UNENE Graduate Course
Reactor Thermal-Hydraulics Design and Analysis

McMaster University
Whitby

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Reactor Thermodynamics

Dr. Nik Popov

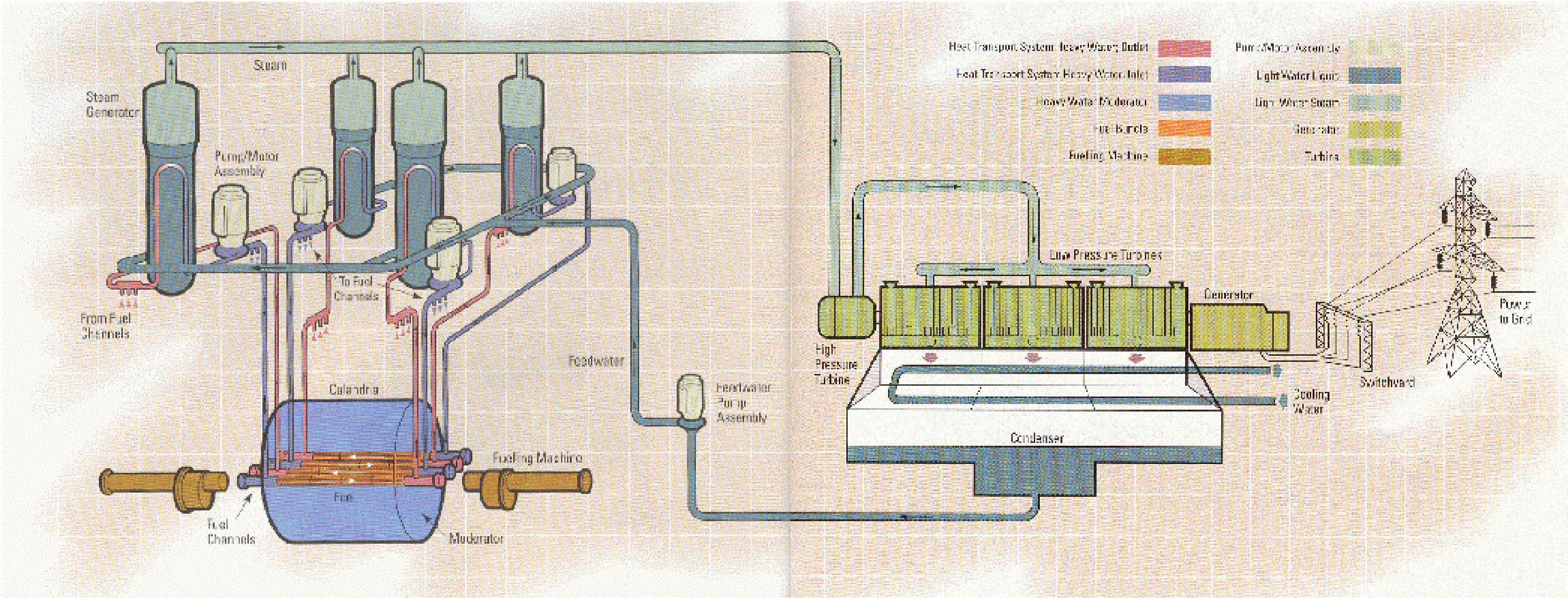
Outline

- Introduction
- The first law of thermodynamics
- The Carnot cycle
- The second law of thermodynamics
- The Rankine cycle
- Summary

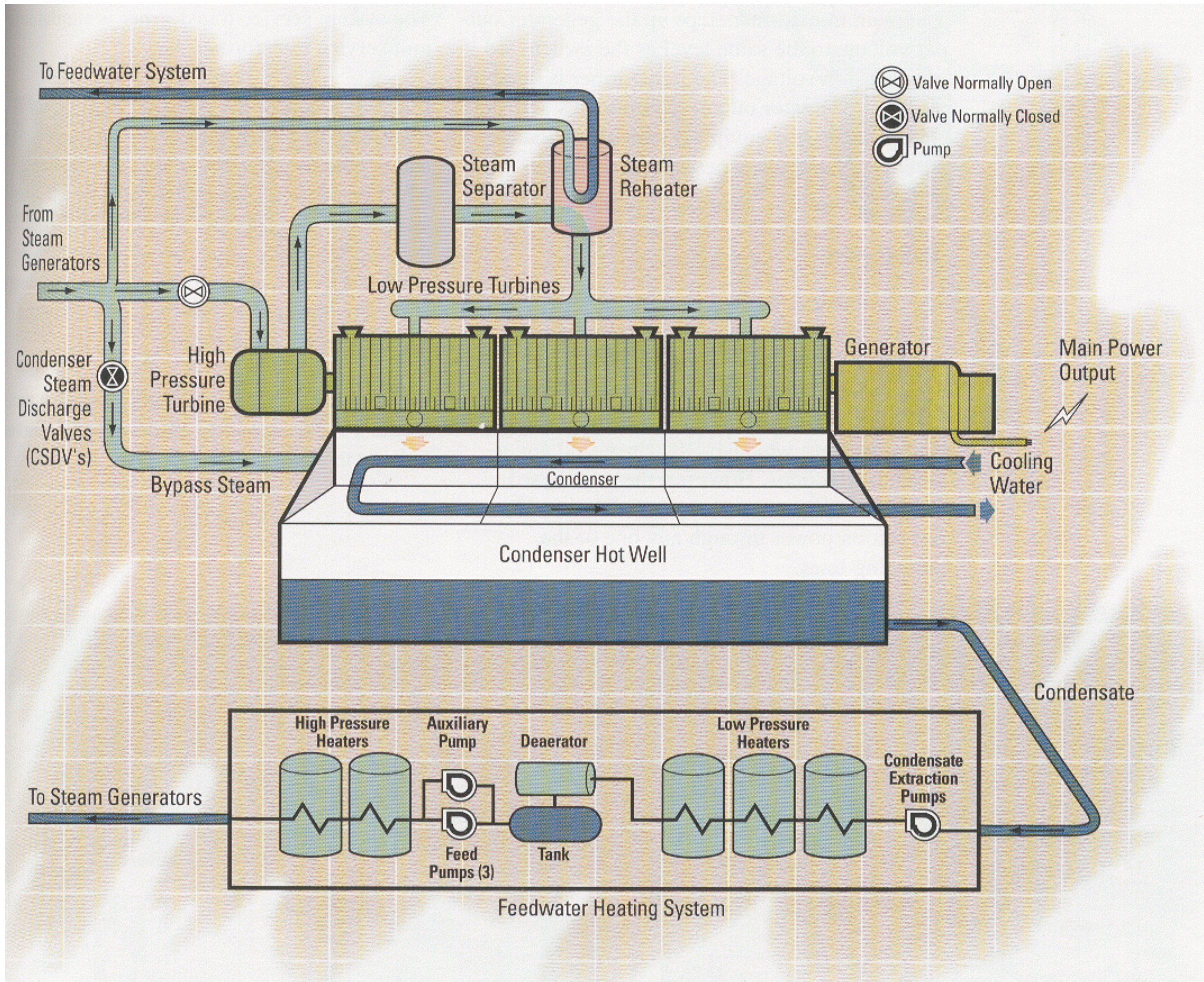
Introduction

- Thermodynamics
  – Conversion of energy from one form into another
- Energy
  – Thermal, electrical, chemical, potential, kinetic, and nuclear
- Nuclear reactor
  – A system converts thermal or heat energy (from fission) into mechanical energy
  – Primary system
    - Coolant is circulated through the reactor core by one or more high-pressure pumps, proceeds to the steam generator where steam is generated and is then pumped back to the core
  – Secondary system
    - Feedwater is evaporated in the steam generator to generate saturated steam, which goes through the turbine, gives up energy, and is condensed in the condenser, where the water returned to the steam generator by boiler feed pumps.

CANDU System



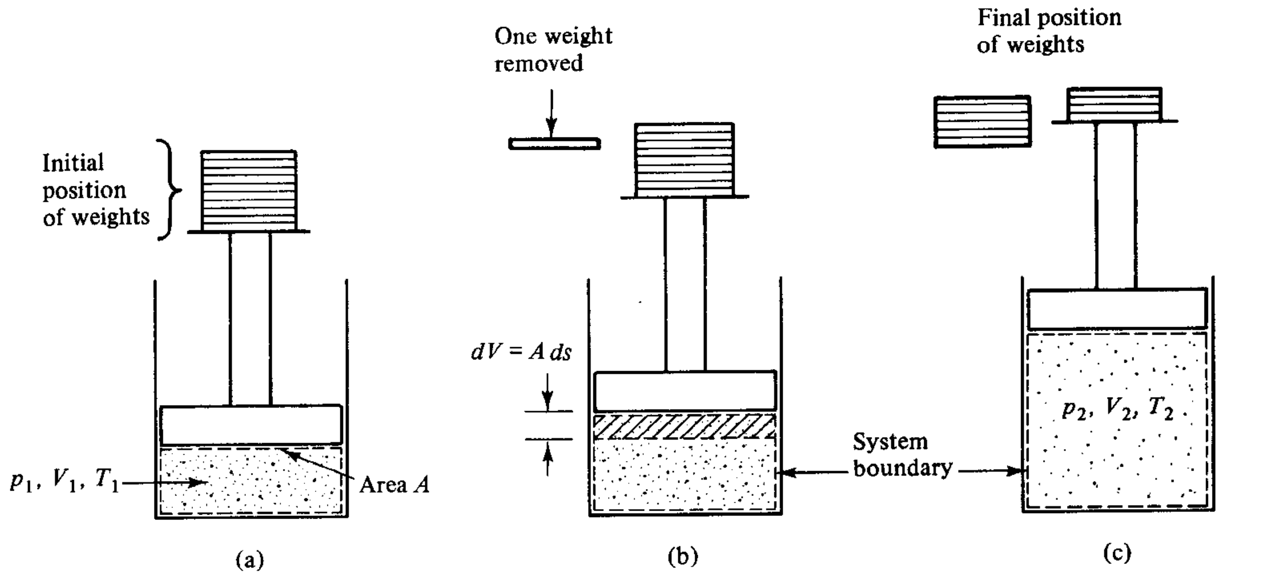
CANDU Power Cycle



Work

- Energy-transfer process
- Usually from one form to mechanical energy output
- Mechanical work done

$$dW = f\,dx = p\,A\,dx = p\,dV$$



Work Processes

- Constant Temperature Process (Isothermal)

$$W_{1-2} = \int_1^2 p\, dV = \int_1^2 mRT\, \frac{dV}{V} = mRT\, \ln\left(\frac{V_2}{V_1}\right)$$

- Constant Pressure Process

$$W_{1-2} = p\int_1^2 dV = p(V_2 - V_1)$$

- Constant Volume Process

$$W_{1-2} = \int_1^2 p\, dV = 0$$

Heat

- A form of energy exists only during the heat-transfer process
- Temperature difference is essential to the heat-transfer process
- Adiabatic process
  - No heat transfer to and from a system
- Isolated system
  - A system has neither heat nor work interactions with the surrounding

Energy

- Depends on temperature, pressure, velocity and elevation
- Consists of internal energy, potential energy and kinetic energy (and other forms not of interest)

$$E = U + PE + KE$$

- Specific energy, e (J/kg)

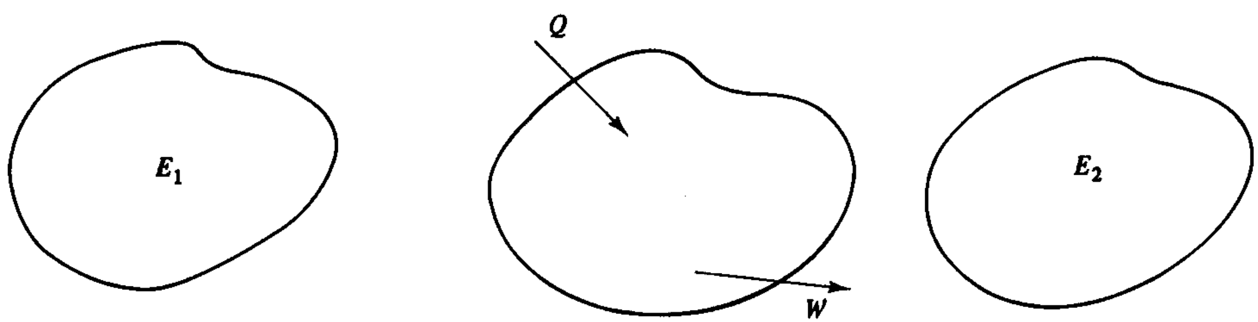
First Law of Thermodynamics

- Energy cannot be created or destroyed; it can only change forms

$$\text{Energy supplied} - \text{Energy removed}$$
$$= \text{Increase in the energy level}$$

$$Q - W = \Delta E = E_2 - E_1 \qquad \text{(for a constant mass)}$$

$$q - w = \Delta e = e_2 - e_1 \qquad \text{(per unit mass basis)}$$



Initial state

Heat and work transfer

Final state

Enthalpy

- Thermodynamic property of a substance
- Sum of its internal energy and the product of its pressure and volume, i.e.,

$$H = U + P\,V$$

- Specific enthalpy, h, (per unit mass basis)

$$h = u + P\,v$$

- Constant pressure process

$$W = \int_1^2 P\,dV = P(V_2 - V_1)$$

$$Q - P(V_2 - V_1) = U_2 - U_1 \qquad \text{(First law)}$$

$$Q = U_2 - U_1 + P(V_2 - V_1)$$

$$= (U_2 + P\,V_2) - (U_1 + P\,V_1) = H_2 - H_1 = \Delta H$$

Reactor Process

- Employ thermodynamic cycles with the objective to deliver work
- Process
  - Receiving heat energy from nuclear reaction
  - Converting part of the energy into work
  - Rejecting the rest of the energy to a large body of water (river, lake, or sea)
- Performance (or thermal efficiency), η_t

$$\eta_t = \frac{W}{Q_{in}}$$

Carnot Cycle

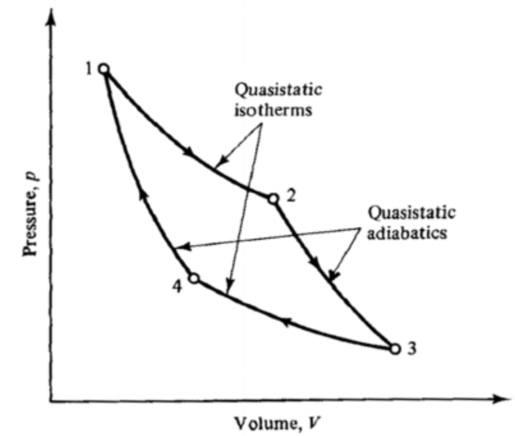
- Process from Point 1 to 2

$$\Delta U_{1-2} = \int_1^2 m\, c_v\, dT = 0$$

$$W_{1-2} = \int_1^2 p\, dV = m\, R\, T_1 \int_1^2 \frac{dV}{V} = m\, R\, T_1 \ln \frac{V_2}{V_1}$$

$$Q_{1-2} - W_{1-2} = \Delta U_{1-2} = 0 \qquad \text{(First law)}$$

$$Q_{1-2} = W_{1-2} = m\, R\, T_1 \ln \frac{V_2}{V_1}$$



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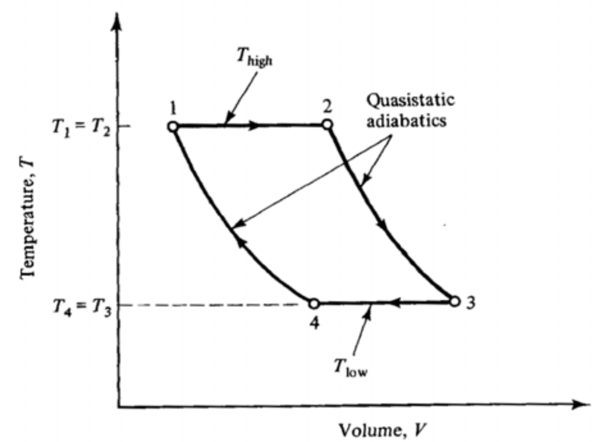
- Process from Point 2 to 3

$$Q_{2-3} = 0$$

$$W_{2-3} = \int_2^3 p\, dV = \int_2^3 C\, V^{-\gamma}\, dV = \frac{p_3 V_3 - p_2 V_2}{-\gamma + 1}$$

$$\Delta U_{2-3} = \int_2^3 m\, c_v\, dT = m\, c_v (T_3 - T_2)$$

$$Q_{2-3} = \Delta U_{2-3} + W_{2-3} = 0 \qquad \text{(First law)}$$



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Carnot Cycle (cont'd)

- Process from Point 3 to 4

$$\Delta U_{3-4} = 0$$

$$W_{3-4} = m\,R\,T_3 \ln\frac{V_4}{V_3} = Q_{3-4}$$

- Process from Point 4 to 1

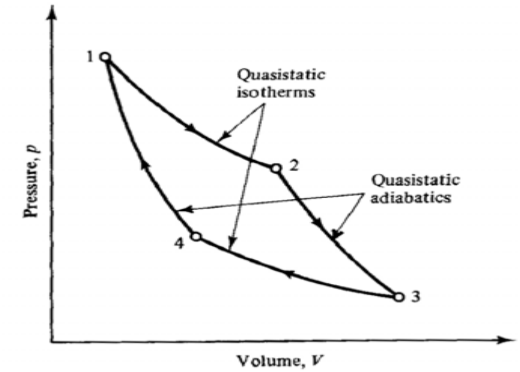
$$Q_{4-1} = 0$$

$$W_{4-1} = \frac{p_1 V_1 - p_4 V_4}{-\gamma + 1}$$

$$\Delta U_{4-1} = m\,c_v (T_1 - T_4) = -W_{4-1}$$

- Net work done

$$W_{cycle} = W_{1-2} + W_{2-3} + W_{3-4} + W_{4-1}$$



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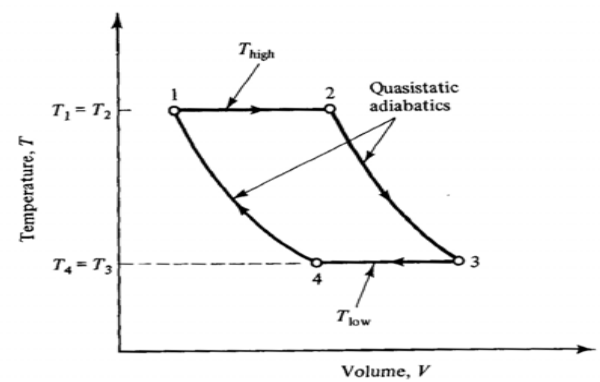

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Carnot Cycle (concluded)

- Quasistatic adiabatic process

$$T_2 V_2^{\gamma-1} = T_3 V_3^{\gamma-1} \quad \text{and} \quad T_4 V_4^{\gamma-1} = T_1 V_1^{\gamma-1}$$

- Isothermal process

$$T_1 = T_2 \quad \text{and} \quad T_3 = T_4 \qquad p_1 V_1 = p_2 V_2 \quad \text{and} \quad p_3 V_3 = p_4 V_4$$

- Volume relation

$$\frac{V_2}{V_1} = \frac{V_3}{V_4}$$

- Net work done

$$W_{cycle} = mR(T_1 - T_3)\ln\frac{V_2}{V_1}$$

- Thermal efficiency

$$\eta_t = \frac{W_{cycle}}{Q_{in}} = \frac{W_{cycle}}{Q_{1-2}} = \frac{mR(T_1 - T_3)\ln(V_2/V_1)}{mR\,T_1\ln(V_2/V_1)} = \frac{T_1 - T_3}{T_1} = 1 - \frac{T_3}{T_1}$$

Second Law of Thermodynamics

- Clausius statement

  "It is impossible to construct a device that executes a thermodynamic cycle so that the sole effect is to produce a transfer of heat energy from a body at a low temperature to a body at a high temperature"

  Heat transfer does not occur from low temperature to high temperature.

- Kevin-Planck statement

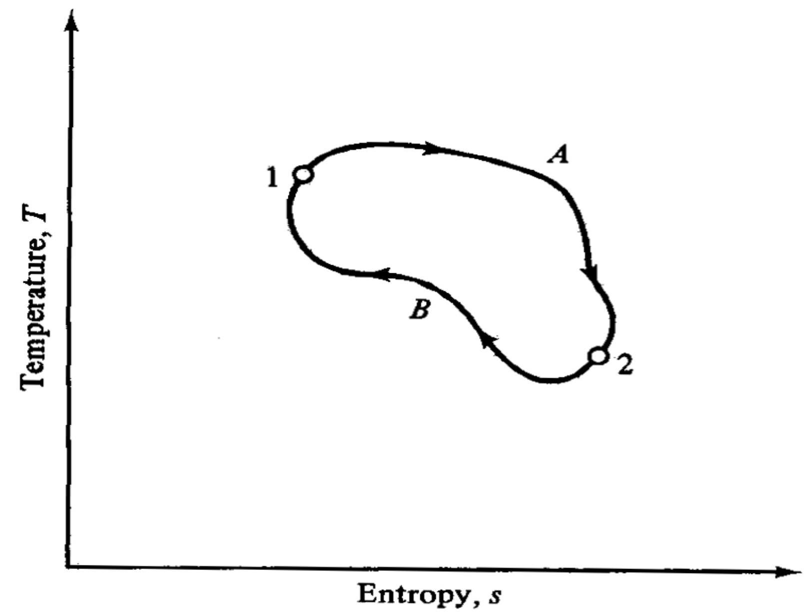
  "It is impossible to construct a device that executes a thermodynamic cycle, exchanges heat energy with a single reservoir, and produces an equivalent amount of work"

  Thermal energy cannot be converted into work by a cyclic process with 100% efficiency.

Entropy

- In a reversible process, the quantity, $\delta Q/T$, from Point 1 to Point 2 is the same regardless of the path
- Entropy, S, is defined as

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\bigg|_{\text{reversible}}$$



- Specific entropy, s (J/kg K)

Carnot Cycle in terms of Entropy

- Heat energy supplied and rejected

$$Q_{in} = T_h(S_2 - S_1)$$

$$Q_{out} = T_l(S_3 - S_4)$$

$$= T_l(S_2 - S_1)$$

- Net work done

$$W_{cycle} = Q_{in} - Q_{out}$$

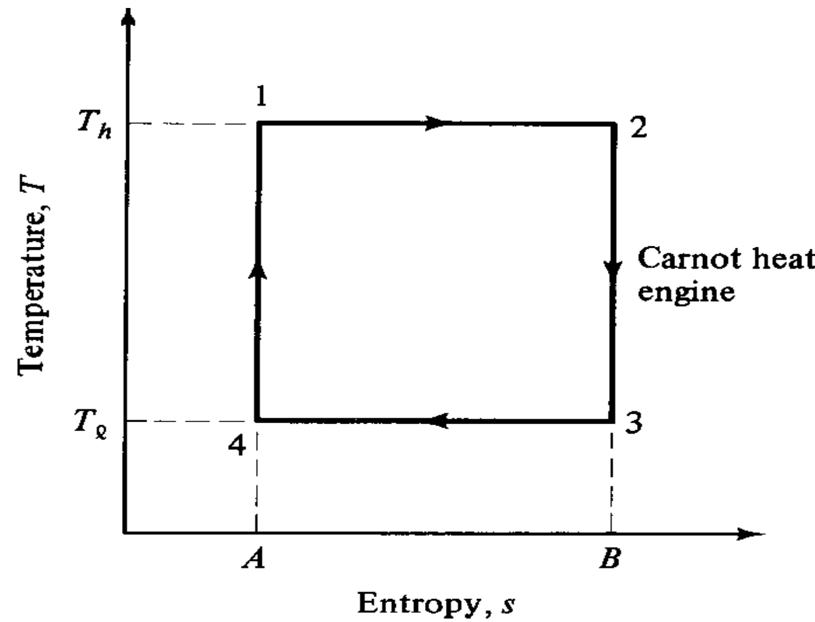
$$= T_h(S_2 - S_1) - T_l(S_2 - S_1)$$

$$= (T_h - T_l)(S_2 - S_1)$$

- Thermal efficiency

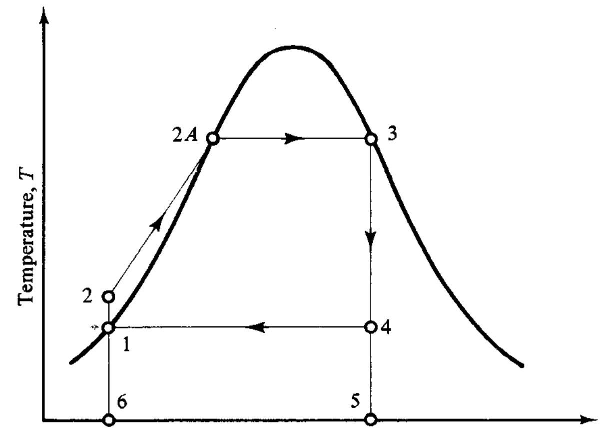
$$\eta_t = \frac{W_{cycle}}{Q_{in}} = \frac{(T_h - T_l)\,(S_2 - S_1)}{T_h\,(S_2 - S_1)}$$

$$= \frac{T_h - T_l}{T_h} = 1 - \frac{T_l}{T_h}$$



Reactor Power Cycle

- Similar to a Carnot cycle
- More heat rejection to bring the feedwater to saturation avoiding liquid-vapour mixture in the pump
- Referred to as a Rankine cycle
  - Heat supplied: Area 6-1-2-2A-3-4-5-6
  - Heat removed: Area 6-1-4-5-6
  - Net work done: Area 1-2-2A-3-4-1
- Assumptions
  - Negligible changes in kinetic energy and potential energy in the medium
  - All processes are reversible
  - Negligible pressure and heat losses



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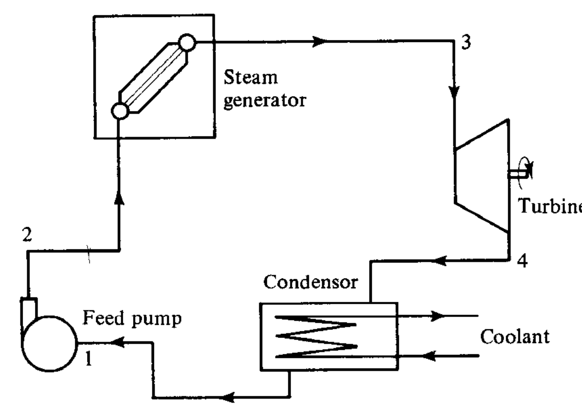

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Simple Rankine Cycle

- Process 1-2 (Isentropic compression)

$$q_{1-2} = 0$$

$$-w_{1-2} = -(h_2 - h_1) = -\int_1^2 v\,dp \sim -v_1(p_2 - p_1)$$

- Process 2-2A-3 (Heating, P constant)

$$w_{2-3} = 0 \quad \text{and} \quad q_{2-3} = q_{in} = h_3 - h_2$$

- Process 3-4 (Isentropic expansion)

$$q_{3-4} = 0 \quad \text{and} \quad w_{3-4} = h_3 - h_4$$

- Process 4-1 (Heat removal, P constant)

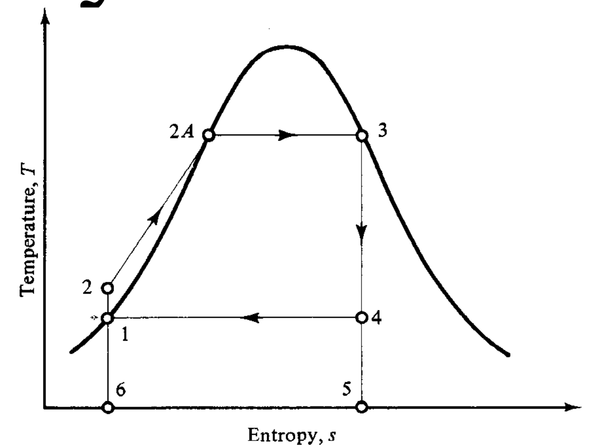
$$w_{4-1} = 0 \quad \text{and} \quad -q_{4-1} = h_4 - h_1$$

- Net work

$$w_{cycle} = w_{3-4} + w_{1-2} = (h_3 - h_4) - (h_2 - h_1)$$

- Thermal efficiency

$$\eta_{Rankine} = \frac{w_{cycle}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} = \frac{q_{2-3} - q_{4-1}}{q_{2-3}}$$



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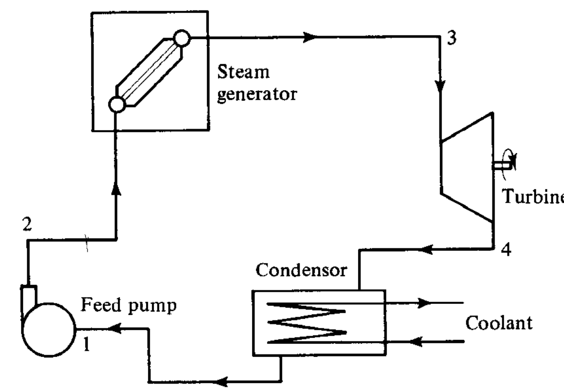

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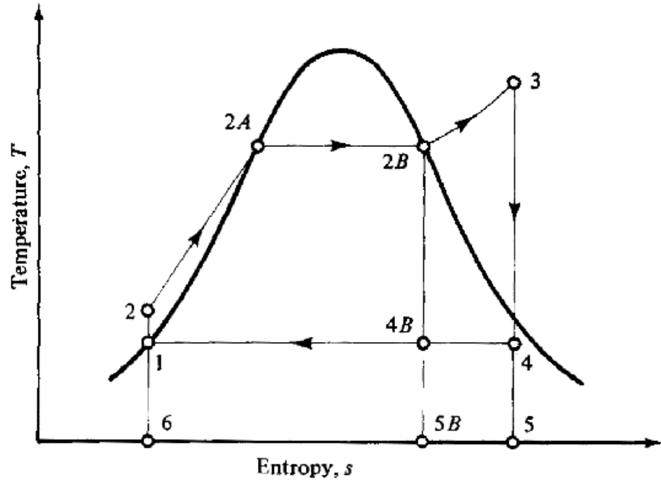
Rankine Cycle with Superheat

- Changes
  - Increase net work output (Area 2B-3-4-4B-2B)
  - Increase heat supply (Area 2B-3-4-5B-2B)
  - Increase in exhaust steam quality from x_{4B} to x_4
- Thermal efficiency

$$\eta_{Superheat} = \frac{w_{cycle}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

$$= \frac{q_{2-3} - q_{4-1}}{q_{2-3}}$$



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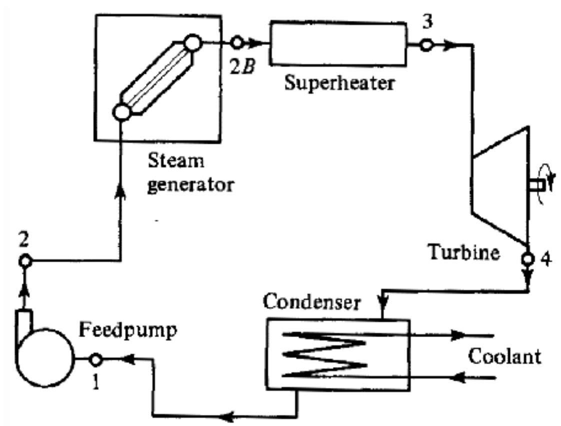

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Reheat Cycle

- Wet steam at Point 4 is removed after the high-pressure stage of the turbine, reheated at constant pressure to a superheated state, and admitted to the low-pressure stage of the turbine
- Superheat steam at Point 3A is expanded to the design exhaust pressure Point 4A
- Net work

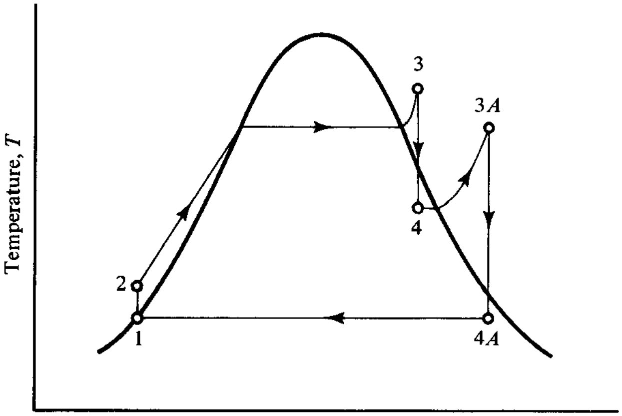
$$w_{cycle} = w_{1-2} + w_{3-4} + w_{3A-4A}$$
$$= (h_1 - h_2) + (h_3 - h_4) + (h_{3A} - h_{4A})$$

- Heat supply

$$q_{in} = (h_3 - h_2) + (h_{3A} - h_4)$$

- Thermal efficiency

$$\eta_{Reheat} = \frac{(h_1 - h_2) + (h_3 - h_4) + (h_{3A} - h_{4A})}{(h_3 - h_2) + (h_{3A} - h_4)}$$



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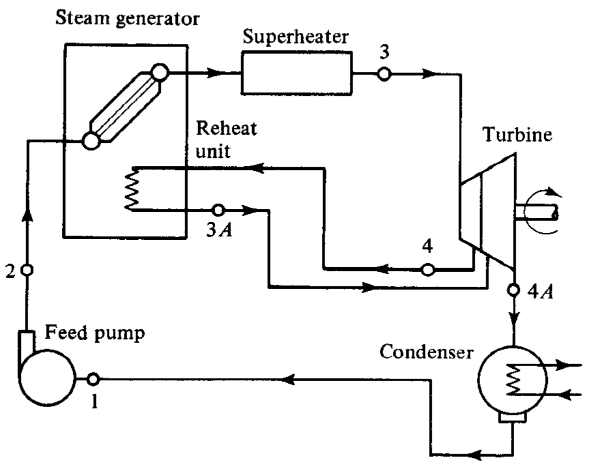
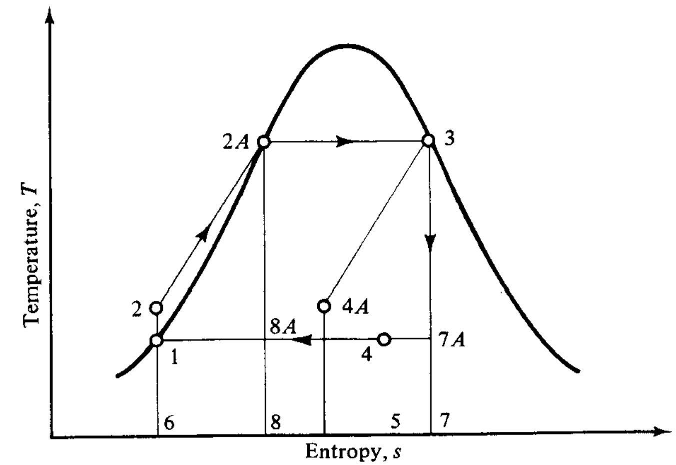


Regeneration Cycle

- Internal heat from the turbine is used to heat the feed water in Process 2-2A
- Ideally, provide the same thermal efficiency as the Carnot cycle
- Not feasible in practice
  - Reversible heat transfer from the expanding steam in the turbine to the water from the feed pump cannot be achieved
  - Quality of the exhaust from the turbine is too low
  - Impossible to design a turbine to be served as both power-production device and heat exchanger



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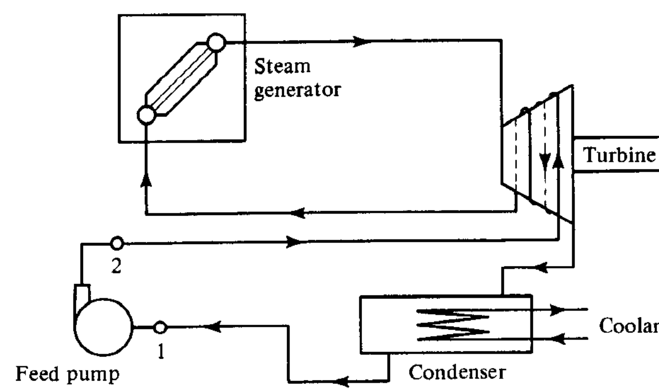

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Rankine Cycle with Feedwater Heater

- Based on the principle of regeneration
- A small amount of steam is extracted at an intermediate pressure from the turbine, and used to heat the feedwater
- Two types of feedwater heaters
  - Open
    - Direct contact between extracted steam and feedwater
    - Good heat transfer
  - Closed
    - Only a thermal contact between extracted steam and feedwater
- Single and multi-stage extraction

Rankine Cycle with Open Feedwater Heater

- **Fraction of steam is calculated from an energy balance on the feedwater heater (internal heat transfer not shown in T-S diagram)**

$$\dot{m}(1-y)h_2 + \dot{m}(y)h_6 = \dot{m}(y + (1-y))h_3$$

$$(1-y)h_2 + y\,h_6 = h_{f,3}$$

- **Pump work**

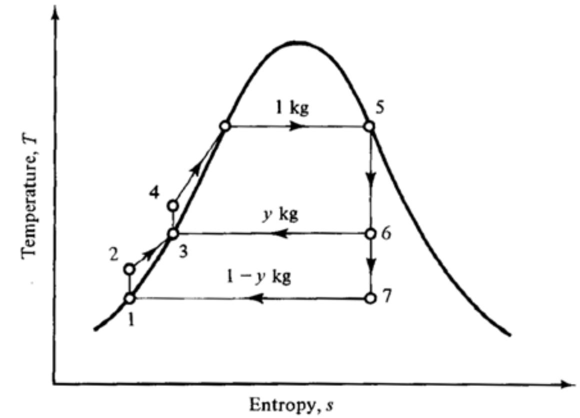
$$w_{pump} = w_{1-2}(1-y) + w_{3-4}$$

- **Turbine work**

$$w_{turbine} = w_{5-6} + (1-y)\,w_{6-7}$$

- **Heat supplied**

$$q_{4-5} = h_5 - h_4$$



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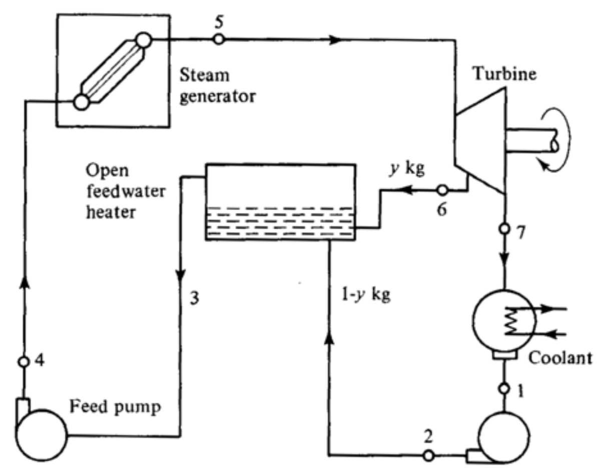

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Rankine Cycle with Closed Feedwater Heater

- **Fraction of steam is calculated from an energy balance on the feedwater heater**

$$(1-y)h_2 + y\,h_6 = (1-y)\,h_{2A} + y\,h_3$$

$$(1-y)h_2 + y\,h_6 = (1-y)\,h_{2A} + y\,h_{f,3}$$

- **Pump work**

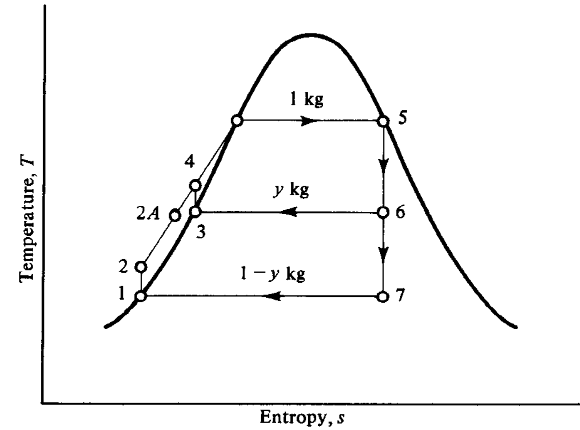
$$w_{pump} = w_{1-2}(1-y) + w_{3-4}$$

- **Turbine work**

$$w_{turbine} = w_{5-6} + (1-y)\,w_{6-7}$$

- **Heat supplied**

$$q_{in} = (h_5 - h_{2A})(1-y) + (h_5 - h_4)\,y$$



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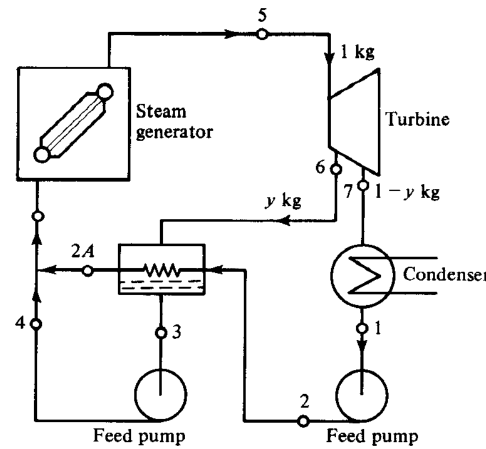

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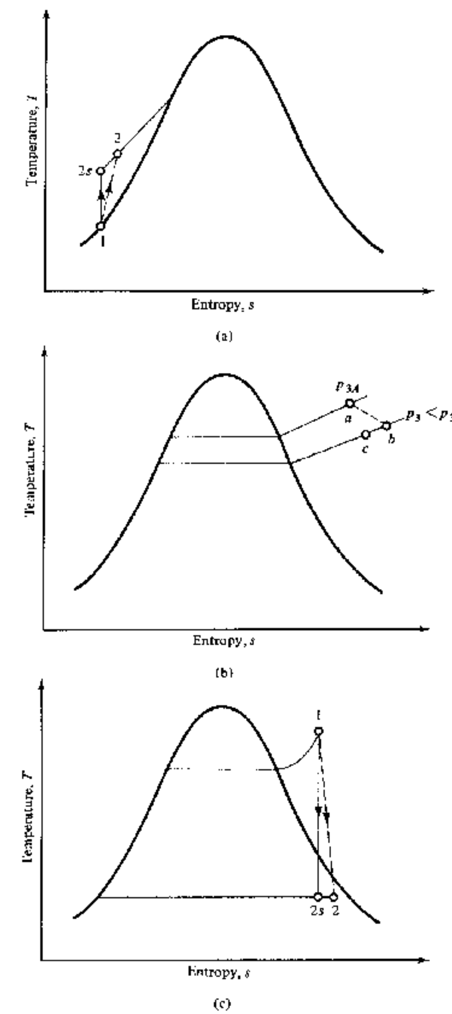
Actual Rankine Cycle

- Actual Rankine cycle is not ideal, or reversible, processes
- Irreversible frictional and heat losses
- At the pump
  - Heat loss to the surrounding (negligible)
  - Fluid friction (requires more work)
  - Mechanical friction (bearings, gears, etc.)
- At the turbine
  - Pressure drop between superheater and turbine reduces entrance pressure from P3A to P3
  - Heat loss to surrounding reduces the temperature from Point b to Point c
  - Steam expansion inside the turbine is irreversible adiabatic (non-isentropic)
    - Reduce efficiency but increase steam quality
  - Mechanical friction



Summary

- Descriptions of work, energy, and enthalpy
- First and second laws of thermodynamics
- Reactor processes and power cycles
  - Ideal cycles: Carnot and Rankine cycles
    - Improvement of thermal efficiency: superheating, reheating, regeneration, and feedwater heating
  - Actual Rankine cycle
- Examples

Questions?