
بسم الله الرحمن الرحيم

# Applied Thermodynamics

## Week_15

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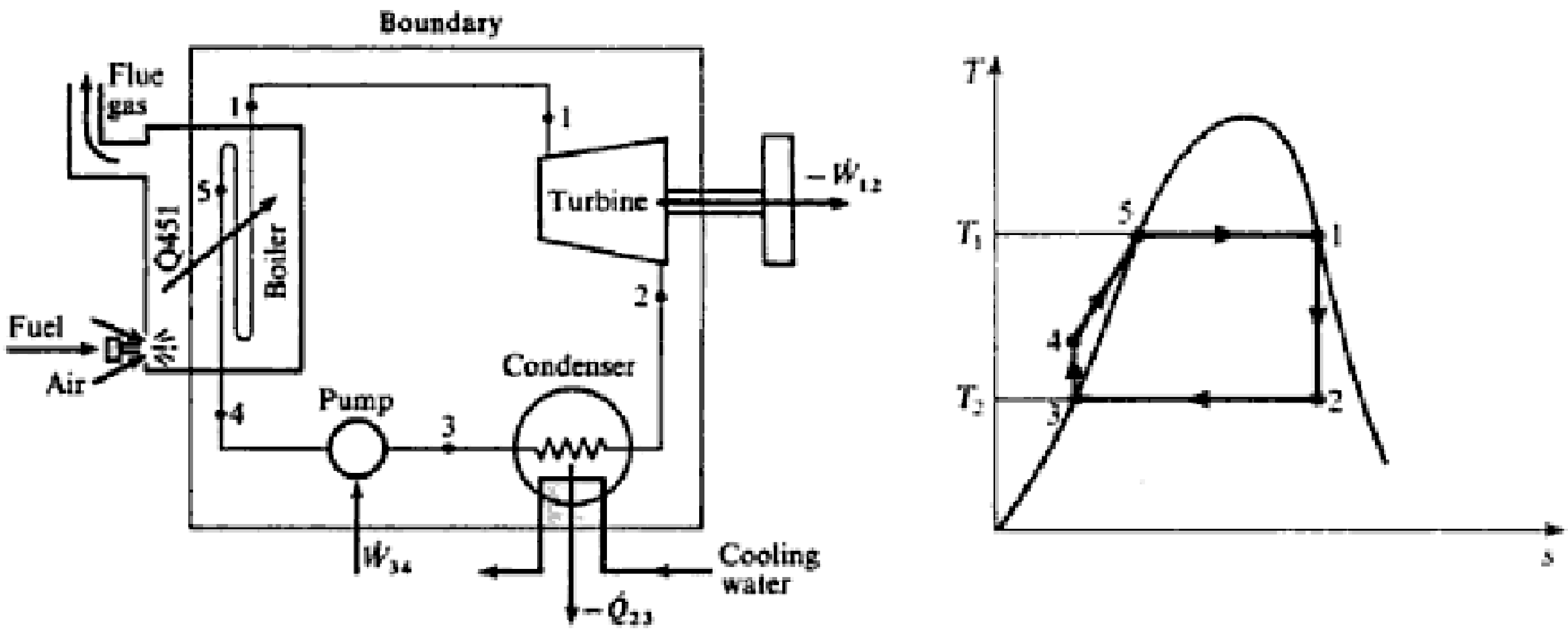
## Mechanical Engineering Department

# ***Steam Cycles-Rankine Cycle***

- The **Rankine cycle** is a model used to predict the performance of steam turbine systems. It was also used to study the performance of reciprocating steam engines.
- The Rankine cycle is an idealized thermodynamic cycle of a heat engine that converts heat into mechanical work while undergoing phase change.
- It is an idealized cycle in which friction losses in each of the four components are neglected. The heat is supplied externally to a closed loop, which usually uses water as the working fluid.
- It is named after William John Macquorn Rankine, a Scottish polymath and Glasgow University professor.

# Steam Cycles-Rankine Cycle

- Rankine cycle is the idealized cycle for steam power plants. This cycle is shown on T-s, diagram in the below figure. It consists of following processes:



# Steam Cycles-Rankine Cycle

- **Process 1-2:** Reversible adiabatic expansion of steam in the steam turbine.

$$W_{12} = h_1 - h_2$$

- **Process 2-3:** Constant pressure heat rejection in the condenser to convert condensate into water.

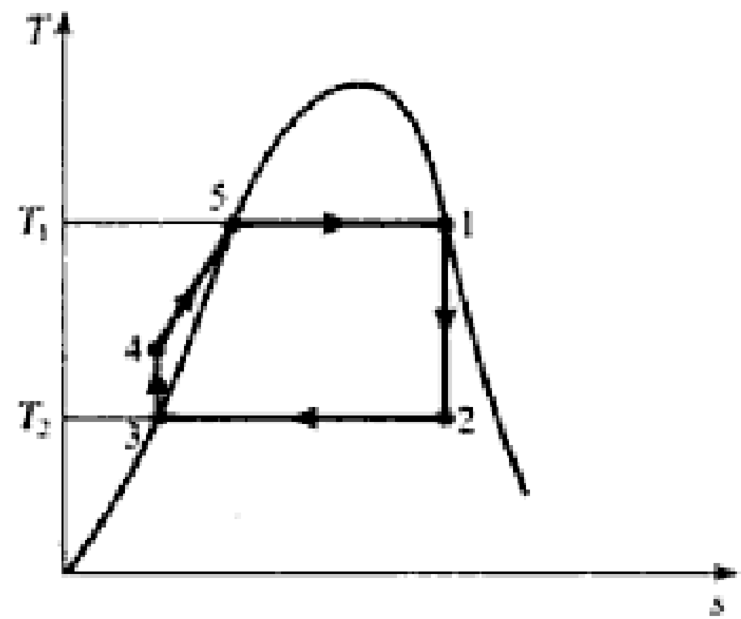
$$Q_{23} = h_2 - h_3$$

- **Process 3-4:** Water from the condenser at low pressure is pumped into the boiler at high pressure. This process is reversible adiabatic.

$$W_{34} = h_4 - h_3$$

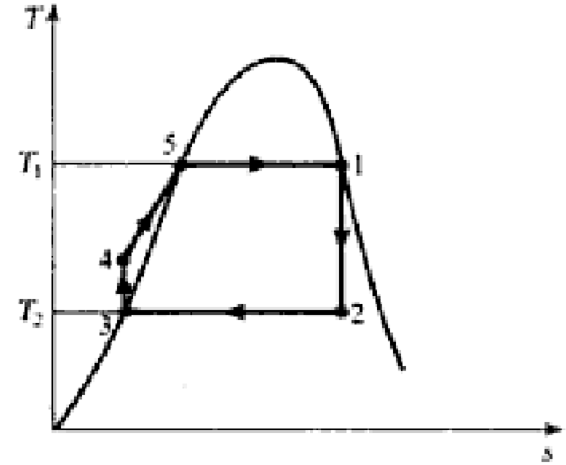
- **Process 4-1:** Water is converted into steam at constant pressure by the addition of heat in the boiler.

$$Q_{41} = h_1 - h_4$$



# Steam Cycles-Rankine Cycle

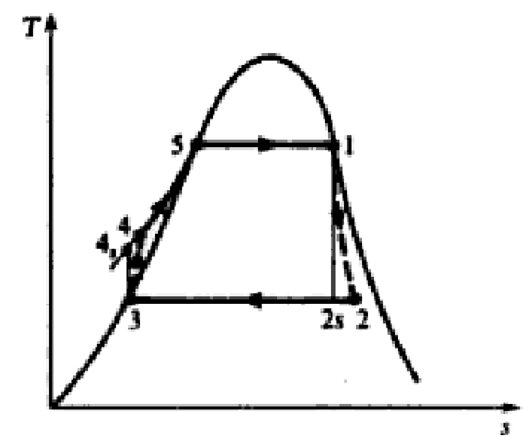
$$\text{Thermal Efficiency of Rankine Cycle} = \frac{Net\ work\ output}{Heat\ supplied\ in\ boile}$$




$$\eta_R = \frac{(W_{out} - W_{in})}{(Q_{in})} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$$

$$\text{Efficiency ratio} = \frac{Cycle\ efficiency}{Rankine\ efficiency}$$

$$\text{Isentropic } efficiency(expension) = \frac{Actual\ work}{Isentropic\ work}$$




$$\text{Isentropic } efficiency(compression) = \frac{Isentropic\ work}{Actual\ work}$$

$$\text{Turbine isentropic } efficiency = \frac{(h_1 - h_2)}{(h_1 - h_{2s})}$$

$$Specific\ steam\ consumption\ (ssc) = \frac{1}{Net\ work\ ouput}\ ) = \frac{1}{(h_1 - h_{2s})}$$

# Steam Cycles-Rankine Cycle

Example 8.1:

A steam power plant operates between a boiler pressure of 42 bar and a condenser pressure of 0.035 bar. Calculate for these limits the cycle efficiency, the work ratio, and the specific steam consumption:

(i) for a Carnot cycle using wet steam;
(ii) for a Rankine cycle with dry saturated steam at entry to the turbine;
(iii) for the Rankine cycle of (ii), when the expansion process has an isentropic efficiency of 80%.

Given Data:

P1= 42 bar P2= 0.035 bar Cycle efficiency = ? Work Ratio = ? SSC = ?

# Steam Cycles-Rankine Cycle

Solution:

(i) A Carnot cycle is shown in Fig. 8.5.

$$T_1 = \text{saturation temperature at 42 bar}$$
$$= 253.2 + 273 = 526.2 \text{ K}$$
$$T_2 = \text{saturation temperature at 0.035 bar}$$
$$= 26.7 + 273 = 299.7 \text{ K}$$

Then from equation (5.1)

$$\eta_{Carnot} = \frac{T_1 - T_2}{T_1} = \frac{526.2 - 299.7}{526.2} = 0.432 \quad \text{or} \quad 43.2\%$$

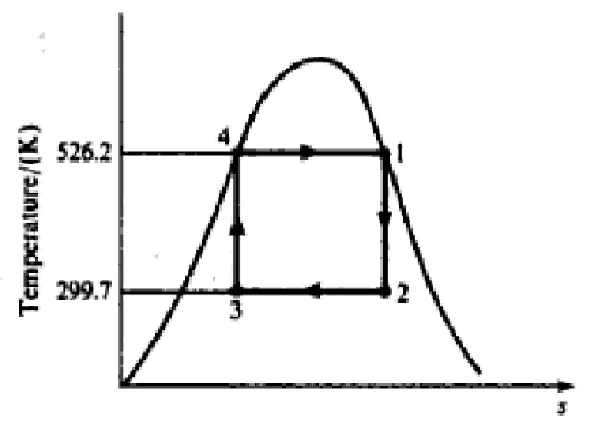



Fig. 8.5 Carnot cycle for Example 8.1(a)

Also Heat supplied $= h_1 - h_4 = h_{fg}$ at 42 bar $= 1698$ kJ/kg

Then $\eta_{Carnot} = \dfrac{\text{Net work output, } -\sum W}{\text{Gross heat supplied}} = 0.432$

Therefore $-\sum W = 0.432 \times 1698$,

i.e. Net work output, $-\sum W = 734$ kJ/kg

# Steam Cycles-Rankine Cycle

Solution:

To find the gross work of the expansion process it is necessary to calculate $h_2$, using the fact that $s_1 = s_2$.

From tables

$$h_1 = 2800 \text{ kJ/kg} \quad \text{and} \quad s_1 = s_2 = 6.049 \text{ kJ/kg K}$$

Using equation (4.10)

$$s_2 = 6.049 = s_{f_2} + x_2 s_{fg_2} = 0.391 + x_2 8.13$$

therefore

$$x_2 = \frac{6.049 - 0.391}{8.13} = 0.696$$

Then using equation (2.2)

$$h_2 = h_{f_2} + x_2 h_{fg_2} = 112 + (0.696 \times 2438) = 1808 \text{ kJ/kg}$$

Hence, from equation (8.2)

$$-W_{12} = h_1 - h_2 = 2800 - 1808 = 992 \text{ kJ/kg}$$

Therefore we have, using equation (8.13),

$$\text{Work ratio} = \frac{\text{net work output}}{\text{gross work output}} = \frac{734}{992} = 0.739$$

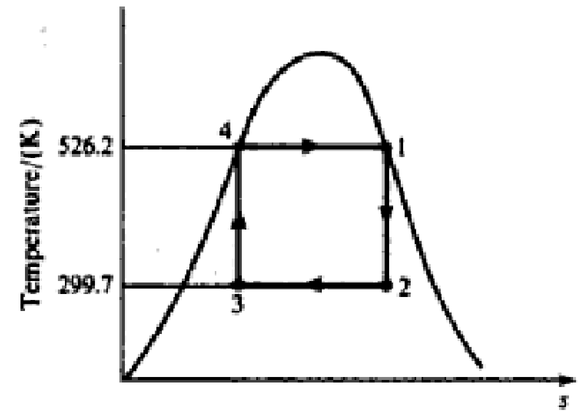



Fig. 8.5 Carnot cycle for Example 8.1(a)

Using equation (8.14)

$$\text{ssc} = \frac{1}{734}$$

i.e. $\text{ssc} = 0.001\,36 \text{ kg/kW s}$

$= 4.91 \text{ kg/kW h}$

# Steam Cycles-Rankine Cycle

Solution:

(ii) The Rankine cycle is shown in Fig. 8.6.
As in part (i)

$$h_1 = 2800 \text{ kJ/kg} \quad \text{and} \quad h_2 = 1808 \text{ kJ/kg}$$

Also, $h_3 = h_f$ at 0.035 bar = 112 kJ/kg

Using equation (8.10), with $v = v_f$ at 0.035 bar

$$\text{Pump work} = v_f(p_4 - p_3) = 0.001 \times (42 - 0.035) \times \frac{10^5}{10^3}$$

$$= 4.2 \text{ kJ/kg}$$

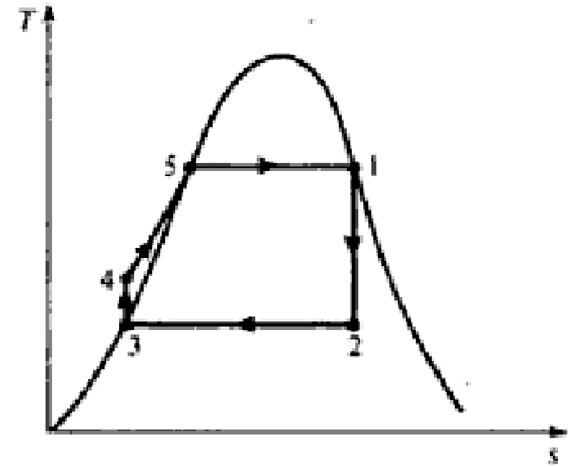



Fig. 8.6 $T$–$s$ diagram for Example 8.1(b)

Using equation (8.2)

$$-W_{12} = h_1 - h_2 = 2800 - 1808 = 992 \text{ kJ/kg}$$

Then using equation (8.8)

$$\eta_R = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_3) - (h_4 - h_3)} = \frac{992 - 4.2}{(2800 - 112) - 4.2} = 0.368$$

i.e. $\eta_R = 36.8\%$

Using equation (8.13)

$$\text{Work ratio} = \frac{\text{net work output}}{\text{gross work output}} = \frac{992 - 4.2}{992} = 0.996$$

# Steam Cycles-Rankine Cycle

Solution:

Using equation (8.14)

$$ssc = \frac{1}{-\sum W}$$

i.e.

$$ssc = \frac{1}{(992 - 4.2)} = 0.001\,01 \text{ kg/kW s} = 3.64 \text{ kg/kW h}$$

(iii) The cycle with an irreversible expansion process is shown in Fig. 8.7.
Using equation (8.12)

$$\text{Isentropic efficiency} = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{-W_{12}}{-W_{12s}}$$

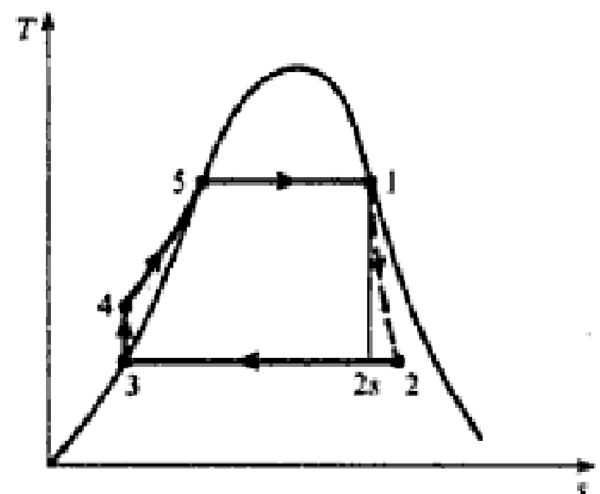



Fig. 8.7 *T–s* diagram for Example 8.1(c)

# Steam Cycles-Rankine Cycle

Solution:

therefore

$$0.8 = \frac{-W_{12}}{992}$$

i.e. $-W_{12} = 0.8 \times 992 = 793.6\ \mathrm{kJ/kg}$

Then the cycle efficiency is given by

$$\text{Cycle efficiency} = \frac{(h_1 - h_2) - (h_4 - h_3)}{\text{gross heat supplied}}$$

$$= \frac{793.6 - 4.2}{(2800 - 112) - 4.2} = 0.294$$

i.e. Cycle efficiency = 29.4%

$$\text{Work ratio} = \frac{-W_{12} - \text{pump work}}{-W_{12}} = \frac{793.6 - 4.2}{793.6} = 0.995$$

Also

$$\text{ssc} = \frac{1}{793.6 - 4.2} = 0.001\,267\ \mathrm{kg/kW\ s} = 4.56\ \mathrm{kg/kW\ h}$$

The feed-pump term has been included in the above calculations, but an inspection of the comparative values shows that it could have been neglected without having a noticeable effect on the results.

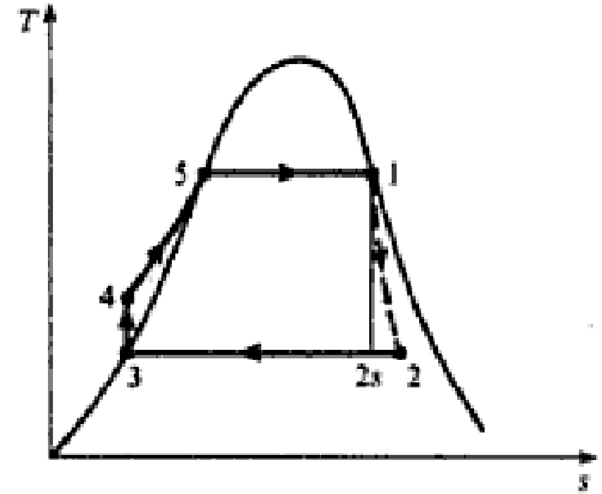



Fig. 8.7 $T$–$s$ diagram for Example 8.1(c)

# ***Steam Cycles-Rankine Cycle***

**Exercise Problems:** 8.1, 8.2


Thank You!