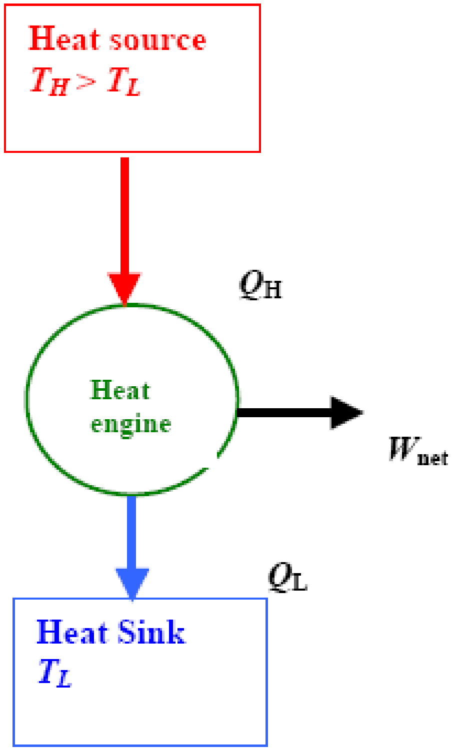
Vapor and Combined Power Cycles

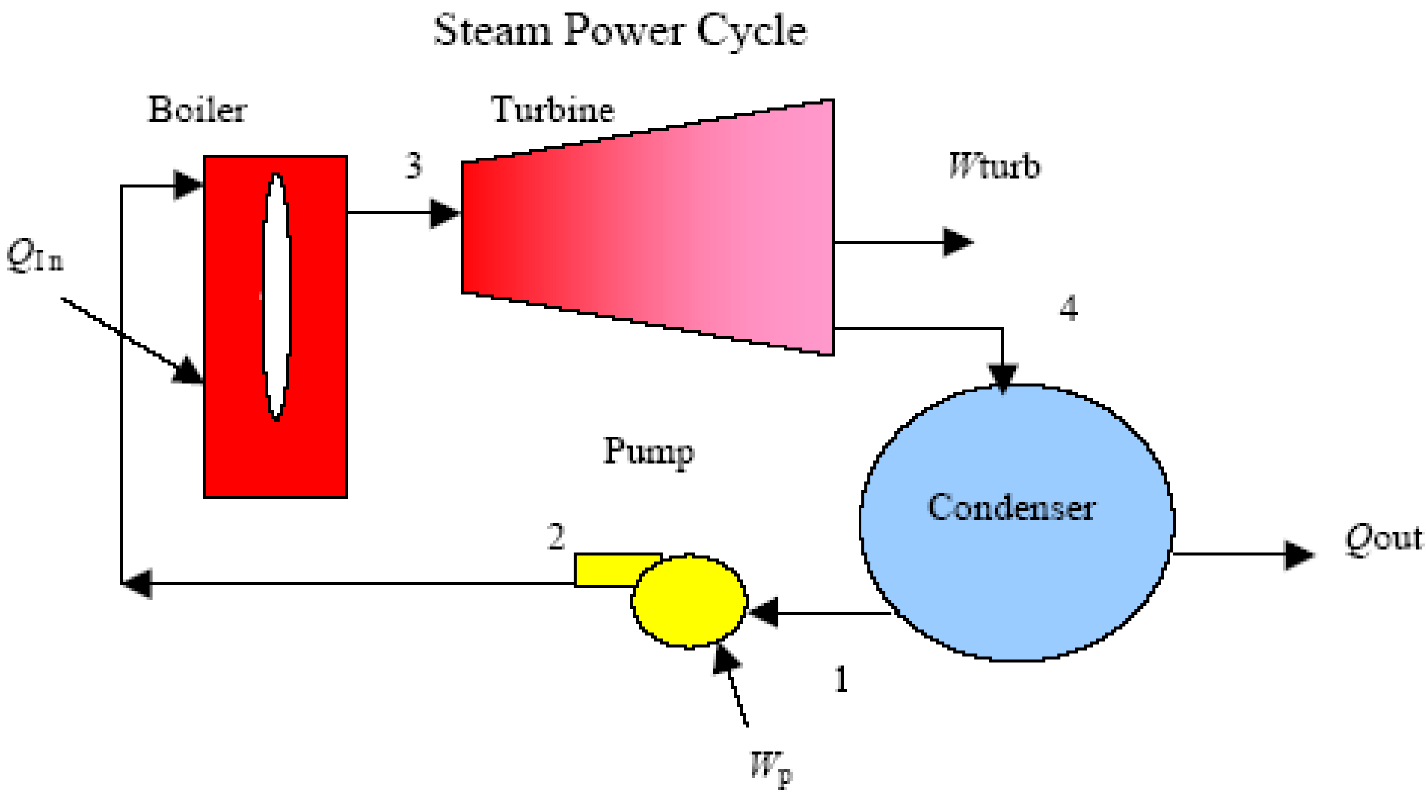
Chapter 10

We consider power cycles where the working fluid undergoes a phase change. The best example of this cycle is the steam power cycle where water (steam) is the working fluid.

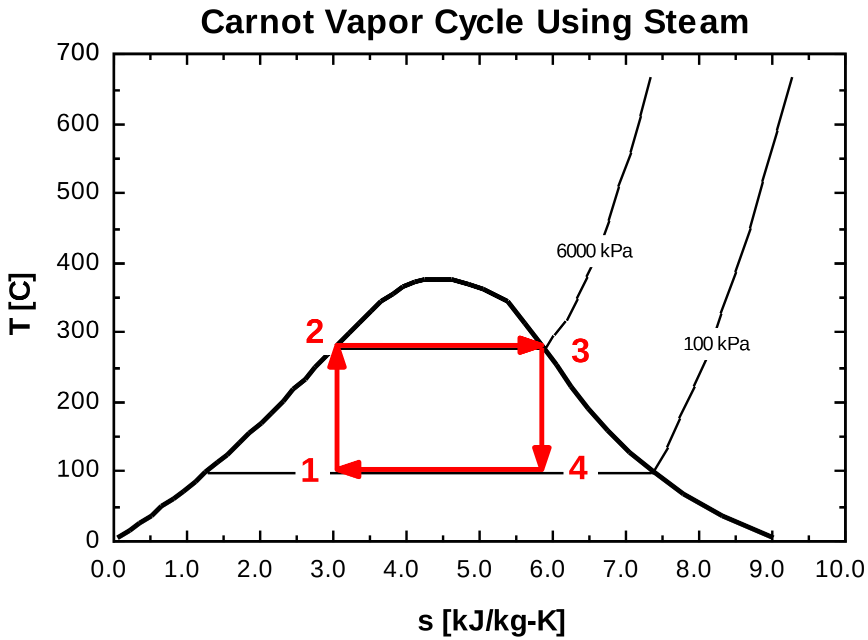
Carnot Vapor Cycle



The heat engine may be composed of the following components.



The working fluid, steam (water), undergoes a thermodynamic cycle from 1-2-3-4-1. The cycle is shown on the following *T-s* diagram.



The thermal efficiency of this cycle is given as

$$\eta_{th,\,Carnot} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$= 1 - \frac{T_L}{T_H}$$

Note the effect of T_H and T_L on $\eta_{th,\ Carnot}$.

- The larger the T_H the larger the $\eta_{th,\ Carnot}$
- The smaller the T_L the larger the $\eta_{th,\ Carnot}$

To increase the thermal efficiency in any power cycle, we try to increase the maximum temperature at which heat is added.

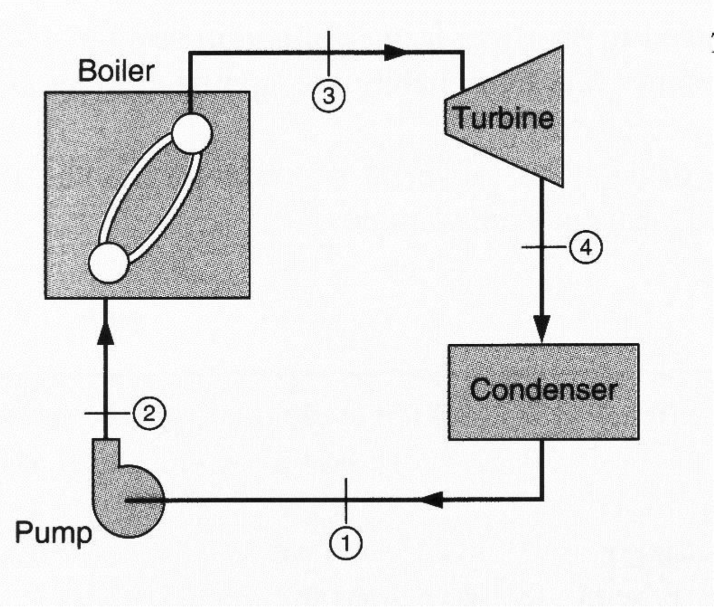
Reasons why the Carnot cycle is not used:

- Pumping process 1-2 requires the pumping of a mixture of saturated liquid and saturated vapor at state 1 and the delivery of a saturated liquid at state 2.

To resolve the difficulties associated with the Carnot cycle, the Rankine cycle was devised.

Rankine Cycle

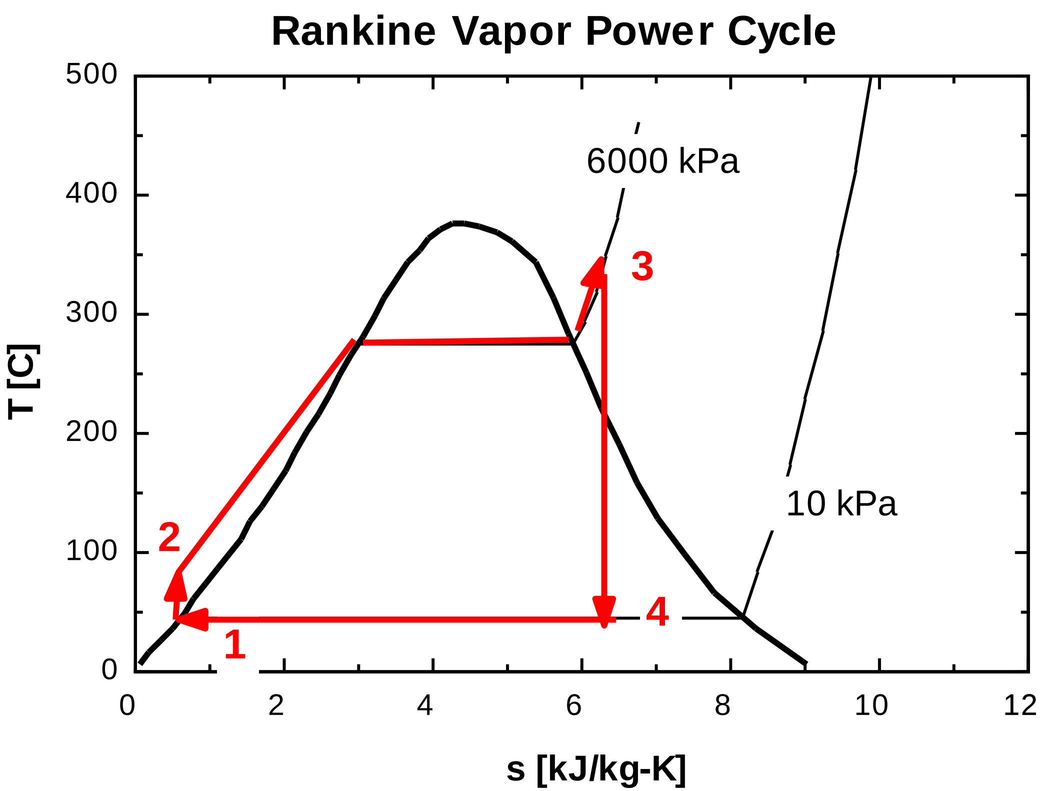
The simple Rankine cycle has the same component layout as the Carnot cycle shown above. The simple Rankine cycle continues the condensation process 4-1 until the saturated liquid line is reached.

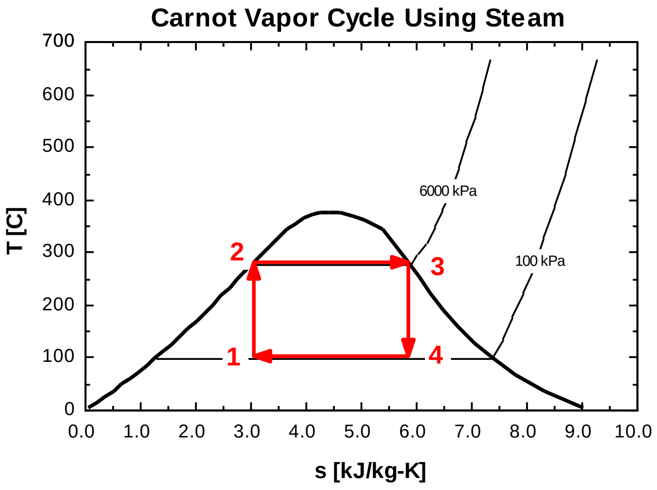


Ideal Rankine Cycle Processes

Process	Description
1-2	Isentropic compression in pump
2-3	Constant pressure heat addition in boiler
3-4	Isentropic expansion in turbine
4-1	Constant pressure heat rejection in condenser

The *T*-*s* diagram for the Rankine cycle is given below.

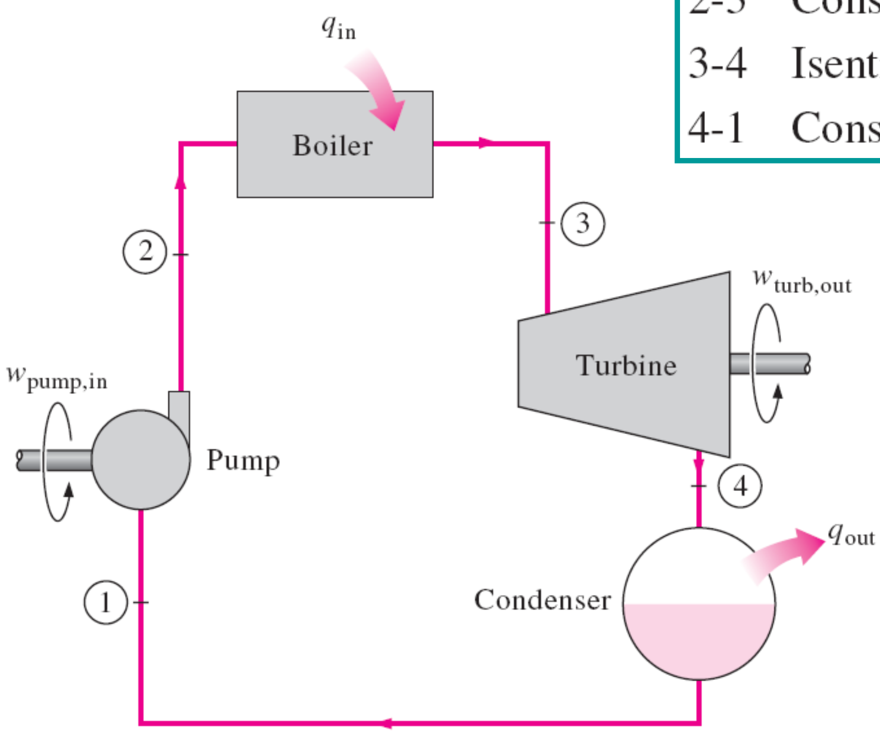


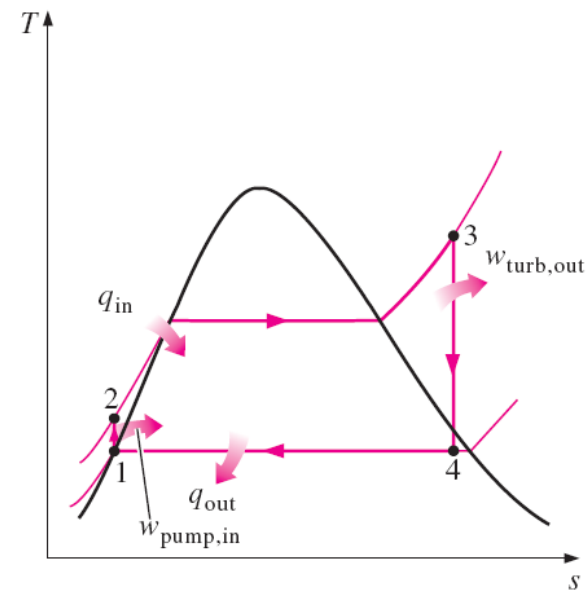


RANKINE CYCLE: THE IDEAL CYCLE FOR VAPOR POWER CYCLES

Many of the impracticalities associated with the Carnot cycle can be eliminated by superheating the steam in the boiler and condensing it completely in the condenser. The cycle that results is the **Rankine cycle**, which is the ideal cycle for vapor power plants. The ideal Rankine cycle does not involve any internal irreversibilities.

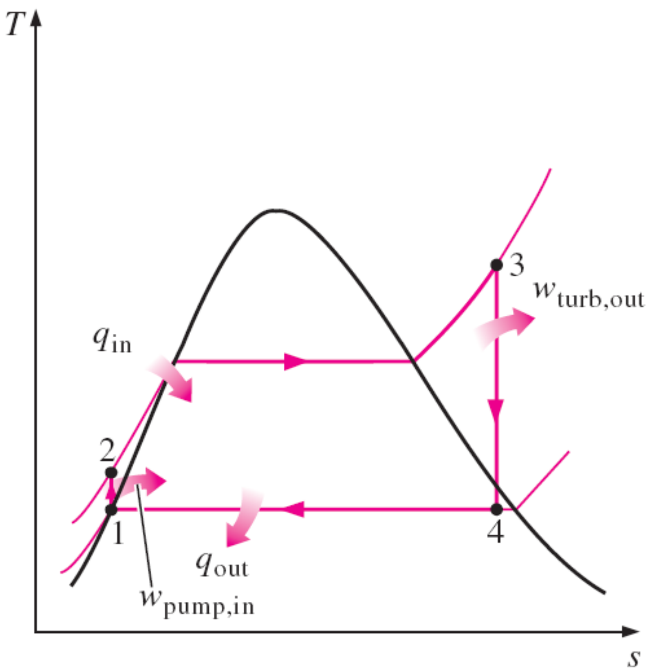
1-2	Isentropic compression in a pump
2-3	Constant pressure heat addition in a boiler
3-4	Isentropic expansion in a turbine
4-1	Constant pressure heat rejection in a condenser





The simple ideal Rankine cycle.

Energy Analysis of the Ideal Rankine Cycle



Steady-flow energy equation

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \qquad (\text{kJ/kg})$$

Pump ($q = 0$): $$w_{pump,in} = h_2 - h_1$$

$$w_{pump,in} = v(P_2 - P_1)$$

$$h_1 = h_{f\,@\,P_1} \quad \text{and} \quad v \cong v_1 = v_{f\,@\,P_1}$$

Boiler ($w = 0$): $$q_{in} = h_3 - h_2$$

Turbine ($q = 0$): $$w_{turb,out} = h_3 - h_4$$

Condenser ($w = 0$): $$q_{out} = h_4 - h_1$$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

The thermal efficiency can be interpreted as the ratio of the area enclosed by the cycle on a *T-s* diagram to the area under the heat-addition process.

The efficiency of power plants in the U.S. is often expressed in terms of **heat rate**, which is the amount of heat supplied, in Btu's, to generate 1 kWh of electricity.

$$\eta_{th} = \frac{3412\ (\text{Btu/kWh})}{\text{Heat rate}\ (\text{Btu/kWh})}$$

Quiz 1 (Example 10-1)

A steam power plant operates on the simple ideal Rankine cycle. Steam enters the turbine at 3 Mpa and 350^{o}C and is condensed at a pressure of 75 kPa. Determine

a) Find the enthalpy of the steam before it enters the boiler
b) Heat supplied in the boiler
c) Steam quality before it enters the condenser
d) Thermal efficiency of this ideal Rankine cycle

DRAW THE SCHEMATIC AND T-s DIAGRAM FIRST!!!

Exercise 10-2

Compute the thermal efficiency of an ideal Rankine cycle for which steam leaves the boiler as superheated vapor at 6 MPa, 350^{o}C, and is condensed at 10 kPa.