

## CHAPTER 9 VAPOR AND COMBINED POWER CYCLES

### 9-1 THE CARNOT VAPOR CYCLE

FIGURE 9-1  $T - s$  diagram of two Carnot vapor cycles.

### 9-2 RANKINE CYCLE: THE IDEAL CYCLE FOR VAPOR POWER CYCLES

FIGURE 9-2 The simple ideal Rankine cycle.

Energy Analysis of the Ideal Rankine Cycle

$$(9-1) \quad (q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \quad (kJ/kg)$$

$$(9-2) \quad \text{Pump} (q = 0): \quad w_{\text{pump, in}} = h_2 - h_1$$

$$(9-3) \quad w_{\text{pump, in}} = v(P_2 - P_1)$$

$$(9-4) \quad h_1 = h_f @ P_1 \quad \text{and} \quad v \cong v_1 = v_f @ P_1$$

$$(9-5) \quad \text{Boiler} (w = 0): \quad q_{in} = h_3 - h_2$$

$$(9-6) \quad \text{Turbine} (q = 0): \quad w_{\text{turb, out}} = h_3 - h_4$$

$$(9-7) \quad \text{Condenser} (w = 0) \quad q_{out} = h_4 - h_1$$

$$(9-8) \quad \mathbf{h}_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$(9-9) \quad h_{th} = \frac{3412 \text{ (Btu/kWh)}}{\text{Heat rate (Btu/kWh)}}$$

*EXAMPLE 9-1*      The Simple Ideal Rankine Cycle

FIGURE 9-3 Schematic and  $T - s$  diagram for Example 9-1.

### 9-3 DEVIATION OF ACTUAL VAPOR CYCLES FROM IDEALIZED ONES

FIGURE 9-4 (a) Deviation of actual vapor power cycle from the ideal Rankine cycle.

(b) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

$$(9-10) \quad h_p = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$(9-11) \quad h_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

*EXAMPLE 9-2*      An Actual Steam Power Cycle

FIGURE 9-5 Schematic and  $T - s$  diagram for Example 9-2.

### 9-4 HOW CAN WE INCREASE THE EFFICIENCY OF THE RANKINE CYCLE?

Lowering the Condenser Pressure (*Lowers*  $T_{\text{low,av}}$ )

Superheating the Steam to High Temperatures (*Increases*  $T_{\text{high,av}}$ )

Increasing the Boiler Pressure (*Increases*  $T_{\text{high,av}}$ )

*EXAMPLE 9-3* Effect of Boiler Pressure and Temperature on Efficiency

FIGURE 9-10  $T - s$  diagrams of the three cycles discussed in Example 9-3.

9-5 THE IDEAL REHEAT RANKINE CYCLE

$$(9-12) \quad q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$(9-13) \quad w_{turb,out} = w_{turb,I} + w_{turb,II} = (h_3 - h_4) + (h_5 - h_6)$$

FIGURE 9-11 The ideal reheat Rankine cycle.

FIGURE 9-12 The average temperature at which heat is transferred during reheating increases as the number of reheat stages is increased.

*EXAMPLE 9-4* The Ideal Reheat Rankine Cycle

FIGURE 9-13 Schematic and  $T - s$  diagram for Example 9-4.

9-6 THE IDEAL REGENERATIVE RANKINE CYCLE

FIGURE 9-14 The first part of the heat-addition process in the boiler takes place at relatively low temperatures.

Open Feedwater Heaters

FIGURE 9-15 The ideal regenerative Rankine cycle with an open feedwater heater.

$$(9-14) \quad q_{in} = h_5 - h_4$$

$$(9-15) \quad q_{out} = (1 - y)(h_7 - h_1)$$

$$(9-16) \quad w_{\text{turb,out}} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

$$w_{\text{pump,in}} = (1 - y)w_{\text{pumpI,in}} + w_{\text{pumpII,in}}$$

where

$$(9-17) \quad y = \dot{m}_6 / \dot{m}_5 \quad (\text{fraction of steam extracted})$$

$$w_{\text{pumpI,in}} = v_1(P_2 - P_1)$$

$$w_{\text{pumpII,in}} = v_3(P_4 - P_3)$$

### Closed Feedwater Heaters

FIGURE 9-16 The ideal regenerative Rankine cycle with a closed feedwater heater.

FIGURE 9-17 A steam power plant with one open and three closed feedwater heaters.

#### EXAMPLE 9-5 The Ideal Regenerative Rankine Cycle

FIGURE 9-18 Schematic and  $T - s$  diagram for Example 9-5.

#### EXAMPLE 9-6 The Ideal Reheat-Regenerative Rankine Cycle

FIGURE 9-19 Schematic and  $T - s$  diagram for Example 9-6.

## 9-7 SECOND-LAW ANALYSIS OF VAPOR POWER CYCLES

$$(9-18) \quad \dot{X}_{\text{dest}} = T_0 \dot{S}_{\text{gen}} = T_0 (\dot{S}_{\text{out}} - \dot{S}_{\text{in}}) = T_0 \left( \sum \dot{m}_e s_e + \frac{\dot{Q}_{\text{out}}}{T_{\text{b,out}}} - \sum \dot{m}_i s_i - \frac{\dot{Q}_{\text{in}}}{T_{\text{b,in}}} \right) \quad (\text{kW})$$

$$(9-19) \quad x_{\text{dest}} = T_0 s_{\text{gen}} = T_0 \left( s_e - s_i + \frac{q_{\text{out}}}{T_{\text{b,out}}} - \frac{q_{\text{in}}}{T_{\text{b,in}}} \right) \quad (\text{kJ/kg})$$

$$(9-20) \quad x_{\text{dest}} = T_0 \left( \sum \frac{q_{\text{out}}}{T_{\text{b,out}}} - \sum \frac{q_{\text{in}}}{T_{\text{b,in}}} \right) \quad (\text{kJ/kg})$$

$$(9-21) \quad x_{\text{dest}} = T_0 \left( \frac{q_{\text{out}}}{T_L} - \frac{q_{\text{in}}}{T_H} \right) \quad (\text{kJ/kg})$$

$$(9-22) \quad y = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \quad (\text{kJ/kg})$$

*EXAMPLE 9-7* Second-Law Analysis of an Ideal Rankine Cycle

## 9-8 COGENERATION

FIGURE 9-20 A simple process-heating plant.

FIGURE 9-21 An ideal cogeneration plant.

$$(9-23) \quad e_u = \frac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{\text{net}} + \dot{Q}_p}{\dot{Q}_{\text{in}}}$$

$$(9-24) \quad e_u = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}}$$

FIGURE 9-22 A cogeneration plant with adjustable loads.

$$(9-25) \quad \dot{Q}_{in} = \dot{m}_3(h_4 - h_3)$$

$$(9-26) \quad \dot{Q}_{out} = \dot{m}_7(h_7 - h_1)$$

$$(9-27) \quad \dot{Q}_p = \dot{m}_5 h_5 + \dot{m}_6 h_6 - \dot{m}_8 h_8$$

$$(9-28) \quad \dot{W}_{turb} = (\dot{m}_4 - \dot{m}_5)(h_4 - h_6) + \dot{m}_7(h_6 - h_7)$$

*EXAMPLE 9-8*      An Ideal Cogeneration Plant

FIGURE 9-23 Schematic and  $T - s$  diagram for Example 9-8.

## 9-9 COMBINED GAS-VAPOR POWER CYCLES

FIGURE 9-24 Combined gas-steam power plant.

*EXAMPLE 9-9*      A combined Gas-Steam Power Cycle

FIGURE 9-25  $T - s$  diagram of the gas-steam combined cycle described in Example 9-9.

## TOPICS OF SPECIAL INTEREST\*

### *Binary Vapor Cycles*

FIGURE 9-26 Mercury-water binary vapor cycle.

## SUMMARY

## REFERENCES AND SUGGESTED READING

## PROBLEMS\*

Carnot Vapor Cycle	9-1C → 9-2C 9-3E → 9-6
The Simple Rankine Cycle	9-7C → 9-14C 9-15 → 9-32
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