Lecture Two

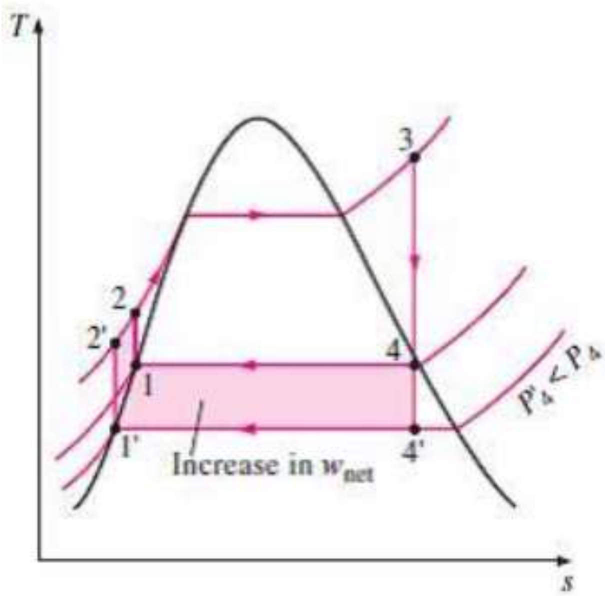
Improving the Rankine Cycle Efficiency

Improving the Rankine Cycle Efficiency

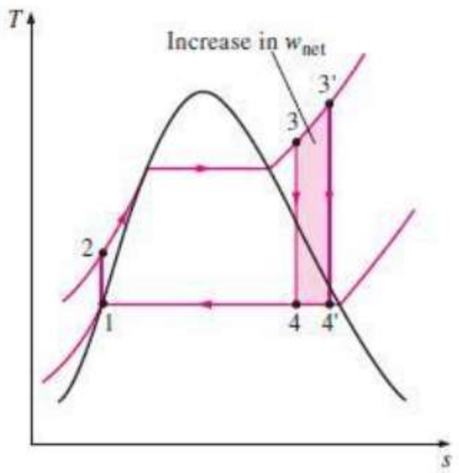
Steam power plants are responsible for the production of most electric power in the world, and even a small increase in thermal efficiency can mean large savings from the fuel requirements.

The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same: **Increase the average temperature at which heat is transferred to the working fluid in the boiler, or decrease the average temperature at which heat is rejected from the working fluid in the condenser**. Three ways can be illustrated to accomplish the subject:

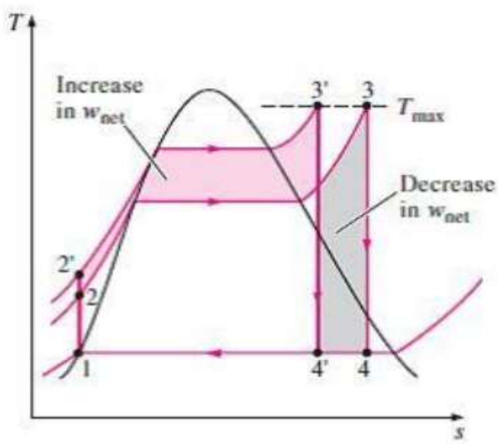
1. Lowering the condenser pressure: lowering the operating pressure of the condenser automatically lowers the temperature of the steam, and thus the temperature at which heat is rejected. The effect of lowering the condenser pressure on the Rankine cycle efficiency is illustrated on the (*T-S*) diagram in the following figure. For comparison purposes, the turbine inlet state is maintained the same. The shaded area on this diagram represents the increase in net work output as a result of lowering the condenser pressure from P_4 to P_4'.



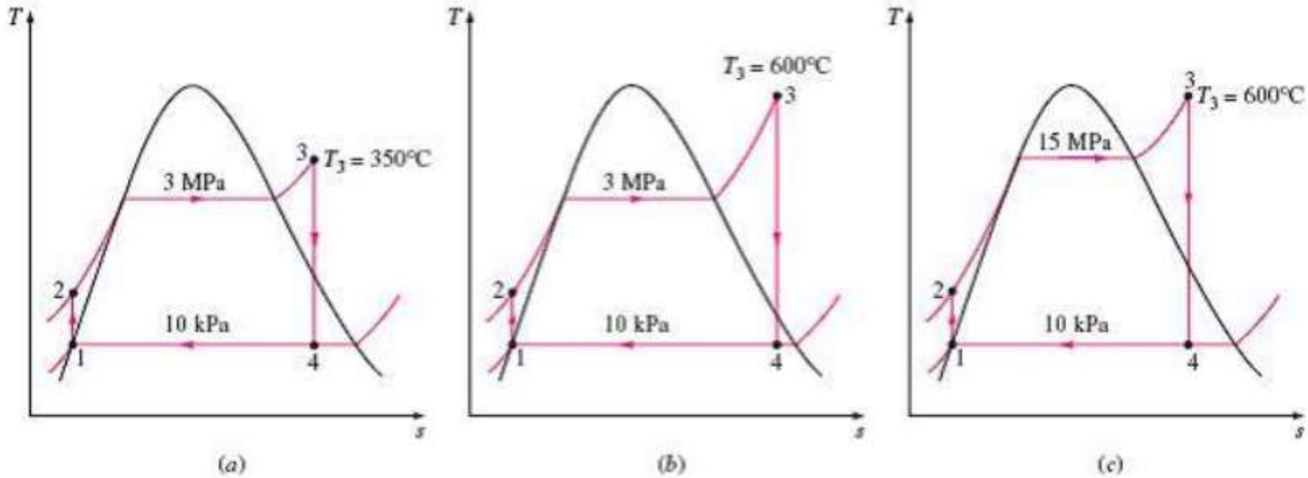
2. Superheating the Seam at High Temperature: the average temperature at which heat is transferred to steam can be increased without increasing the boiler pressure by superheating the steam to high temperatures. The effect of superheating on the performance of vapor power cycles is illustrated on a (*T-S*) diagram in the following figure. The shaded area on this diagram represents the increase in the net work. The total area under the process curve 3-3′ represents the increase in the heat input. Thus both the net work and heat input increase as a result of superheating the steam to a higher temperature. The overall effect is an increase in thermal efficiency, however, since the average temperature at which heat is added increases.



3. Increasing the Boiler Pressure: another way of increasing the average temperature during the heat addition process is to increase the operating pressure of the boiler, which automatically raises the temperature at which boiling takes place. This, in turn, raises the average temperature at which heat is transferred to the steam and thus raises the thermal efficiency of the cycle. The effect of increasing the boiler pressure on the performance of vapor power cycles is illustrated on a (*T-S*) diagram in the following figure. Notice that for a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases. This undesirable side effect can be corrected.



Solution:



a. From saturated steam tables:

State 1: at $P_1 = 10$ kPa $\rightarrow h_1 = h_f = 191.81$ kJ/kg, $v_1 = v_f = 0.00101$ m^3/kg

State 2: $P_2 = 3$ MPa

$$w_{pump} = v_1(P_2 - P_1) = 0.00101 \times (3 \times 10^3 - 10) = 3.02 \text{ kJ/kg}$$

$$w_{pump} = h_2 - h_1 \rightarrow h_2 = h_1 + w_{pump} = 191.81 + 3.02 = 194.83 \text{ kJ/kg}$$

State 3: at $P_3 = 3$ MPa and $T_3 = 350°C$ from superheated steam tables:

$h_3 = 3116.1$ kJ/kg and $s_3 = 6.745$ kJ/kg. K

State 4: at $P_4 = 10$ kPa and $s_4 = s_3 = 6.745$ kJ/kg. K

From saturated steam tables: $s_f = 0.6492\ kJ/kg.K$, $s_{fg} = 7.4996$ kJ/kg. K

$$h_f = 191.81 \text{ kJ/kg}, h_{fg} = 2392.1 \text{ kJ/kg}$$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.745 - 0.6492}{7.4996} = 0.8128$$

$$h_4 = h_f + x_4.h_{fg} = 191.81 + 0.8128 \times 2392.1 = 2136.1 \text{ kJ/kg}$$

$$q_{in} = h_3 - h_2 = 3116.1 - 194.83 = 2921.3 \text{ kJ/kg}$$

$$q_{out} = h_4 - h_1 = 2136.1 - 191.81 = 1944.3 \text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1944.3}{2921.3}$$

$\boldsymbol{\eta_{th} = 33.4\%}$ **Ans.**

b. States 1 and 2 remain the same in this case, and the enthalpies at state 3 (3 MPa and 600°C) and state 4 (10 kPa and $s_4 = s_3$) are determined to be:

$h_3 = 3682.8$ kJ/kg

$h_4 = 2380.3$ kJ/kg ($x_4 = 0.915$)

$q_{in} = h_3 - h_2 = 3682.8 - 194.83 = 3488$ kJ/kg

$q_{out} = h_4 - h_1 = 2380.3 - 191.81 = 2188.5$ kJ/kg

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2188.5}{3488}$$

$\boldsymbol{\eta_{th} = 37.3\%}$ **Ans.**

Therefore, the thermal efficiency increases from 33.4% to 37.3% as a result of superheating the steam from 350°C to 600°C. At the same time, the quality of the steam (dryness fraction) increases from 0.813 to 0.915.

c. State 1 remains the same in this case, but the other states change. The enthalpies at state 2 (15 MPa and $s_2 = s_1$), state 3 (15 MPa and 600°C) and state 4 (10 kPa and $s_4 = s_3$) are determined in a similar manner to be:

$h_2 = 206.95$ kJ/kg, $h_3 = 3583.1$ kJ/kg and $h_4 = 2115.3$ kJ/kg ($x_4 = 0.804$)

$q_{in} = h_3 - h_2 = 3583.1 - 206.95 = 3376.2$ kJ/kg

$q_{out} = h_4 - h_1 = 2115.3 - 191.81 = 1923.5$ kJ/kg

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1923.5}{3376.2}$$

$\boldsymbol{\eta_{th} = 43\%}$ **Ans.**

The thermal efficiency increases from 37.3% to 43% as a result of raising the boiler pressure from 3 MPa to 15 MPa while maintaining the turbine inlet temperature at 600°C. At the same time, the quality of the steam decreases from 0.915 to 0.804 (in other words, the moisture content increases from 0.085 to 0.196).