Vapor Power Cycles

We know that the Carnot cycle is most efficient cycle operating between two specified temperature limits. However; the Carnot cycle is not a suitable model for steam power cycle since:

- The turbine has to handle steam with low quality which will cause erosion and wear in turbine blades.

- It is impractical to design a compressor that handles two phase.

- It is difficult to control the condensation process that precisely as to end up with the desired at point 4.
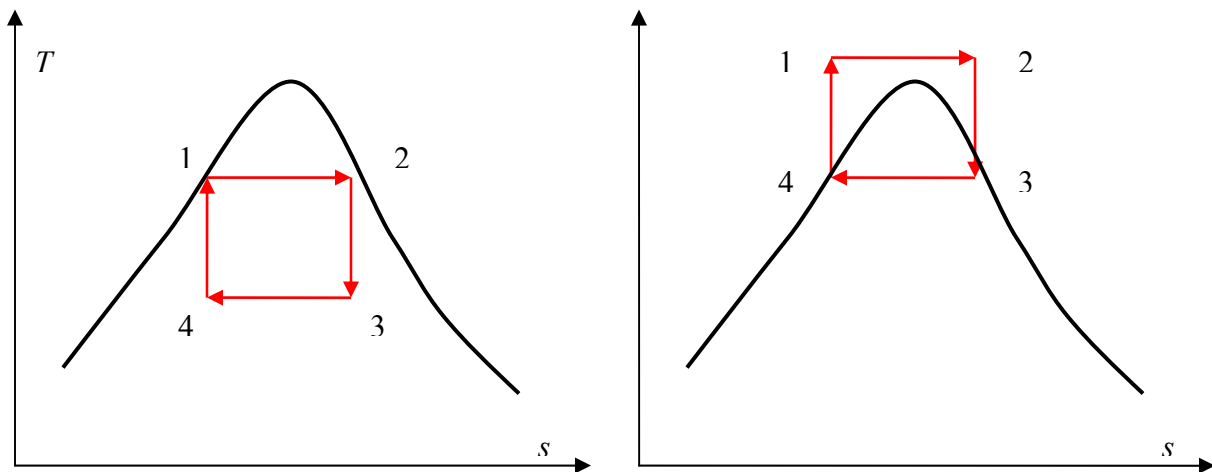

Fig. 1: *T-s* diagram for two Carnot vapor cycle.

Other issues include: isentropic compression to extremely high pressure and isothermal heat transfer at variable pressures. Thus, the Carnot cycle cannot be approximated in actual devices and is not a realistic model for vapor power cycles.

Ideal Rankine Cycle

The Rankine cycle is the ideal cycle for vapor power plants; it includes the following four reversible processes:

| 1-2:	Isentropic compression	Water enters the pump as state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler.
2-3:	Const P heat addition	Saturated water enters the boiler and leaves it as superheated vapor at state 3
3-4:	Isentropic expansion	Superheated vapor expands isentropically in turbine and produces work.
4-1:	Const P heat rejection	High quality steam is condensed in the condenser
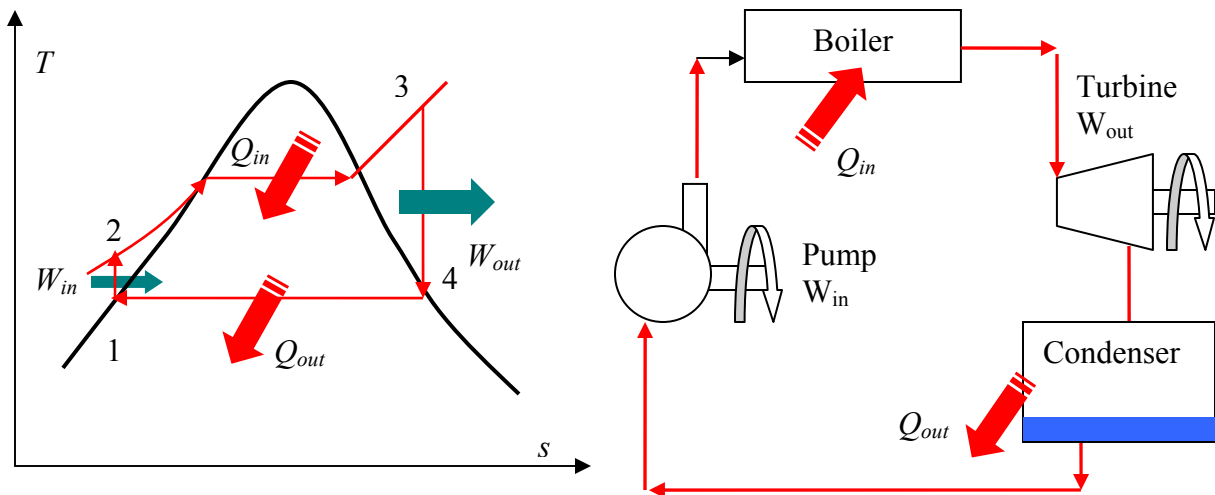
Fig. 2: The ideal Rankine cycle.

Energy Analysis for the Cycle

All four components of the Rankine cycle are steady-state steady-flow devices. The potential and kinetic energy effects can be neglected. The first law per unit mass of steam can be written as:

Pump	$q = 0$	$w_{pump,in} = h_2 - h_1$
Boiler	$w = 0$	$q_{in} = h_3 - h_2$
Turbine	$q = 0$	$w_{turbine,out} = h_3 - h_4$
Condenser	$w = 0$	$q_{out} = h_4 - h_1$

The thermal efficiency of the cycle is determined from:

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

where

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

If we consider the fluid to be incompressible, the work input to the pump will be:

$$(h_2 - h_1) = v(P_2 - P_1)$$

where $\quad h_1 = h_{f@P1} \& v = v_1 = v_{f@P1}$

Deviation of Actual Vapor Power Cycle from Ideal Cycle

As a result of irreversibilities in various components such as fluid friction and heat loss to the surroundings, the actual cycle deviates from the ideal Rankine cycle. The deviations of actual pumps and turbines from the isentropic ones can be accounted for by utilizing isentropic efficiencies defined as:

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$
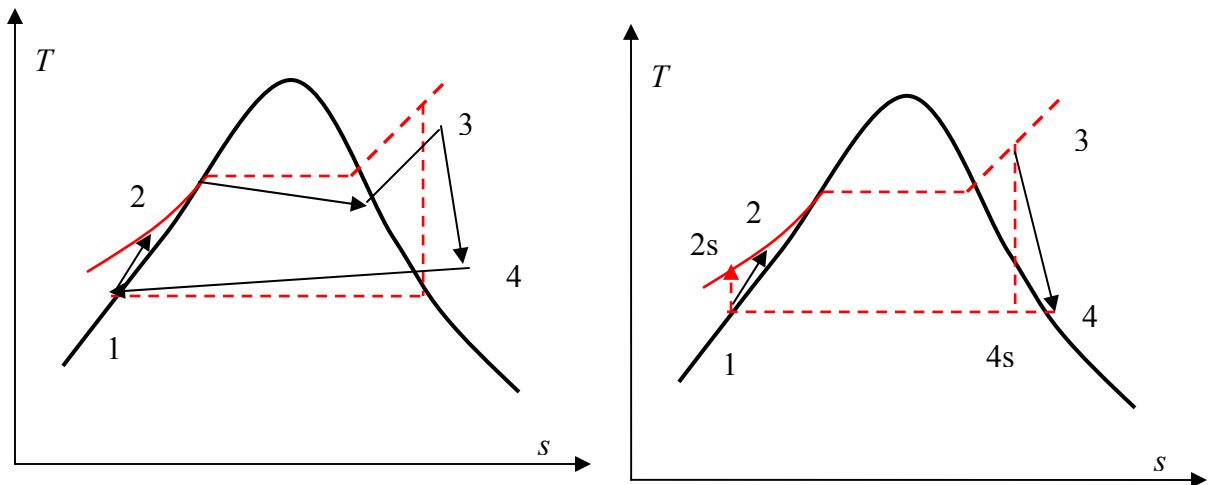
Fig. 3: Deviation from ideal Rankine cycle.

Increasing the Efficiency of Rankine Cycle

We know that the efficiency is proportional to: $\eta_{th} \propto 1 - \dfrac{T_L}{T_H}$

That is, to increase the efficiency one should increase the average temperature at which heat is transferred to the working fluid in the boiler, and/or decrease the average temperature at which heat is rejected from the working fluid in the condenser.

Decreasing the of Condenser Pressure (Lower T_L)

Lowering the condenser pressure will increase the area enclosed by the cycle on a *T-s* diagram which indicates that the net work will increase. Thus, the thermal efficiency of the cycle will be increased.
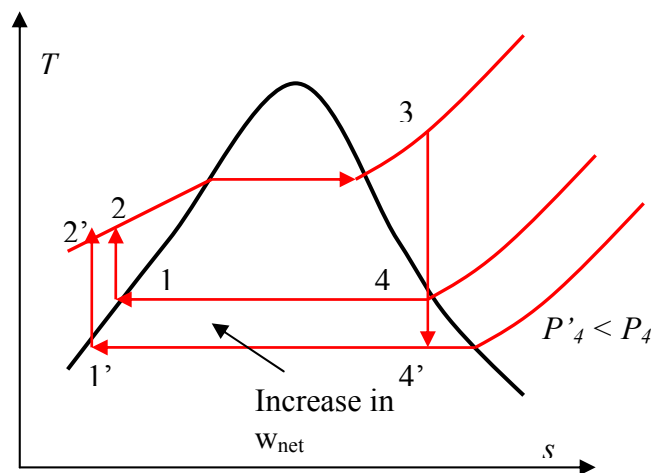

Fig. 4: Effect of lowering the condenser pressure on ideal Rankine cycle.

The condenser pressure cannot be lowered than the saturated pressure corresponding to the temperature of the cooling medium. We are generally limited by the thermal reservoir temperature such as lake, river, etc. Allow a temperature difference of 10°C for effective heat transfer in the condenser. For instance lake @ 15°C + ΔT (10°C) = 25°C. The steam saturation pressure (or the condenser pressure) then will be ⇒ $P_{sat} = 3.2 \, kPa$.

Superheating the Steam to High Temperatures (Increase T_H)

Superheating the steam will increase the net work output and the efficiency of the cycle. It also decreases the moisture contents of the steam at the turbine exit. The temperature to which steam can be superheated is limited by metallurgical considerations (~ 620°C).
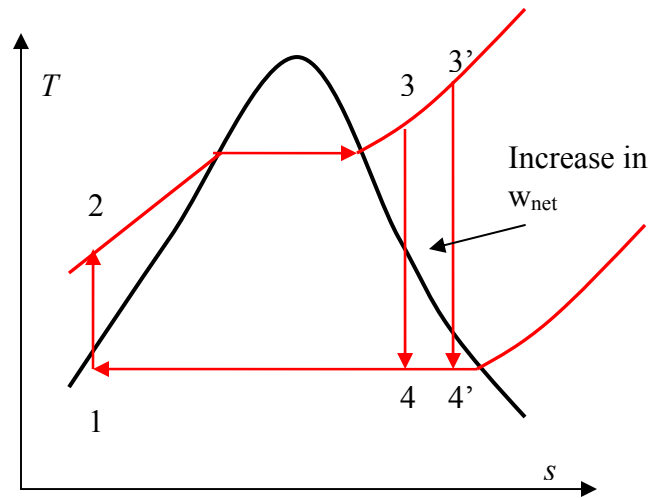

Fig. 5: The effect of increasing the boiler pressure on the ideal Rankine cycle.

Increasing the Boiler Pressure (Increase T_H)

Increasing the operating pressure of the boiler leads to an increase in the temperature at which heat is transferred to the steam and thus raises the efficiency of the cycle.
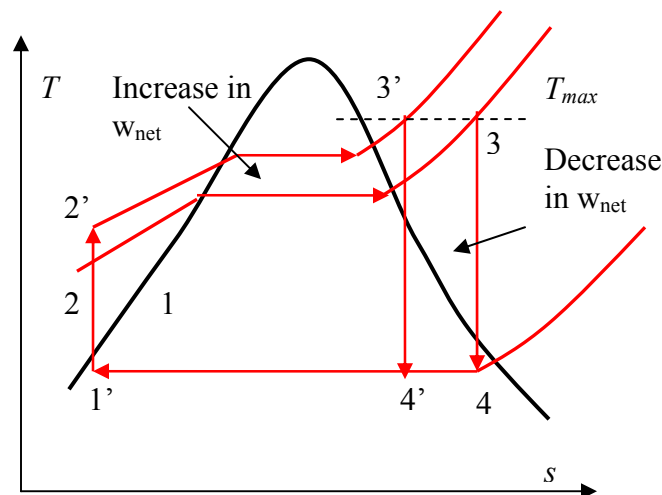

Fig.6: The effect of increasing the boiler pressure on the ideal cycle.

Note that for a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of the steam at the turbine exit increases. This undesirable side effect can be corrected by *reheating* the steam.

The Ideal Reheat Rankine Cycle

To take advantage of the increased efficiencies at higher boiler pressure without facing the excessive moisture at the final stages of the turbine, reheating is used. In the ideal reheating cycle, the expansion process takes place in two stages, i.e., the high-pressure and low-pressure turbines.
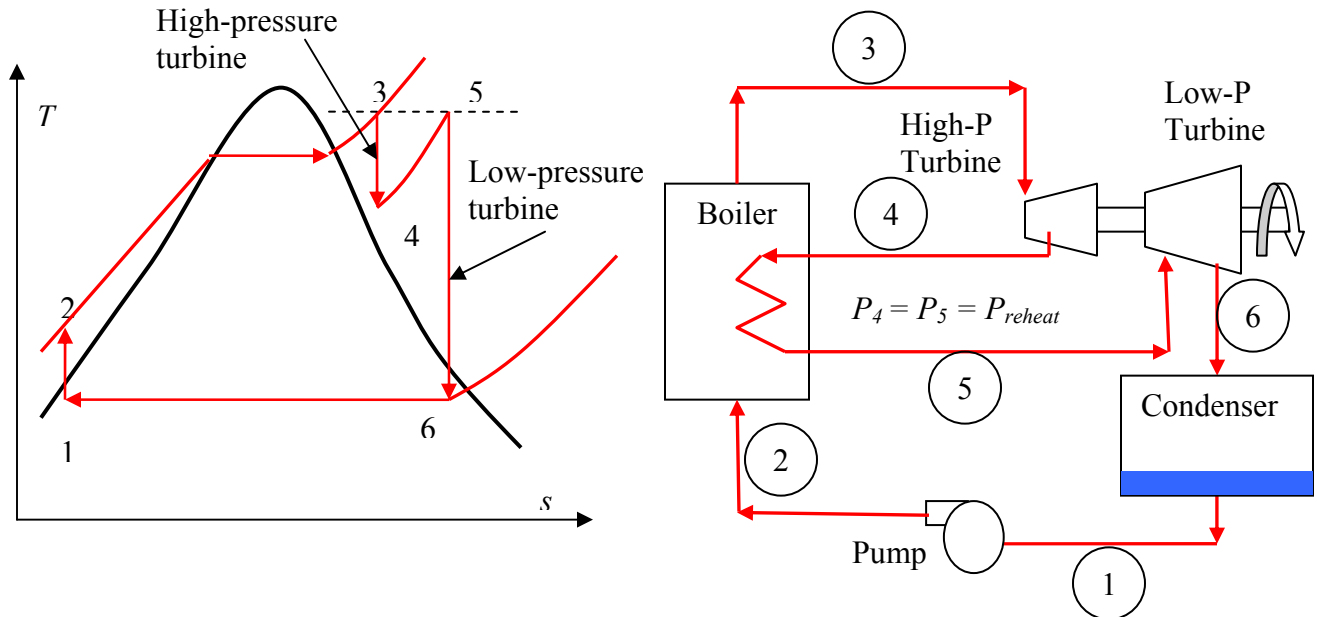

Fig. 7: The ideal reheat Rankine cycle.

The total heat input and total turbine work output for a reheat cycle become:

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

$$w_{turbine,out} = w_{H-P\ turbine} + w_{L-P\ turbine} = (h_3 - h_4) + (h_5 - h_6)$$

The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent by increasing the average temperature at which heat is transferred to the steam.

The Ideal Regenerative Rankine Cycle

The regeneration process in steam power plants is accomplished by extracting (or bleeding) steam from turbine at various stages and feed that steam in heat exchanger where the feedwater is heated. These heat exchangers are called regenerator or feedwater heater (FWH).

FWH also help removing the air that leaks in at the condenser (deaerating the feedwater).

There are two types of FWH's, open and closed.

Open (Direct-Contact) Feedwater Heaters

An open FWH is basically a mixing chamber where the steam extracted from the turbine mixes with the feedwater exiting the pump. Ideally, the mixture leaves the heater as a saturated liquid at the heater pressure.
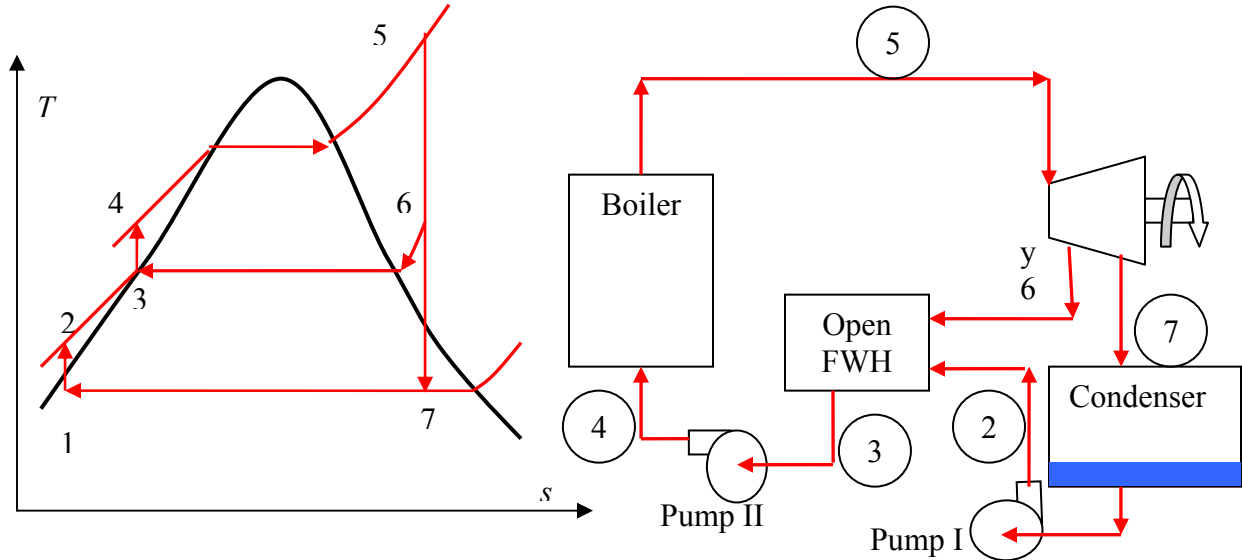

Fig. 8: The ideal regenerative Rankine cycle with an open FWH.

Using Fig. 8, the heat and work interactions of a regenerative Rankine cycle with one FWH can be expressed per unit mass of steam flowing through the boiler as:

$$q_{in} = h_5 - h_4$$
$$q_{out} = (1-y)(h_7 - h_1)$$
$$w_{turbine,out} = (h_5 - h_6) + (1-y)(h_6 - h_7)$$
$$w_{pump,in} = (1-y)w_{PumpI} + w_{PumpII}$$

where

$$y = \dot{m}_6 / \dot{m}_5$$
$$w_{PumpI} = v_1(P_2 - P_1) \qquad w_{PumpII} = v_3(P_4 - P_3)$$

Thermal efficiency of the Rankine cycle increases as a result of regeneration since FWH raises the average temperature of the water before it enters the boiler. Many large power plants have as many as 8 FWH's.

Closed Feedwater Heaters

In closed FWH, heat is transferred from the extracted steam to the feedwater without any mixing taking place. Thus; two streams can be at different pressures, since they don't mix.

In an ideal closed FWH, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.
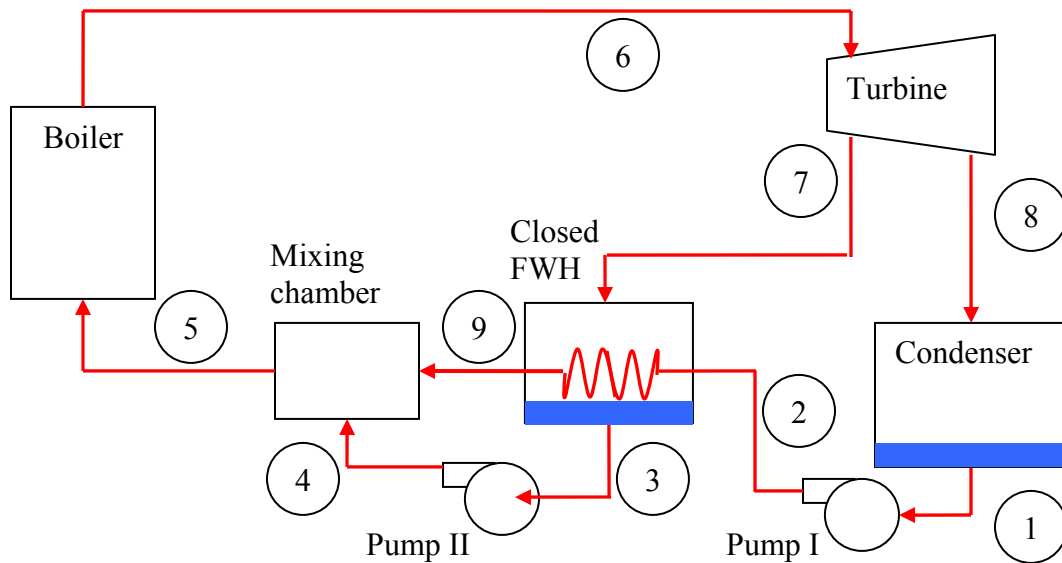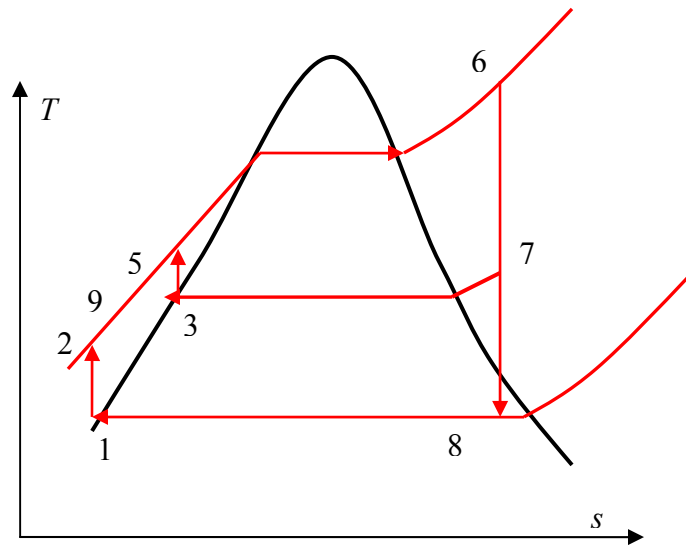
Fig.9: Ideal regenerative Rankine cycle with a closed FWH.

Open FWH	Closed FWH
• simple	• more complex (internal tubing)
• inexpensive	• less effective (no mixing)
• good heat transfer characteristics	• do not require a pump for each FWH
• bring feedwater to the saturation state	
• a pump is required for each FWH	

Cogeneration

Many system and industries require energy input in the form of heat, called *process heat*. Some industries such as chemical, pulp and paper rely heavily on process heat. The process heat is typically supplied by steam at 5 to 7 atm and 150 to 200 C. These plants also require large amount of electric power. Therefore, it makes economical and engineering sense to use the already-existing work potential (in the steam entering the condenser) to use as process heat. This is called cogeneration.
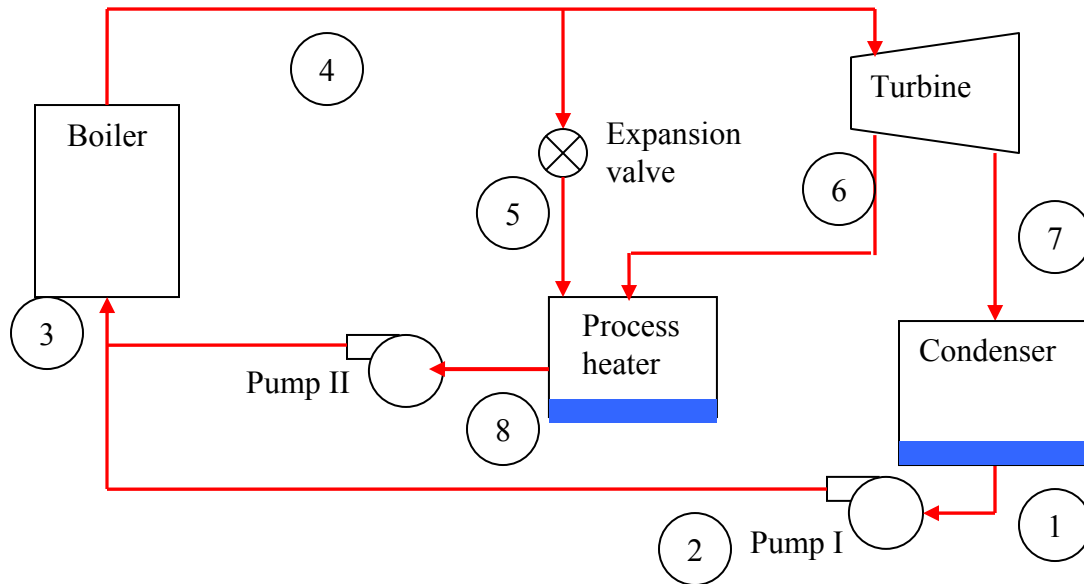

Fig. 10: A cogeneration plant with adjustable loads.

In the cogeneration cycle shown in the above figure, at times of high demands for process heat, all the steam is routed to the process heating unit and none to the condenser.

Combined Gas-Vapor Power Cycle

Gas-turbine cycles typically operate at considerably higher temperatures than steam cycles. The maximum fluid temperature at the turbine inlet is about 620C for modern steam power plants, but over 1425C for gas-turbine power plants. It is over 1500C at the burner exit of turbojet engines.

It makes engineering sense to take advantage of the very desirable characteristics of the gas-turbine cycle at high-temperature and to use the high temperature exhaust gases as the energy source for the bottoming cycle as a steam power cycle. This is called *combined cycle*. Combined cycles can achieve high thermal efficiencies, some of recent ones have η about 60%.