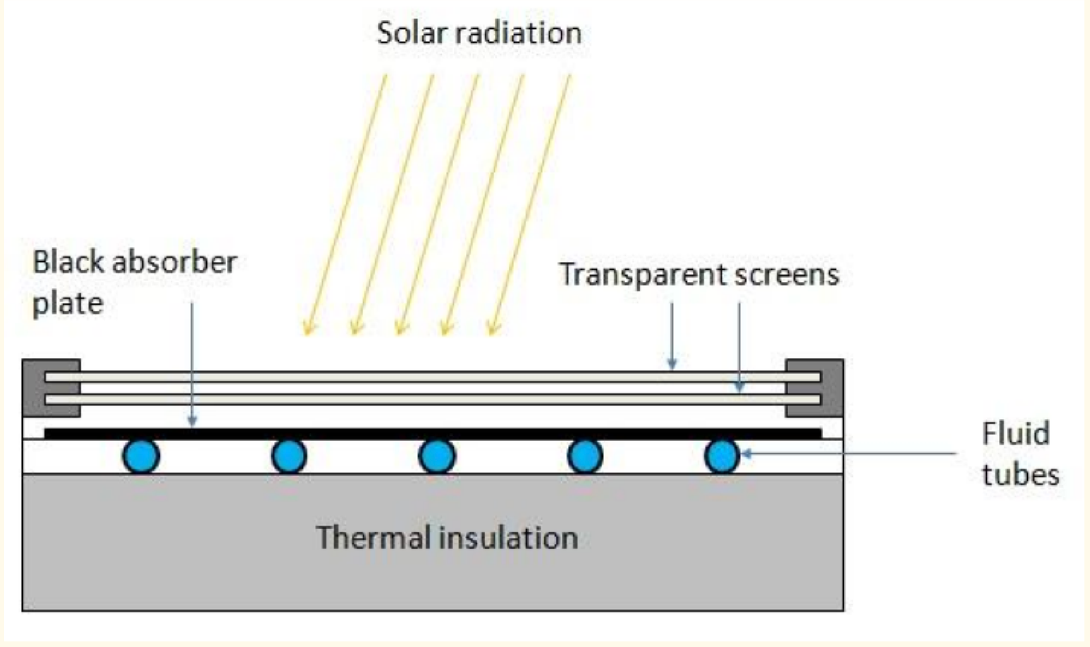
ST Application = heating, elect (processed w/ TEH)

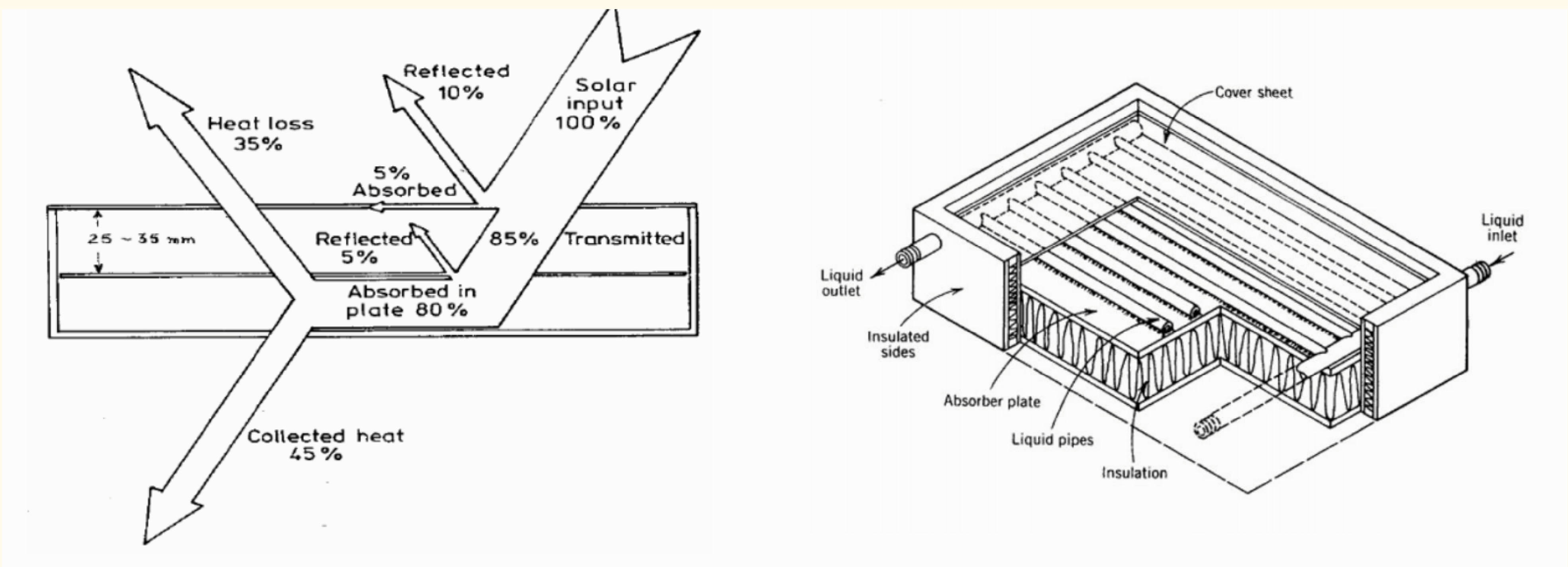
mechanism
- conduction → solid
- convection → fluid
- radiation → no medium

Type
- w/o consentration → surface colc, tube coled. → 80 - 150°C.
- concentrated → 300 - 500°C

Flat Plate Collectors (FPC)

- in winter, usually 'Anti-Freeze Agent' is added so the working fluid will not freeze up.





absorbed solar radiation (S) using:

$$S = G_T \times (\tau\alpha)_{av}$$

useful energy gain ($\dot{Q}_u$) using:

$$\dot{Q}_u = A_c \times F_R \times [S - U_L(T_{in} - T_{amb})]$$

e outlet temperature (T_{out}) of the working fluid using:

$$T_{out} = T_{in} + \frac{\dot{Q}_u}{\dot{m}c_p}$$

thermal efficiency (η) of the collector:

$$\eta = \frac{\dot{Q}_u}{A_c G_T}$$

Evacuated Tube Collector (ETC)

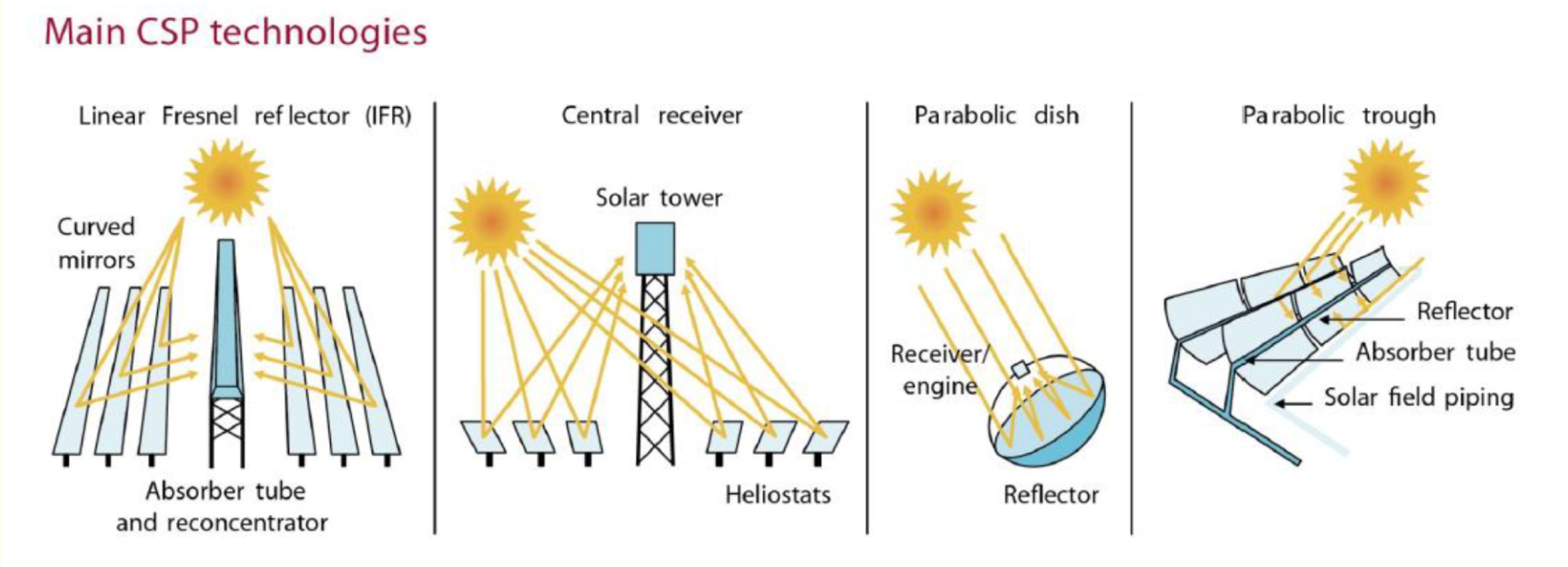
- Vacuum-insulated tube

Concentrated Solar Power (CSP)

- Parabolic/V through
- Dish system
- Fresnel reflector

$$C_{geo} = \frac{A_a}{A_r}$$

$$U_L = \dot{Q}_s = \eta_0 \times A_a \times I_0 \times \text{heat transfer efficiency}$$



Wind & Hydro

$$\text{Power} = \frac{1}{2}\rho A U^3 = \frac{1}{2}\rho \pi R^2 U^3$$

$$C_p = \frac{P_{aero}}{P_{wind}} = \frac{P_{aero}}{1/2\,\rho A U^3} = \frac{P_{aero}}{1/2\,\rho \pi R^2 U^3}$$

U relatif

Betz limit (max) = 0.59

Wind variability properties

Turbulence intensity -> std ratio of wind speed to mean/avg wind speed
Turbulent kinetic energy -> energy associated w/ turbulent motion
Autocorrelation -> wind speed values at diff point of time
Integral time scale/length scale ->
Power spectral density function -> freq vs amplitude of sinusoidally varying wave
Wind speed & direction

Wind

- Small scale/miniature turbine
- Vortex-induced vibration
- Galloping (transverse & wake)
- Flutter
- Turbulence-induced vibration

Hydro

- ballistic electrostatic: droplet's inertia to electricity
  -> triboelectricity

Technology apa aja -

Pilih 1 tech, jelaskan teknis detail