VII. Power and Refrigeration Cycles

A. Overview

1. Vapor power cycles - steam power plants and their idealized representation, the Rankine cycle (Sections 10-1 to 10-2)
2. Gas power cycles
    - a. the Carnot cycle
    - b. the spark-ignition, internal combustion engine and its idealized representation, the Otto cycle (Sections 9-1 to 9-5)
3. Refrigeration cycles - the ideal vapor-compression cycle (Sections 11-1 to 11-3)

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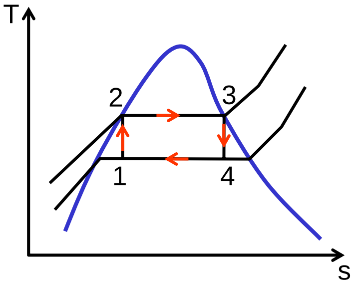
B. Vapor Power Cycles

1. Introduction
    - a. working fluid is cycled between vapor and liquid state.
    - b. steam is most common working fluid.
2. Carnot vapor cycle is impractical because of low quality of steam in process 3-4 and because of difficulty of pumping two phase mixture in process 1-2.

Carnot
vapor
cycle



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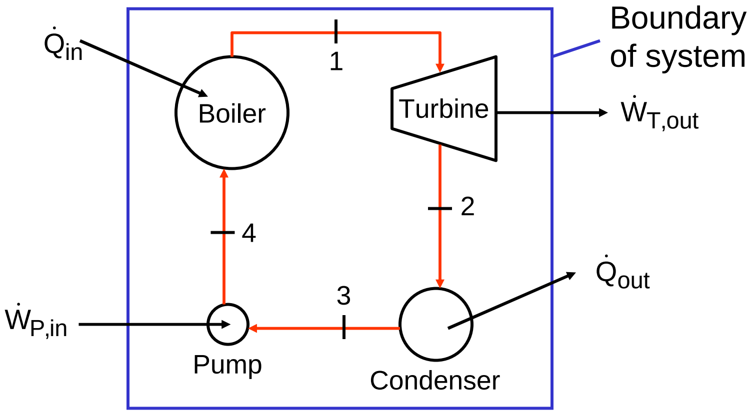
3. The ideal Rankine cycle

a. schematic of process



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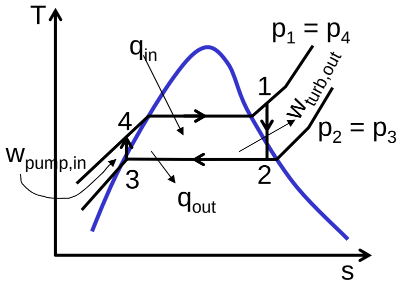
b. T-s diagram



- 3-4 isentropic compression in pump,
- 4-1 constant p heat addition in boiler
- 1-2 isentropic expansion in turbine
- 2-3 constant p heat rejection in condenser

$$w_{t,out} = h_1 - h_2 \qquad (10\text{-}6)$$

$$w_{pump,in} = \int_3^4 v\,dp = v_{ave}\left(p_4 - p_3\right) \cong v_{f3}\left(p_4 - p_3\right) \qquad (10\text{-}3)$$

$$\boxed{\eta_{th,rankine} = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{h_2 - h_3}{h_1 - h_4}}$$

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4. Generation of electricity

   a. Steam power plants operating on the Rankine cycle produce about 90% of the electricity consumed in the US.

   b. Energy sources for net electricity generation (data for US for year 2000, utilities only)

Fuel	kWh x 10^9	%	
coal	1697	56.3	
nuclear	705	23.4	
gas	291	9.65	
hydro	248	8.23	
petroleum	72	2.39	
other	2	0.07	
total	3015	100	

Source: http://www.eia.doe.gov/cneaf/electricity/epav1/generation.html

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c. General information for fossil fuel steam power plants

Overall efficiency

36 - 40 % or 1 kWh electricity for each 8500 - 9500 Btu (8970 - 10,000 kJ) supplied by fuel.

Turbine generators, steam flow, temperatures and pressures

Rated to 1300 MW. Boilers producing 10^6 - 10^7 lb/h steam (126 - 1260 kg/s) with pressures ranging from 1800 - 3500 psi (12.4 - 24.1 MPa) and temperatures from 950 to 1000ºF (510 - 538ºC).

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d. Sample calculations for coal-fired, 1000 MW$_e$, steam power plant

Thermal efficiency

Highest temperature: 510ºC (superheater)
Lowest temperature: 40ºC (condenser)
Carnot efficiency:

$$\eta_{th,carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{40 + 273}{510 + 273} = 0.60$$

For our calculations, a more realistic value for the thermal efficiency is

$$\eta_{th} = \frac{\dot{W}_e}{\dot{Q}_H} = 0.40$$

VII. Power and Refrigeration Cycles

d. Sample calculations for coal-fired, 1000 MW$_e$, steam power plant (cont.)

Heat supplied to boiler by combustion, Q$_H$

$$\eta_{th} = \frac{\dot{W}_e}{\dot{Q}_H} = 0.40 \qquad \dot{Q}_H = \frac{\dot{W}_e}{\eta_{th}} = \frac{1000x10^6 W}{0.40} = 2.5x10^9 W$$

Heat rejected to surroundings, Q$_L$

$$\dot{Q}_H - \dot{Q}_L - \dot{W}_e = 0$$

$$\dot{Q}_L = \dot{Q}_H(1 - \eta_{th}) = 0.60\dot{Q}_H = 0.60(2.5x10^9) = 1.5x10^9 W$$

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d. Sample calculations for coal-fired, 1000 MW_e, steam power plant (cont.)

What to do with rejected heat, Q_L?

Most cooling systems are closed and utilize large evaporative coolers. If the “waste” heat is transferred to a river, the temperature rise can be quite large.

The upper Hudson River has an average flow of 5800 ft^3/s ($1.64x10^5$ kg/s). For comparison, the Bear River is 640 ft^3/s and the Jordan is 144 ft^3/s. How much will the Hudson increase in temperature if $\dot{Q}_L = 1.5x10^9 W$?

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d. Sample calculations for coal-fired, 1000 MW_e, steam power plant (cont.)

Temperature rise of Hudson is calculated from steady state energy balance on river, with control volume boundaries located upstream and downstream of the power plant. (Assume constant heat capacity, C).

$$\dot{Q}_L + \dot{m}h_{in} - \dot{m}h_{out} = \dot{Q}_L + \dot{m}C(T_{in} - T_{out}) = 0$$

$$\Delta T = \frac{\dot{Q}_L}{\dot{m}C} = \frac{1.5x10^9 W}{1.64x10^5 \frac{kg}{s} 4180 \frac{J}{kg\ K}} = 2.2^\circ C$$

VII. Power and Refrigeration Cycles

d. Sample calculations for coal-fired, 1000 MW$_e$, steam power plant (cont.)

How much coal must our plant burn?

The overall efficiency is defined as (Lesson 13 & Eqn. 2-43)

$$\eta_{overall} = \frac{\dot{W}_e}{\dot{m}_{fuel} \bullet HHV}$$

For an overall efficiency of 36%,

$$\dot{m}_{fuel} = \frac{\dot{W}_e}{\eta_{overall} \bullet HHV} = \frac{1000 x 10^6 \, J/s}{(0.36) 12{,}000 \frac{Btu}{lbm} 1055 \frac{J}{Btu} 2.2046 \frac{lbm}{kg}}$$

$$\dot{m}_{fuel} = 99.5 \frac{kg}{s} = 13{,}800 \frac{lbm}{min} = 6.58 \frac{ton}{min} = 3{,}460{,}000 \frac{ton}{yr}$$