Basic Thermodynamics
Cycle analysis
Objectives and other details of modules

Duration – 90 minutes

Training aids
Power point Presentations
Reading Material

Objective

At the end of the session participants will be able to:

- Recap the basic thermodynamics, laws and thermodynamics cycles and its application in thermal power generation
- Effect various parameters on the cycle performance
- Undertake thermal cycle analysis and efficiency calculation
Thermodynamic laws
The four laws of thermodynamics define fundamental physical quantities (temperature, energy, and entropy) that characterize thermodynamic systems. The laws describe how these quantities behave under various circumstances, and forbid certain phenomena (such as perpetual motion).

The four laws of thermodynamics are:

- From the above, all the energy associated with a system must be accounted for as heat, work, chemical energy etc., thus perpetual motion machines of the first kind, which would do work without using the energy resources of a system, are impossible.

If two systems are both in thermal equilibrium with a third system then they are in thermal equilibrium with each other. This law helps define the notion of temperature.
There is a state function, called temperature which has the symbol $T$, which has the following relationship to heat, $q$:

addition of heat to a system will increase the temperature of the system.

if two closed system (together isolated), with different temperatures are brought into thermal contact, then the temperatures of the two systems will change to approach the same temperature.

That is, the temperature of the system which is at a higher temperature will decrease and the temperature of the system with the lower temperature will increase. They will eventually have the same temperature.
First Law of thermodynamics

Use of internal energy or change in internal energy, $\Delta E$, is not very convenient in chemistry. The reason for this is that when chemical reactions occur or samples are heated, the volume does not stay constant. If one is therefore interested in only $q$, the $\Delta E$ is complicated by an additional $w$. To avoid this a new quantity called enthalpy is defined, given the symbol $H$.

$H = E + PV$ or

$\Delta H = \Delta E + P \Delta V$

Since at constant pressure $P \Delta V = -w$ if no other external form of work is present, then:

$\Delta H = w + q + P \Delta V$

and

$\Delta H = q$

Therefore at constant pressure $\Delta H$ will yield the heat transferred. All thermodynamic tables use this as the tabulated "heat of reaction," etc.
There exists a useful thermodynamic variable called entropy ($S$). A natural process that starts in one equilibrium state and ends in another will go in the direction that causes the entropy of the system plus the environment to increase for an irreversible process and to remain constant for a reversible process.

$$S_f = S_i \quad \text{(reversible)} \quad S_f > S_i \quad \text{(irreversible)}$$
**Critical State:** Saturated liquid and saturated vapor states are identical. The two phases are indistinguishable. [Water: $p_c = 22.09$ MPa & $T_c = 647.3$ K], The critical point is the tip of the vapor dome.
Mollier chart
Pressure-enthalpy diagram
Isentropic and actual process
Carnot Cycle

Four processes.

1-2 Isothermal Heat Addition
2-3 Isentropic Expansion
3-4 Isothermal Heat Rejection
4-1 Isentropic Compression

The net cycle work done is the area enclosed by the cycle on the P-v diagram.

The net heat added is the area enclosed by the cycle on the T-s diagram.

For a cycle $W_{net} = Q_{net}$, the areas on the P-v and T-s diagrams are equal.

$$\eta_{th, Carnot} = 1 - \frac{T_L}{T_H}$$
Rankine Cycle:

(a) The Major Components

A useful diagram is a plot displaying temperature versus entropy (T-s diagram).

(1)→(2): pump isentropic compression
(2)→(3): boiler constant pressure heat addition
(3)→(4): turbine isentropic expansion
(4)→(1): condenser constant pressure heat rejection.
Rankine Cycle
Efficiency of Rankine cycle

\[ q_{\text{absorb}} = h_2 - h_1 \]

\[ q_{\text{exhaust}} = h_3 - h_4 \]

\[ \eta = \frac{q_{\text{absorb}} - q_{\text{exhaust}}}{q_{\text{absorb}}} \]

\[ = \frac{h_2 - h_1 - (h_3 - h_4)}{h_2 - h_1} \]

\[ = \frac{h_2 - h_1 - h_3 + h_4}{h_2 - h_1} \]
Turbine analysis

adiabatic  no kinetic or potential energy
\[ q - w = \Delta h + \Delta e + \Delta pe \]

- \[ h_1 = 3583 \text{ kJ/kg} \]
- \[ s_1 = 6.68 \text{ kJ/kg.K} \]
- \[ P_1 = 15 \text{ MPa} \]
- \[ T_1 = 600^\circ \text{C} \]

\[ w_{HP} = h_1 - h_2 = 762 \text{ kJ/kg} \]

- \[ P_3 = 1 \text{ MPa} \]
- \[ T_3 = 600^\circ \text{C} \]

- \[ h_3 = 3699 \text{ kJ/kg} \]
- \[ s_3 = 8.031 \text{ kJ/kg.K} \]

\[ w_{LP} = h_3 - h_4 = 1163 \text{ kJ/kg} \]

\[ P_4 = 10 \text{ kPa} \]

- \[ T_4 = T_{sat@10kPa} = 46^\circ \text{C} \]

Linear interpolation from superheat steam tables

\[ s = \begin{array}{ccc}
6.585 & 6.680 & 6.696 \\
2777 & 2821 & 2828 \\
180^\circ \text{C} & 197^\circ \text{C} & 200^\circ \text{C}
\end{array} \]

\[ s_4 = s_3 = 8.031 \text{ kJ/kg.K} < s_g@10kPa = 8.1488 \text{ kJ/kg.K} \]

thus: State 4 is in the Quality region

\[ T_4 = T_{sat@10kPa} = 46^\circ \text{C} \]

quality: \[ X = \left[ \frac{s - s_f}{s_{fg}} \right] = \left[ \frac{h - h_f}{h_{fg}} \right] \]

- \[ s_f = 0.6492 \text{ kJ/kg.K}, s_{fg} = 7.500 \text{ kJ/kg.K} \]
- \[ X_4 = 0.98 \]
- \[ h_f = 192 \text{ kJ/kg}, h_{fg} = 2392 \text{ kJ/kg} \]
- \[ h_4 = 2536 \text{ kJ/kg} \]

\[ w_T = w_{HP} + w_{LP} = 1925 \text{ kJ/kg} \]
In this ideal cycle we assume that the feedwater pump is isentropic. Furthermore, since the suction temperature of the water is 46°C, we assume that it behaves as an incompressible liquid, even at 15 MPa.

\[
\begin{align*}
\Delta T &= 0 \\
q - w &= \Delta h + \Delta ke + \Delta pe \\
-w_{pump} &= \Delta h = [v \Delta P + C_{H2O} \Delta T] \\
&= [0.001 (15,000 - 10)] = 15 \text{ kJ/kg}
\end{align*}
\]

\[
\begin{align*}
\h_6 &= \h_5 + \Delta h_{\text{pump}} \\
&= 192 + 15 = 207 \text{ kJ/kg}
\end{align*}
\]

Feedwater Pump

\[
\begin{align*}
P_6 &= 15 \text{ MPa} \\
T_6 &= T_5 = 46°C
\end{align*}
\]
Boiler

P₁ = P₆ = 15 MPa
T₁ = 600°C
h₁ = 3583 kJ/kg

P₂ = 1 MPa, T₂ = 197°C
s₂ = s₁ = 6.68 kJ/kg.K
h₂ = 2821 kJ/kg

Reheat

P₃ = P₂ = 1 MPa
T₃ = 600°C
h₃ = 3699 kJ/kg

qᵢn = Δh = (h₁ - h₆) + (h₃ - h₂)
= (3376 + 878) kJ/kg
= 4254 kJ/kg

qᵢn = no work
no kinetic or potential energy

q – w = Δh + Δke + Δpe
Carnot and Rankin cycle

250 °C
30 °C
523 K
( ~ 4 MPa)
303 K
( ~ 0.004 MPa)
Carnot Cycle 1 - 3 - 5 - 6

\[ \eta = \frac{T_H - T_C}{T_H} = \frac{523 - 303}{523} = \frac{220}{523} = 0.42 = 42\% \]

Rankine Cycle 1 - 2 - 4 - 5 - 6

1. \( h_1 = 126 \) kJ/kg
2. \( h_2 = 130 \) kJ/kg
3. \( h_4 = 535 \) kJ/kg
4. \( h_5 = 2802 \) kJ/kg
5. \( h_6 = 1835 \) kJ/kg

\[ \eta = \frac{h_5 - h_6}{h_5 - h_2} = \frac{2802 - 1835}{2802 - 130} = \frac{976}{2676} = 0.36 = 36\% \]
The two cycles are shown above 1-2-3-4-1 and 1-2'-3'-4'-1 have the same minimum pressure but different maximum pressures. As the result of increasing the maximum pressure from \( p \) to \( p' \), the net work output has increased by the area shown by horizontal hatching and decreased by the area shown by vertical hatching. Since, these two areas are nearly equal, the network is nearly the same, but the net heat rejected decreases by the area \( 4'-4-C-B \). Hence, the thermal efficiency increases.
Rankin cycle saturated

Heat Input

\[ q_{in} = (h_4 - h_2) \]

Work Output

\[ w = (h_4 - h_{10}) \]

Pump Work

\[ w = (h_2 - h_1) \]

Efficiency

\[ \eta = \frac{(h_4 - h_{10}) - (h_2 - h_1)}{(h_4 - h_2)} \]
Heat Input

\[ q_{in} = (h_5 - h_2) \]

Work Output

\[ w = (h_5 - h_9) \]

Pump Work

\[ w = (h_2 - h_1) \]

Efficiency

\[ \eta = \frac{(h_5 - h_9) - (h_2 - h_1)}{(h_5 - h_2)} \]
Cycle with out Reheating
We notice that reheating the output of the HP turbine back to 600°C (process (2)-(3)) allows both significantly more power output as well as increasing the quality at the LP turbine output (4) to 98%.
Rankin cycle - reheated

Heat Input

\[ q_{\text{in}} = (h_7 - h_6) + (h_5 - h_2) \]

Work Output

\[ w = (h_5 - h_6) + (h_7 - h_8) \]

Pump Work

\[ w = (h_2 - h_1) \]

Efficiency

\[ \eta = \frac{(h_5 - h_6) + (h_7 - h_8) - (h_2 - h_1)}{(h_7 - h_6) + (h_5 - h_2)} \]
If the condenser pressure is reduced from \( p_4 \) to \( p_4' \), the net work is increased by area 1-4-4'-1'-2'-2-1. And the heat supplied to steam increases by the area A-2'-2-B. These two areas are nearly equal; however, the net effect is to increase the thermal efficiency. This could be expected because the average temperature of heat rejection of the cycle decreases with decrease in condenser pressure.
Feed water heating

Some heat transferred to feedwater from 2 to 3
Slightly less work produced in turbine from 7 to 8
Slightly less heat rejected in condenser from 8 to 1
Heat added in boiler only from 4 to 6
Closer to Carnot Cycle therefore higher efficiency
With multiple heaters more feedwater heating
In limit boiler adds heat only from 5 to 6
Equal to Carnot Cycle therefore maximum efficiency.
Thank You