ME 266 THERMODYNAMICS 1 - The 2^{nd} Law

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SECOND LAW OF THERMODYNAMICS

- The second law of thermodynamics continues where the first law stops, and helps us establish the direction of particular processes.
  - heat flows from a hot body to a cold one.
  - rubber bands unwind.
  - fluid flows from a high-pressure region to a low-pressure region.
- The first law of thermodynamics relates several variables involved in a physical process, but does not give any information as to the direction of the process.

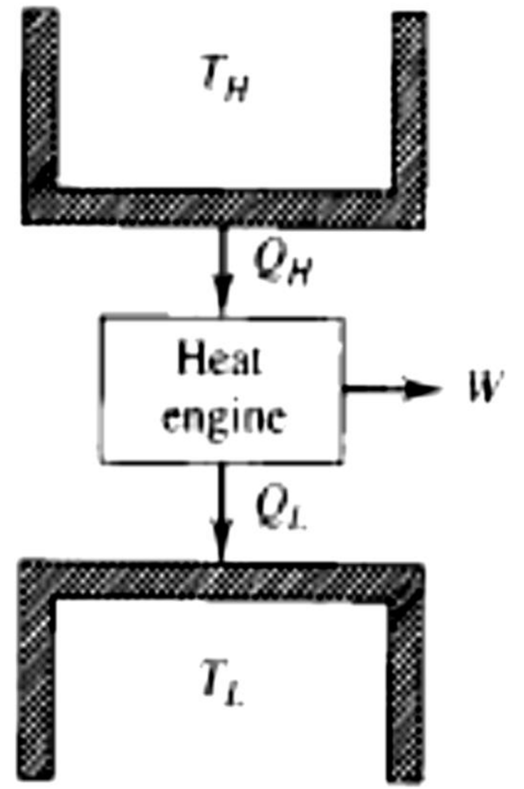
HEAT ENGINES, HEAT PUMPS, AND REFRIGERATORS

- **Cyclic devices** are either heat pumps, heat engines or refrigerators and operate between two **thermal reservoirs**.

- Thermal reservoirs are entities that are capable of providing or accepting heat without changing temperatures. E.g. atmosphere, lakes and furnaces.

HEAT ENGINES

- A heat engine is defined as a device that converts heat energy into mechanical energy.
- T_H and T_L are the temperatures of the source and sink respectively.
- $\mathbf{Q_H}$ is the heat transfer from the high temp reservoir and $\mathbf{Q_L}$ the heat transfer to the low temp reservoir.



HEAT ENGINES

- The net work output is given as:

$$W = Q_H - Q_L$$

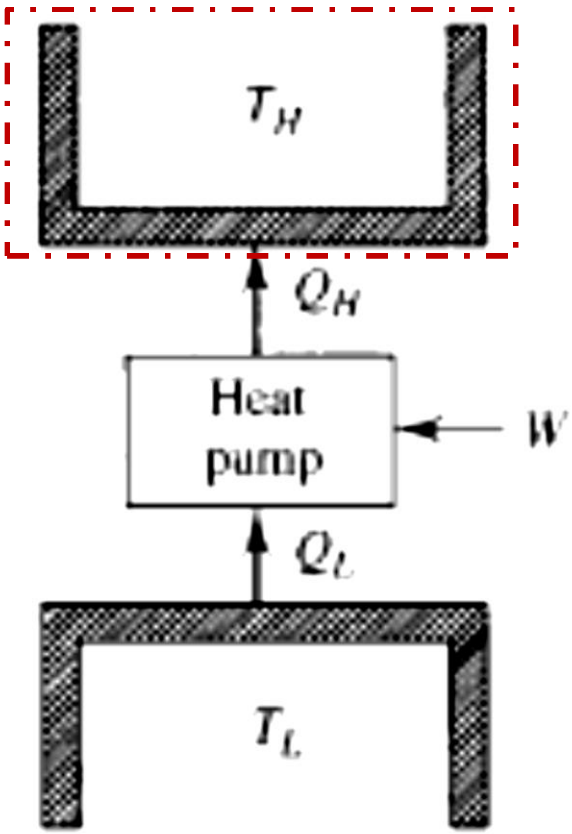
  – First law for cyclic processes, **Net Work = Net Heat**.

- The performance of a heat engine is the thermal efficiency:

$$\eta = \frac{W}{Q_H}$$

HEAT PUMPS

- A **heat pump** is a device that moves heat from one location (heat source) at a lower temperature to another location (heat sink) at a higher temperature using mechanical work.



$$Q_H = W + Q_L$$

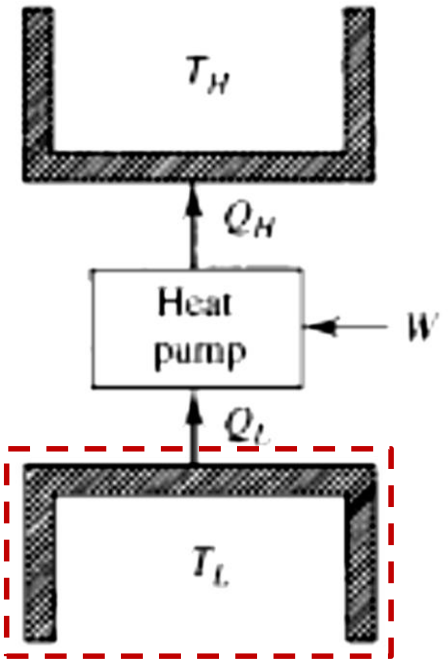
$$COP_{h.p} = \frac{Q_H}{W}$$

The measure of performance of a heat pump is the Coefficient of Performance (COP).

REFRIGERATORS

- Refrigerators, like, heat pumps move heat from a cooler region to a hotter one with the input of work.

Note - each of the performance measures represents:



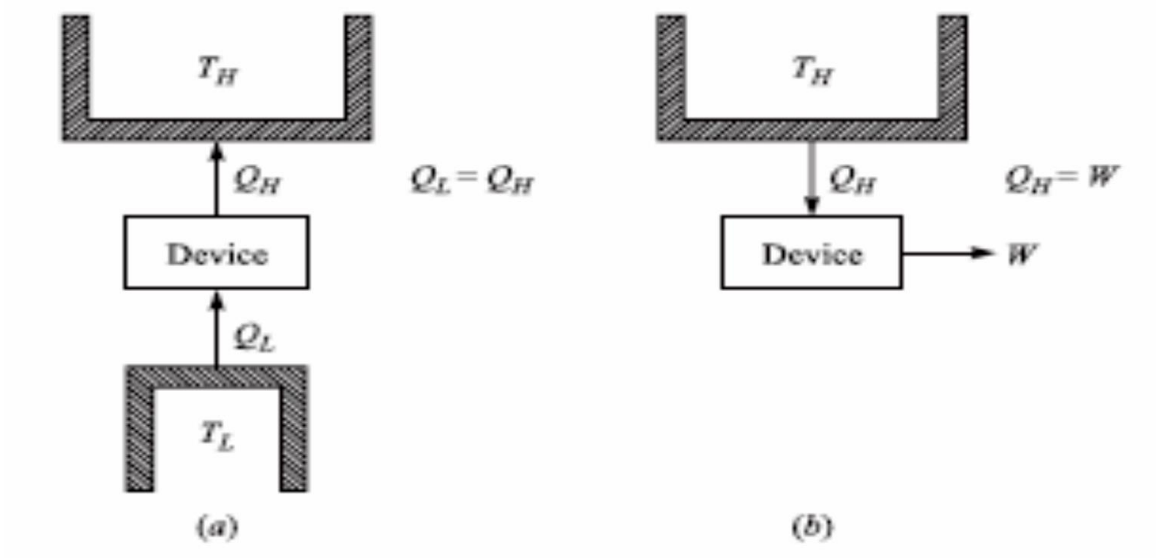
$$Performance = \frac{desired\ output}{required\ input}$$

$$COP_{refrig} = \frac{Q_L}{W}$$

$$COP_{h.p} = COP_{refrig} + 1$$

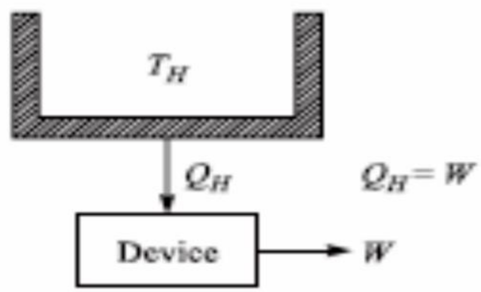
STATEMENTS OF THE SECOND LAW

- There are a number of statements of the 2nd Law, two are presented:
- **Clausius Statement**: *It is impossible to construct a device that operates in a cycle and whose sole effect is the transfer of heat from a cooler body to a hotter body.*



STATEMENTS OF THE SECOND LAW

- **Kelvin-Planck Statement***:* It is impossible to construct a device that operates in a cycle and produces no other effect than the production of work and the transfer of heat from a single body.
  - it is impossible to construct a heat engine that extracts energy from a reservoir, does work, and does not transfer heat to a low-temperature reservoir.



REVERSIBILITY

- A reversible process is defined as a process which, having taken place, can be reversed and in so doing leaves no change in either the system or the surroundings.
- A reversible engine is an engine that operates with reversible processes only.
  - A reversible engine is most efficient engine that can possibly be constructed.

REVERSIBILITY

- The process has to be a quasi-equilibrium process; and:
  - No friction is involved in the process.
  - Heat transfer occurs due to an infinitesimal temperature difference only.
  - Unrestrained expansion does not occur.
- Losses such as that due to friction are referred to as **irreversibilities**.

REVERSIBILITY

Some sources of irreversibilities:

- Friction
- Unrestrained expansion
- Mixing of two gases
- Heat transfer across finite temperature difference
- Electric resistance
- Inelastic deformation of solids, and
- Chemical reaction

THE CARNOT ENGINE

- The Carnot Engine is an ideal engine that uses reversible processes to form its cycle of operation; thus it is also called a **reversible engine**.

- The efficiency of the Carnot engine establishes the maximum possible efficiency of any real engine.

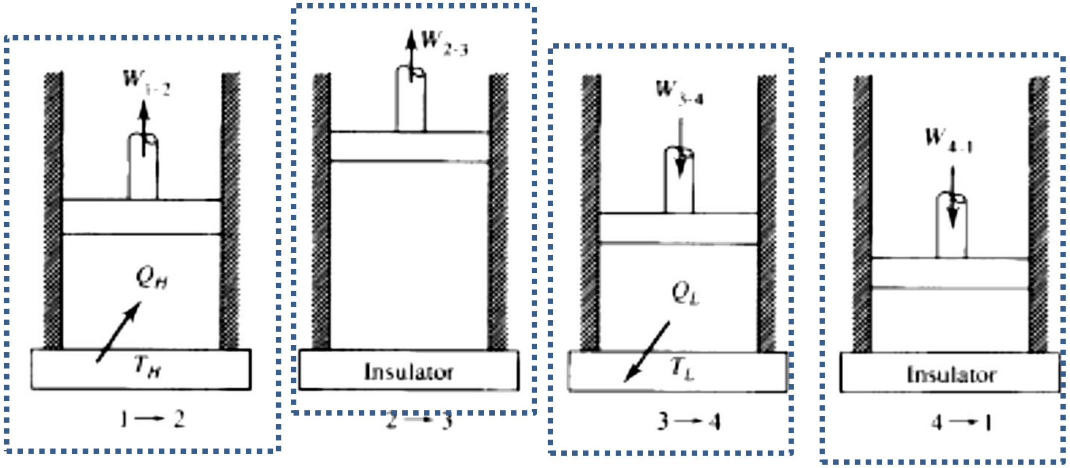
THE CARNOT ENGINE

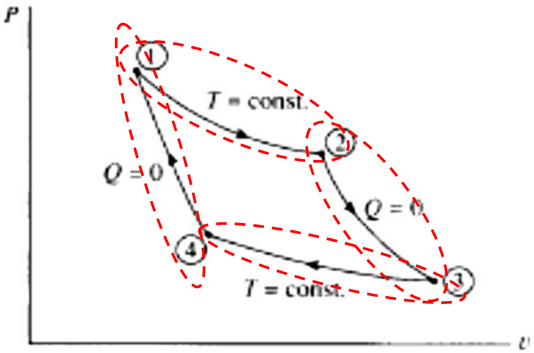
1 → 2: *Isothermal expansion*.

2 → 3: *Adiabatic reversible expansion*.

3 → 4: *Isothermal compression*.

4 → 1: *Adiabatic reversible compression*.





THE CARNOT ENGINE

Applying the first law to the cycle:

$$Q_H - Q_L = W_{net}$$

The thermal efficiency is then written as:

$$\eta = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Postulates based on the Carnot engine:

Postulate 1: *It is impossible to construct an engine, operating between two given temperature reservoirs, that is more efficient than the Carnot engine.*

Postulate 2: *The efficiency of a Carnot engine is not dependent on the working substance used or any particular design feature of the engine.*

Postulate 3: *All reversible engines, operating between two given temperature reservoirs, have the same efficiency as a Carnot engine operating between the same two temperature reservoirs.*

THE CARNOT ENGINE

CARNOT EFFICIENCY:

Isothermal expansion

$$1 \rightarrow 2: \; Q_H = W_{1-2} = \int_{V_1}^{V_2} PdV = mRT_H In \frac{V_2}{V_1}$$

Adiabatic expansion

$$2 \rightarrow 3: \; Q_{2-3} = 0$$

Isothermal compression

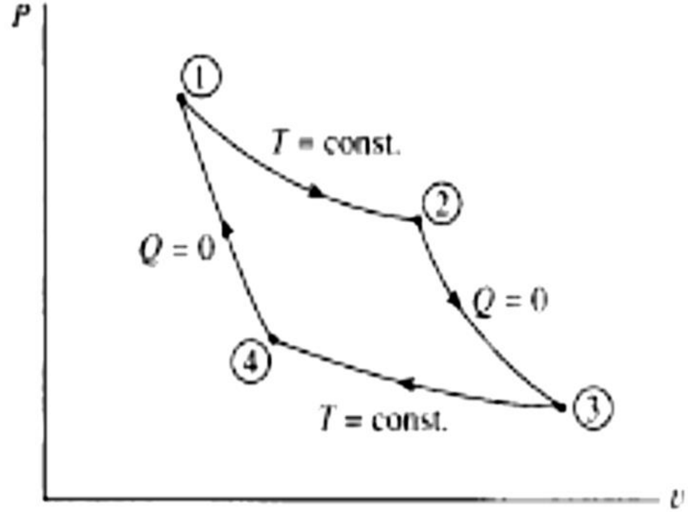
$$3 \rightarrow 4: Q_L = -W_{3-4} = -\int_{V_3}^{V_4} PdV = -mRT_L In \frac{V_4}{V_3}$$

Adiabatic expansion

$$4 \rightarrow 1: Q_{4-1} = 0$$

$$\eta = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

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



THE CARNOT ENGINE

The coefficient of performance for a Carnot heat pump becomes

$$COP = \frac{Q_H}{W_{net}} = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L}$$

The coefficient of performance for a Carnot refrigerator takes the form

$$COP = \frac{Q_L}{W_{net}} = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}$$

The above measures of performance set limits that real devices can only approach.

ENTROPY

Entropy is a measure of the disorder that exists in a system.

$$The\ relation\ \oint \frac{\delta Q}{T} \leq 0\ is\ termed\ Classius\ Inequality.$$

$$\oint \frac{\delta Q}{T} = 0 \qquad for\ a\ reversible\ process$$

$$\oint \frac{\delta Q}{T} < 0 \qquad for\ irreversible\ processs$$

For a given reversible process we may write:

$$\left(\frac{\delta Q}{T}\right)_{rev} = dS$$

ENTROPY

The change in entropy during a reversible process can be written as

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_{rev} = \int_1^2 dS = (S_2 - S_1) = \Delta S$$

There exists a property called entropy of a system such that for any reversible process from state point 1 to state point 2, its change is given by:

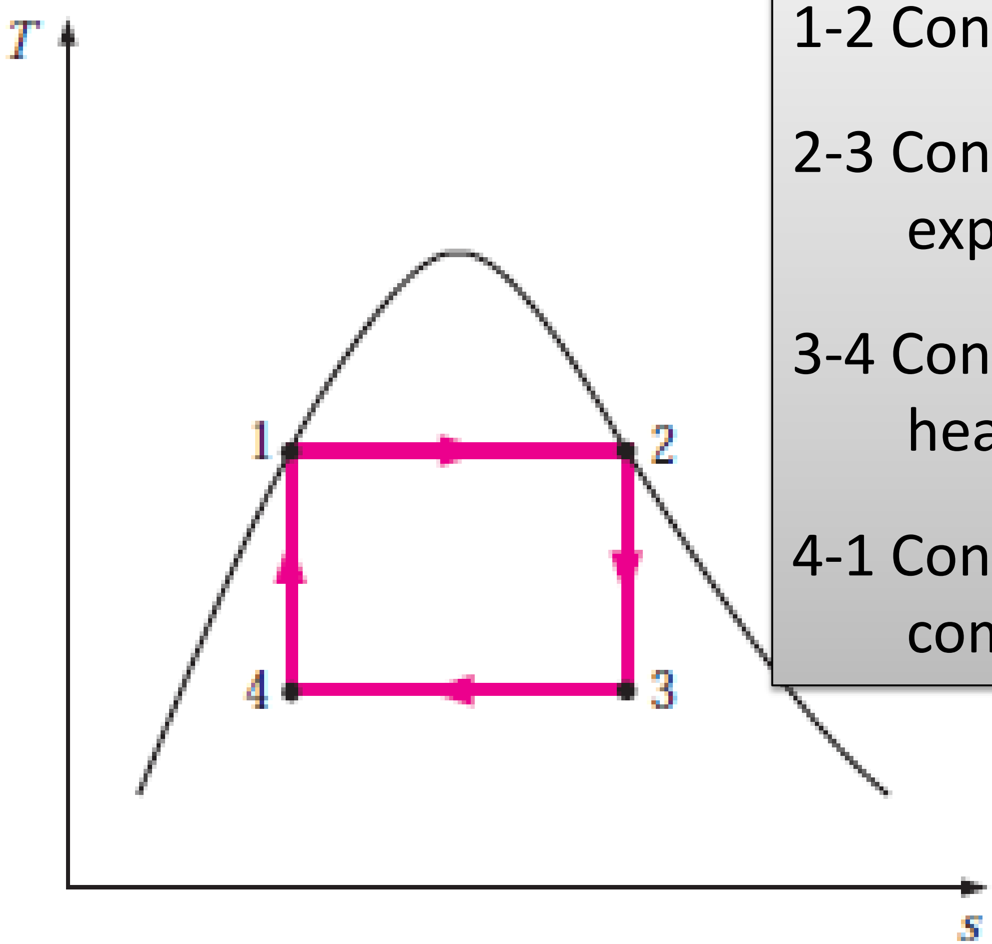
$$\int_1^2 \left(\frac{\delta Q}{T}\right)_{rev} = (S_2 - S_1)$$

For a temperature – entropy diagram we have:

$$Q_{1-2} = \int_{S_1}^{S_2} T\,dS$$

VAPOUR POWER CYCLES

Carnot vapour power cycle



1-2 Constant, T (isothermal) heat addition

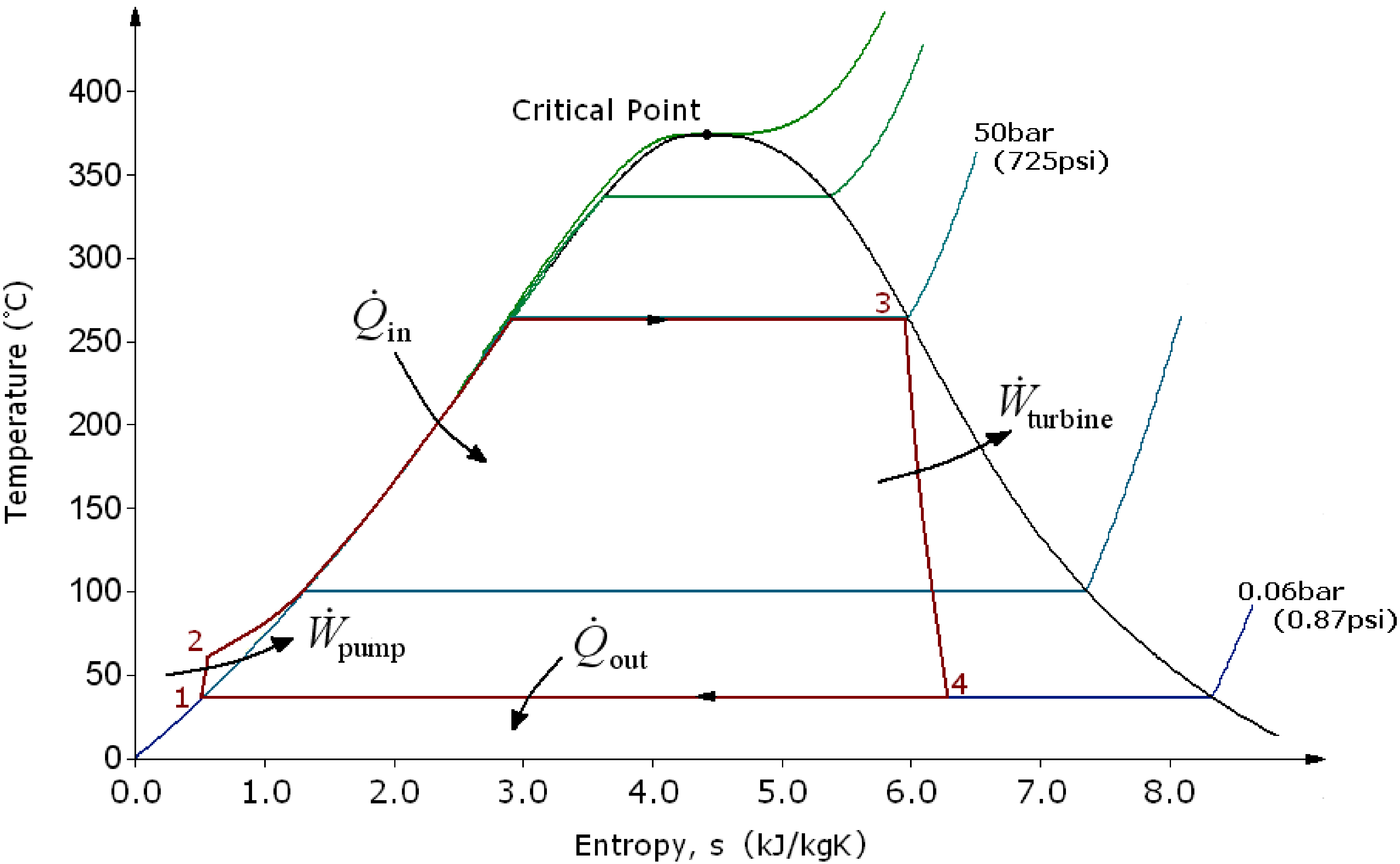
2-3 Constant entropy (isentropic) expansion in turbine

3-4 Constant P const, T (isothermal) heat rejection (condenser)

4-1 Constant entropy (isentropic) compression

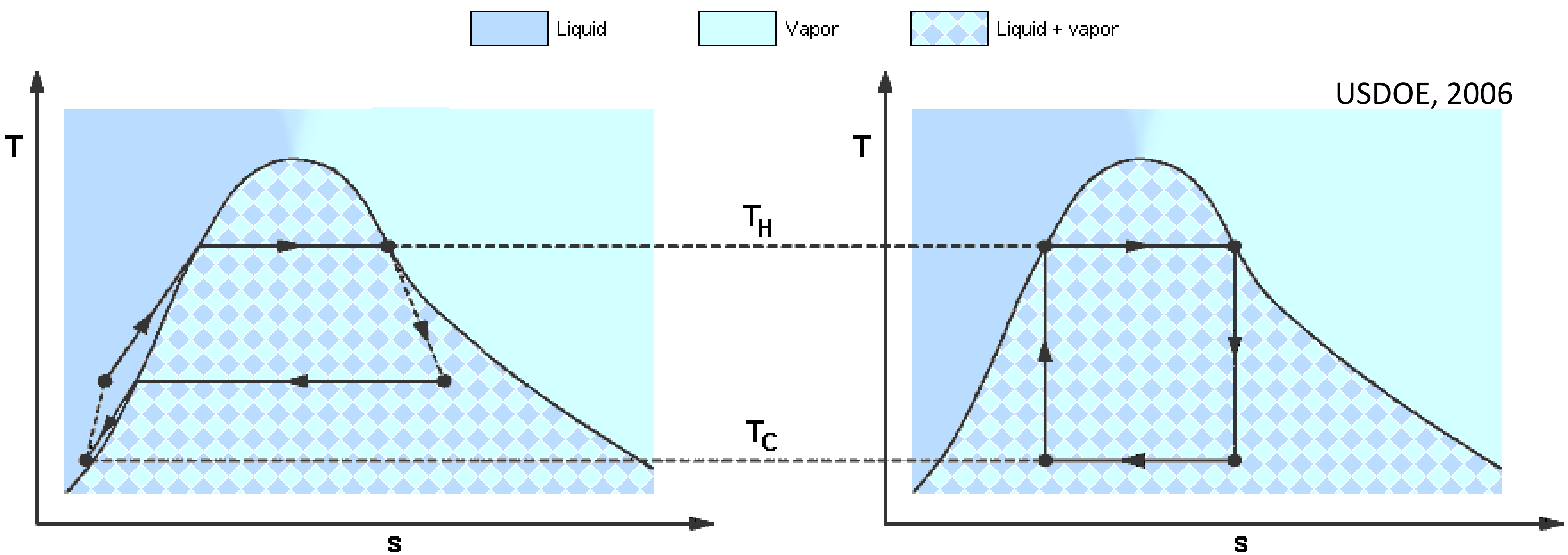
VAPOUR POWER CYCLES

Simple Rankine Cycle



VAPOR POWER CYCLES

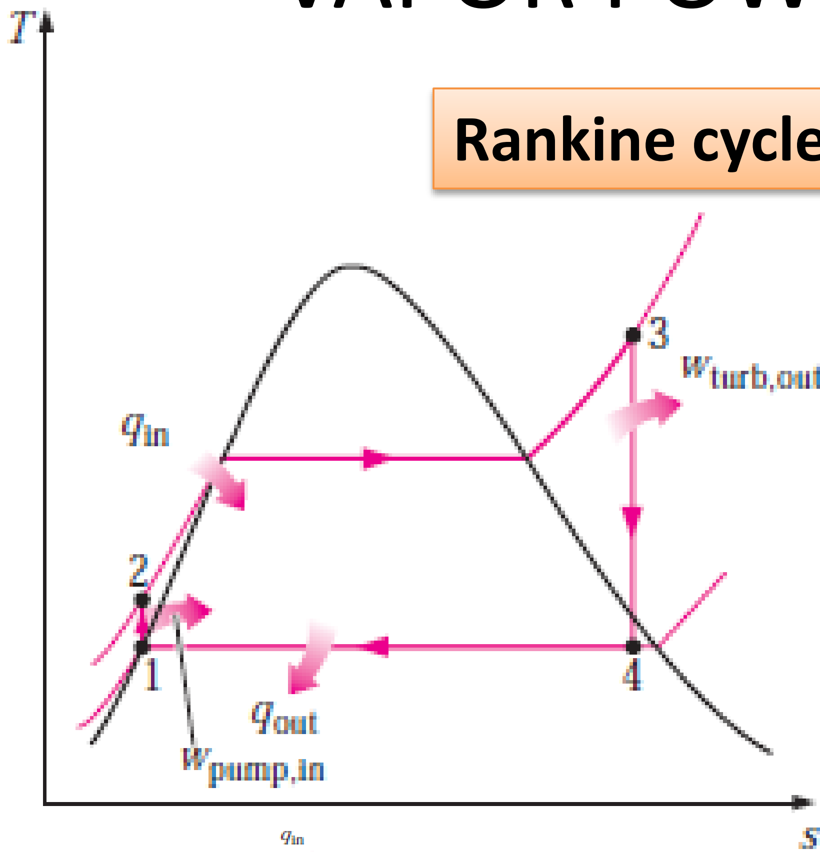
Real vs Carnot

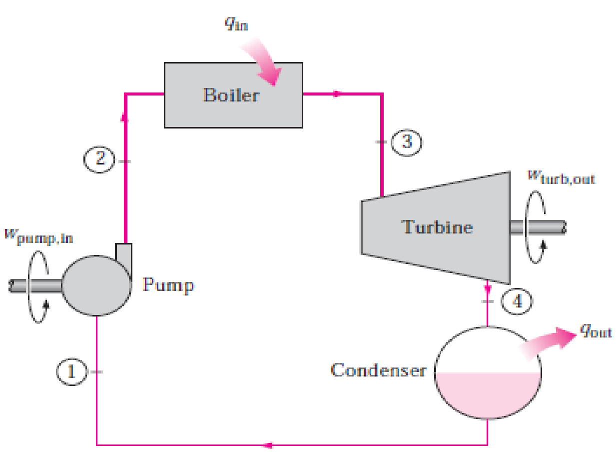


Working fluid is completely condensed and cooled.
Entropy of real processes increase.

VAPOR POWER CYCLES

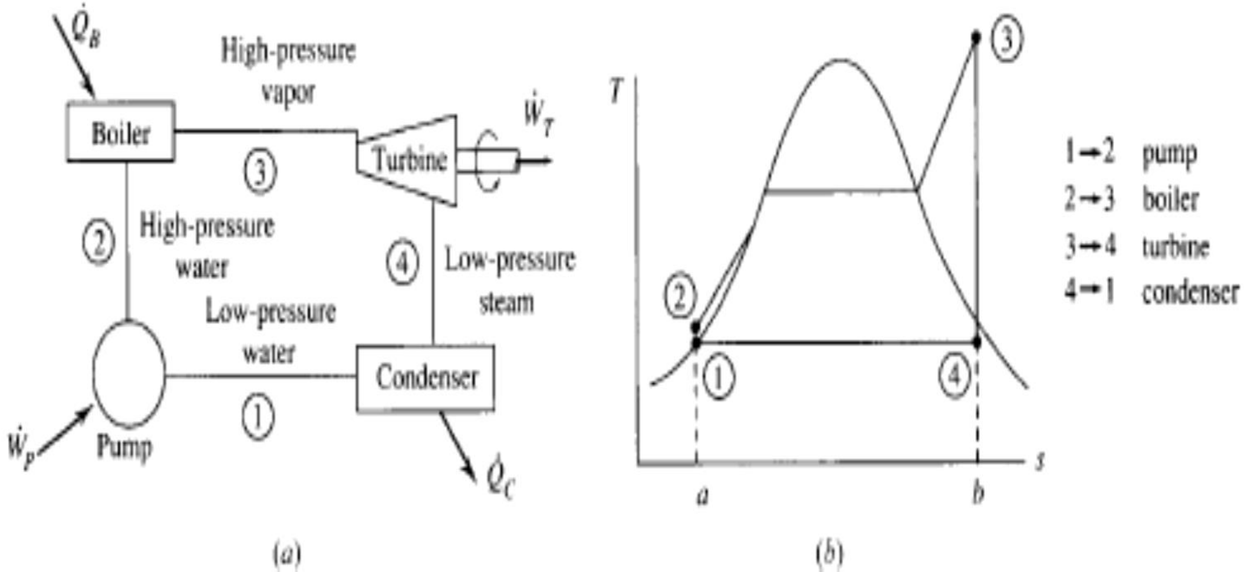
Rankine cycle with superheat





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

VAPOR POWER CYCLES



$$w_p = v_1(P_2 - P_1)$$

$$q_B = h_3 - h_2$$

$$w_T = h_3 - h_4$$

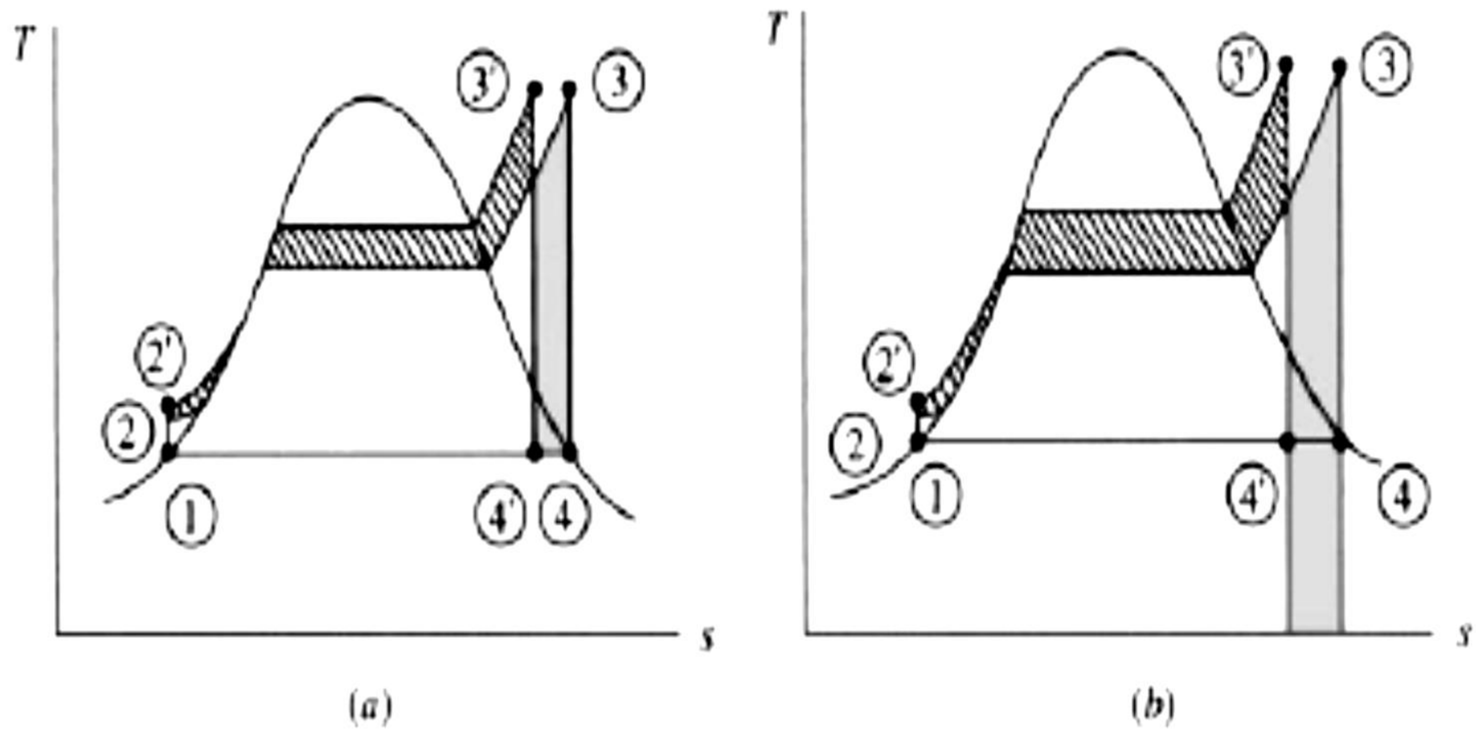
$$q_C = h_4 - h_1$$

$$\eta = \frac{area\, 1-2-3-4-1}{area\, a-2-3-b-a}$$

$$\eta = \frac{w_T - w_p}{q_B}$$

IMPROVING THE RANKINE CYCLE EFFICIENCY

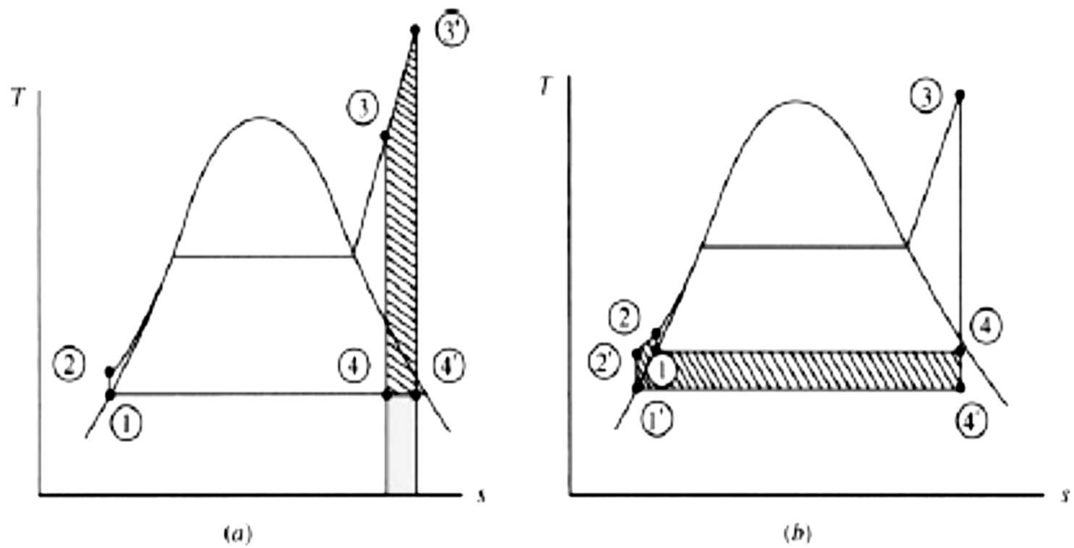
Increasing the boiler pressure while maintaining the maximum temperature and the minimum pressure.



Problem with moisture at turbine outlet.

IMPROVING THE RANKINE CYCLE EFFICIENCY

Increasing the maximum temperature – also results in higher steam quality at turbine exit

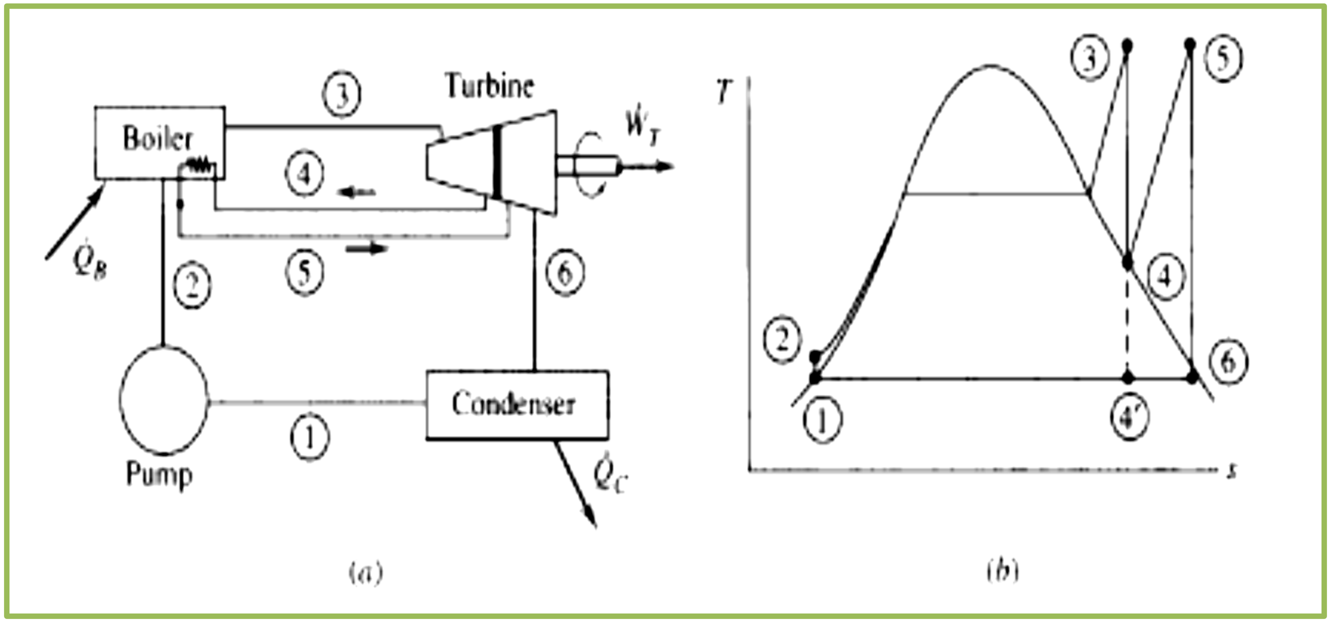


Effect of increased pressure on the Rankine cycle

A decrease in condenser pressure improves efficiency, but creates risk of ambient air infiltration into condenser and lower exit steam quality

IMPROVING THE RANKINE CYCLE EFFICIENCY

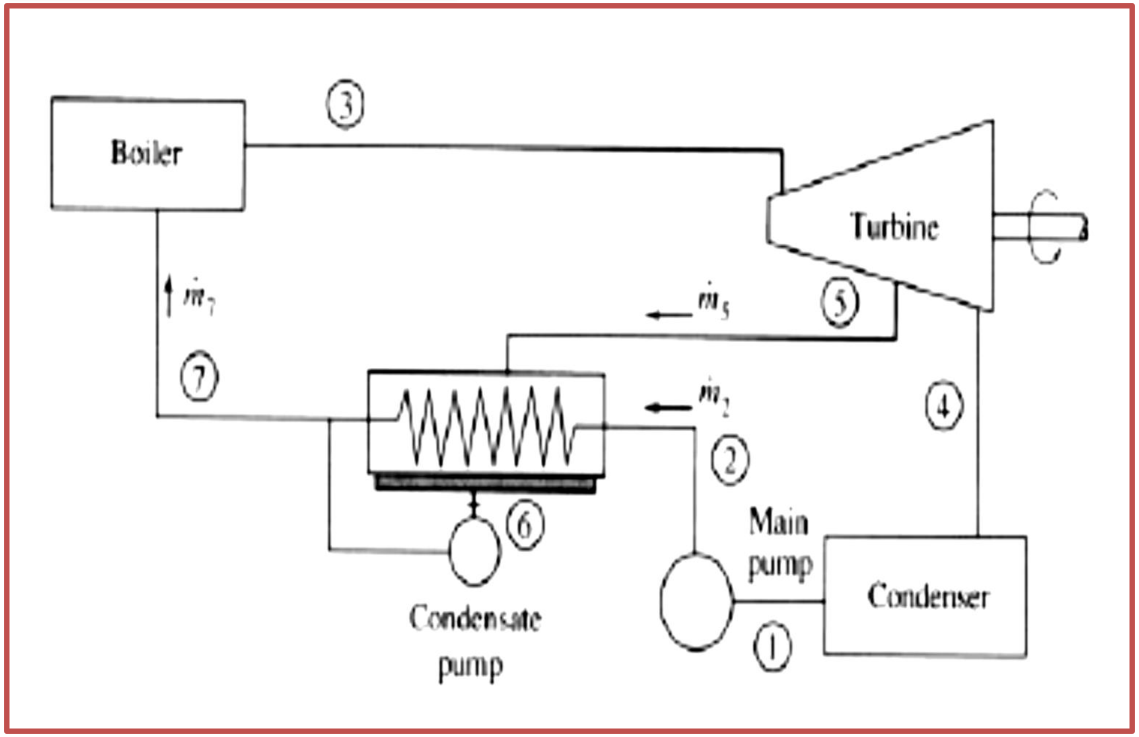
Reheat – solves the problem of moisture with increased boiler pressure or reduced condenser pressure.

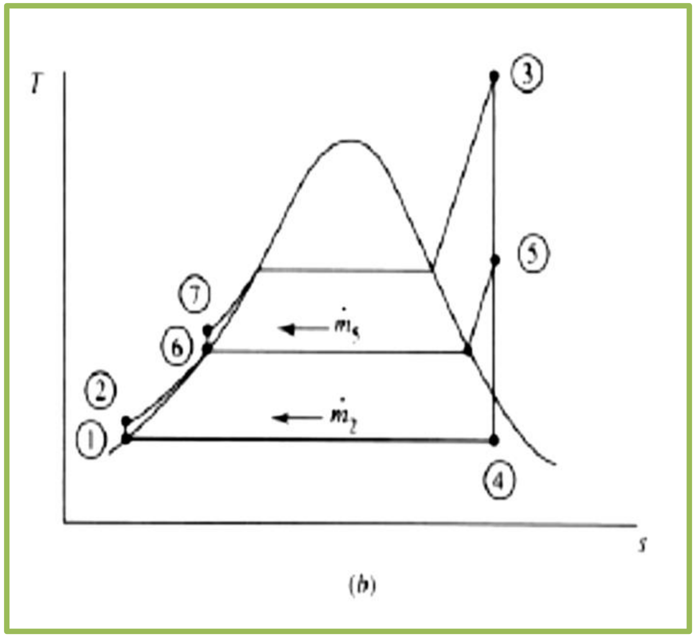


Rankine cycle with reheat

IMPROVING THE RANKINE CYCLE EFFICIENCY

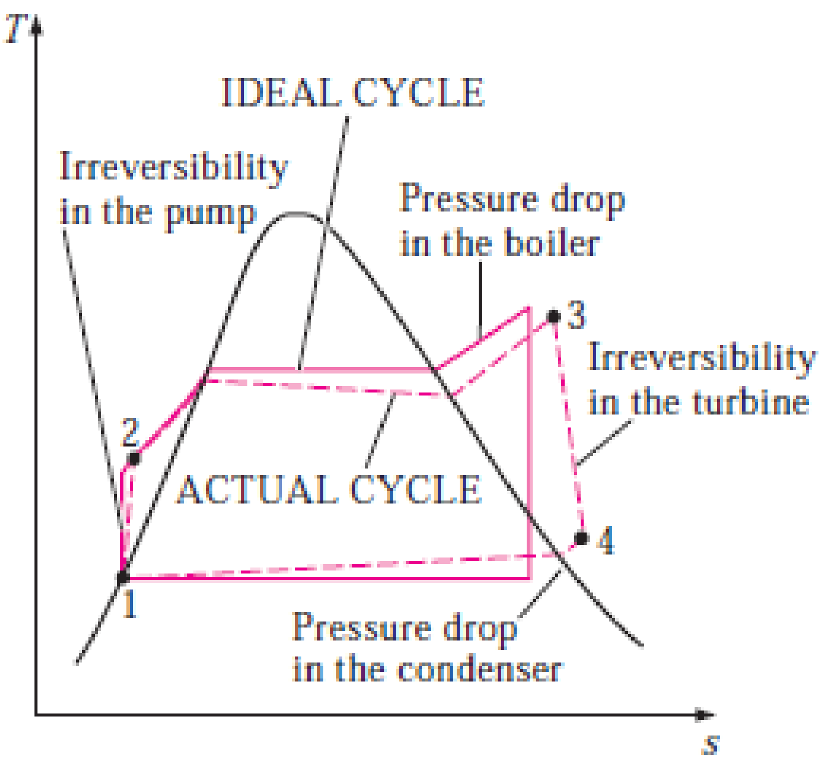
Regeneration

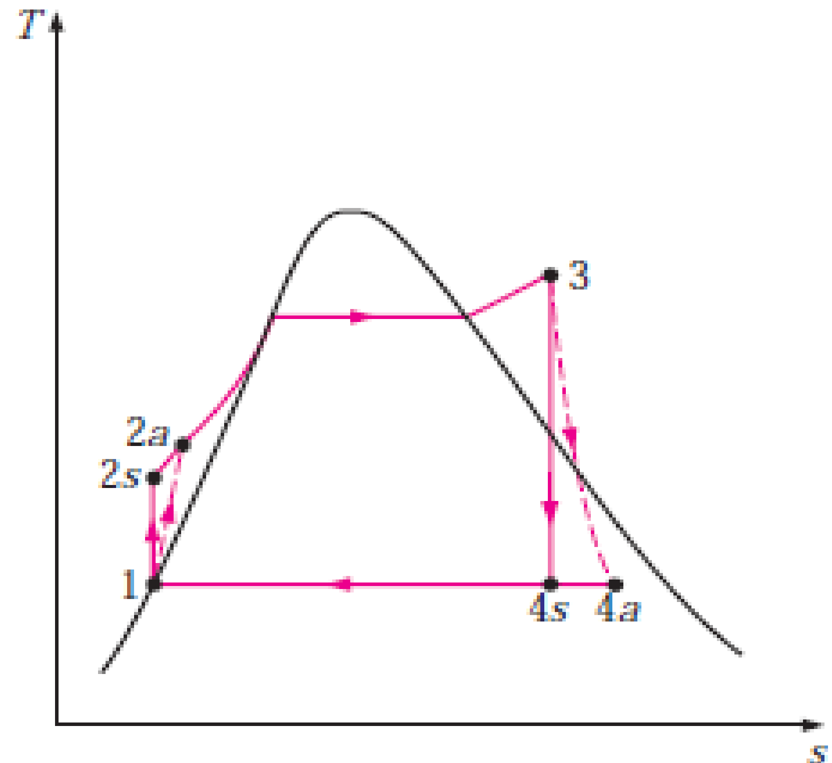




This technique taps some of the steam expanding in the turbine to preheat water entering the boiler. The net effect is a reduced heat input at the boiler side

EFFECT OF LOSSES ON POWER CYCLE EFFICIENCY





$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{\boxed{h_{2a} - h_1}}$$

More input that ideal case.

$$\eta_T = \frac{w_a}{w_s} = \frac{\boxed{h_3 - h_{4a}}}{h_3 - h_{4s}}$$

Less output than ideal case.