Classification Of Power Plant Cycles

Thermal power plants, in general, may work on vapour cycles or gas power cycles.

Vapour power cycles—Classification:

1. Rankine cycle.
2. Reheat cycle.
3. Regenerative cycle.
4. Combined Cycle Power Plant.
5. Binary vapour cycle.

Gas power cycles—Classification :

1. Otto cycle.
2. Diesel cycle.
3. Dual combustion cycle.
4. Gas turbine cycles.

Vapor Power Plant Cycles

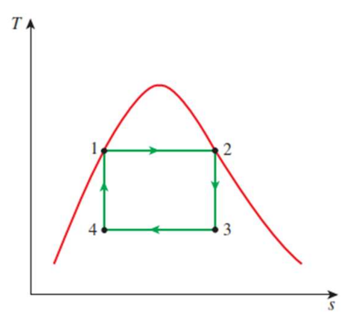
1. Introduction

Steam is the most common working fluid which used in vapor power cycles because of its many desirable characteristics such as: -

1. low cost.
2. Availability.
3. High enthalpy of vaporization.

Steam power plants are commonly referred to as coal plants, nuclear plants and natural gas plants, depending on type of fuel used to supply to steam. The objective of the present lecture is to study vapor power plants in which the working fluid is alternately vaporized and condensed.

The Carnot cycle is the most efficient cycle operating between two specified temperature limits



Thermal efficiency of the Carnot cycle can be calculated from:

$$\eta_{th} = 1 - \frac{T_{min}}{T_{max}}$$

Several impracticalities are associated with this cycle:

- The turbine has to handle steam with low quality, that is, steam with a high moisture content. The impingement of liquid droplets on the turbine blades causes erosion and is a major source of wear. Thus, steam with qualities less than about 90 percent cannot be tolerated in the operation of power plants.
- It is difficult to compress a wet vapour isentropically to the saturated state as required by the process 4–1.
- Limiting the maximum temperature (it has to remain under the critical-point value, which is 374 °C for water) in the cycle also limits the thermal efficiency.

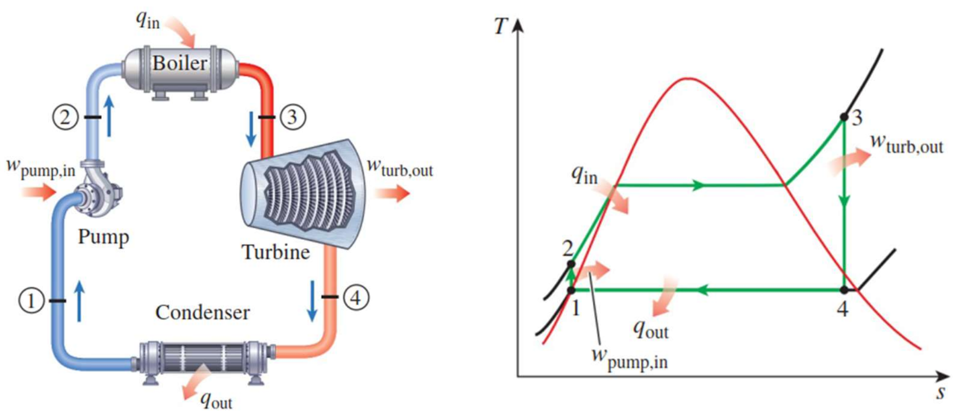
Components of a Vapor Power Plant

Main Component on Steam Power Plant:

1. **Boiler.**
2. **Steam Turbine**
3. **Condenser.**
4. **Pump.**

2. Rankine Cycle

In a steam power plant supply and rejection of heat is more easily realized at constant pressure than at constant temperature. It was **William John Rankine**, after whom the Rankine cycle is named, who first calculated the maximum possible work that could be developed by an engine using dry saturated steam between the pressure limits of the boiler and condenser. The simplest steam cycle using dry saturated steam as the working fluid has the following basic components



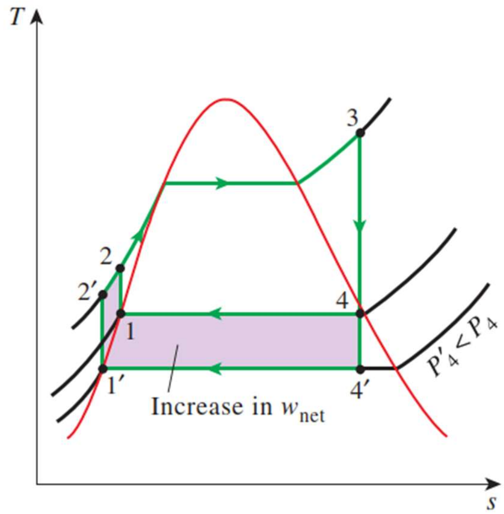
The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes:

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

How Can We Increase the Efficiency of The Rankine Cycle?

1. **Lowering the Condenser Pressure**

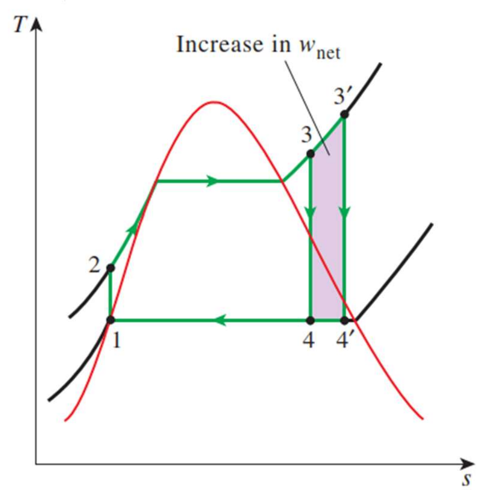
Steam exists as a saturated mixture in the condenser at the saturation temperature corresponding to the pressure inside the condenser. Therefore, lowering the operating pressure of the condenser automatically lowers the temperature of the steam, and thus the temperature at which heat is rejected. The effect of lowering the condenser pressure on the Rankine cycle efficiency is illustrated on the below T-s diagram



2. **Superheating the Steam to High Temperatures**

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 the below T-s diagram.

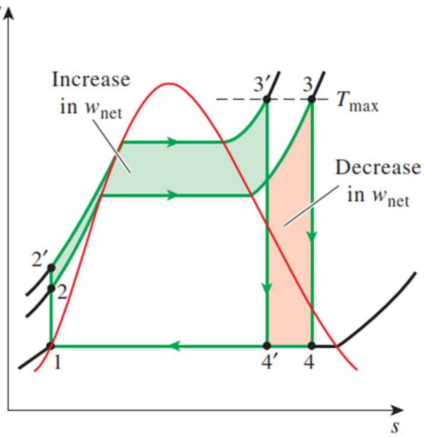
Superheating the steam to higher temperatures has another very desirable effect: It decreases the moisture content of the steam at the turbine exit, as can be seen from the T-s diagram (the quality at state 4′ is higher than that at state 4).



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 the below T-s diagram. 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, however, by reheating the steam.



Energy Analysis of the Ideal Rankine Cycle

All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes.
The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore usually neglected. Then the steady-flow energy equation per unit mass of steam reduces to

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

The boiler and the condenser do not involve any work, and the pump and the turbine are assumed to be isentropic. Then the conservation of energy relation for each device can be expressed as follows:

Pump ($q = 0$): $w_{pump} = (h_2 - h_1)$ kJ/kg

or

$$w_{pump} = v_1(P_2 - P_1) \text{ kJ/kg}$$

Where

$$h_1 = h_f \text{ at } P_1 \text{ and } v_1 = v_f \text{ at } P_1$$

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

Turbine ($q = 0$): $w_{turbine} = (h_3 - h_4)$ kJ/kg

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

The thermal efficiency of the Rankine cycle is determined from

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

$$w_{net} = q_{in} - q_{out}$$

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

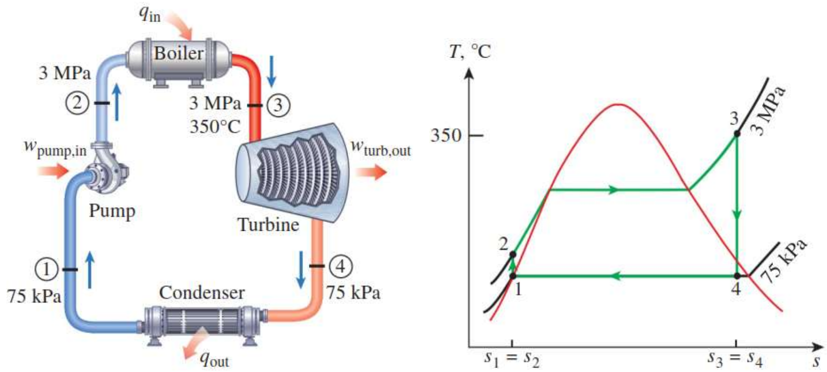
or

$$w_{net} = w_{turbine} - w_{pump}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{turbine} - w_{pump}}{q_{in}}$$

Example 1

Consider a steam power plant operating on the simple ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350 °C and is condensed in the condenser at a pressure of 75 kPa. Determine the thermal efficiency of this cycle.



Solution:

State 1: Saturated liquid at $P_1 = 75\ kpa = 0.75\ bar$ then from steam table (page no. 3) at P_1

$$h_1 = h_f = 384\ kj/kg$$

$$v_1 = v_f = 0.001037\ m^3/kg$$ [from steam table (page no. 10) at P_1]

State 2: $P_2 = 3\ Mpa = 30\ bar$ and $s_1 = s_2$

$$w_{pump} = v_1(P_2 - P_1) = 0.001037(3000 - 75) = 3.03\ kJ/kg$$

$$h_2 = h_1 + w_{pump} = 384 + 3.03 = 387.03\ kJ/kg$$

State 3: Superheated Steam at $P_3 = 30\ bar$ and $T_3 = 350$ °C then from steam table (page no. 3)

$$h_3 = 3117\ kj/kg$$

$$s_3 = 6.744\ kJ/kg.K$$

State 4: $P_4 = 0.75\ bar$ and $s_4 = s_3 = 6.744\ kJ/kg.K$

$s_{fg} = 6.243\ kJ/kg.K$ and $s_f = 1.213\ kJ/kg.K$ [from steam table (page no. 3) at P_4]

$h_{fg} = 2278\ kJ/kg$ and $h_f = 384\ kJ/kg$ [from steam table (page no. 3) at P_4]

$$s_4 = s_f + x_4(s_{fg}) \rightarrow 6.744 = 1.213 + x_4\ (6.243)$$

$$x_4 = \frac{6.744 - 1.213}{6.243} = 0.8859$$

$$\therefore\ h_4 = h_f + x_4(h_{fg}) \rightarrow h_4 = 384 + 0.8859(2278) = 2402.08\ kJ/kg$$

Thus,

$$q_{in} = h_3 - h_2 = 3117 - 387.03 = 2729.97\ kJ/kg$$

$$q_{out} = h_4 - h_1 = 2402.08 - 384 = 2018.08\ kJ/kg$$

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

$$w_{net} = q_{in} - q_{out}$$

$$\eta_{th} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{2729.97 - 2018.08}{2729.97} = 0.26\ or\ 26\%$$

or

$$w_{net} = w_{turbine} - w_{pump}$$

$$w_{turbine} = h_3 - h_4 = 3117 - 2402.08 = 714.92\ kJ/kg$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{turbine} - w_{pump}}{q_{in}} = \frac{714.92 - 3.03}{2729.97} = 0.26\ or\ 26\%$$

3. The Ideal Reheat Rankine Cycle

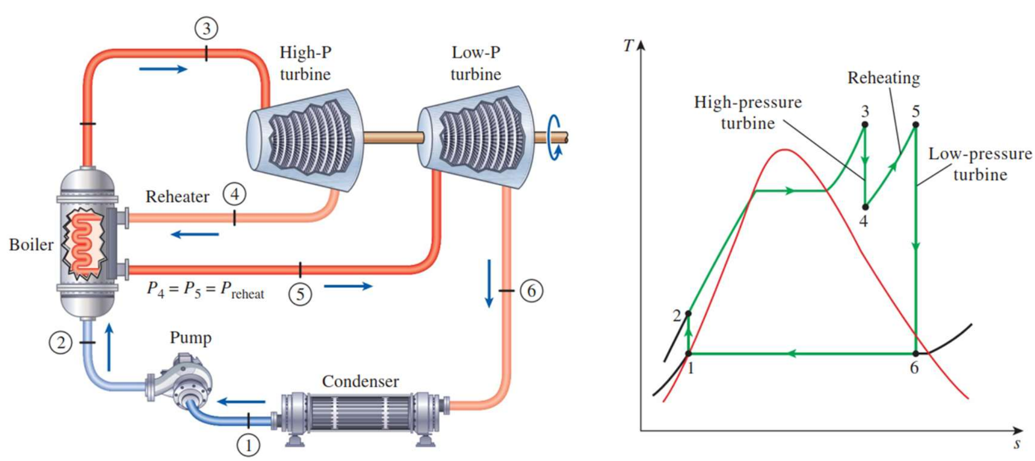
We noted in the last section that increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels. Then it is natural to ask the following question:

How can we take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine?

Two possibilities come to mind:

1. Superheat the steam to very high temperatures before it enters the turbine. This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency. This is not a viable solution, however, since it requires raising the steam temperature to metallurgically unsafe levels.
2. Expand the steam in the turbine in two stages, and reheat it in between. In other words, modify the simple ideal Rankine cycle with a reheat process. Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.

The T-s diagram of the ideal reheat Rankine cycle and the schematic of the power plant operating on this cycle are shown in the below Fig.



The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages. In the first stage (the high-pressure turbine), steam is expanded is entropically to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the first turbine stage. Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure. Thus, the total heat input and the total turbine work output for a reheat cycle become

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

$$w_{turbine} = w_{\text{turbine I}} + w_{\text{turbine II}} = (h_3 - h_4) + (h_5 - h_6)$$

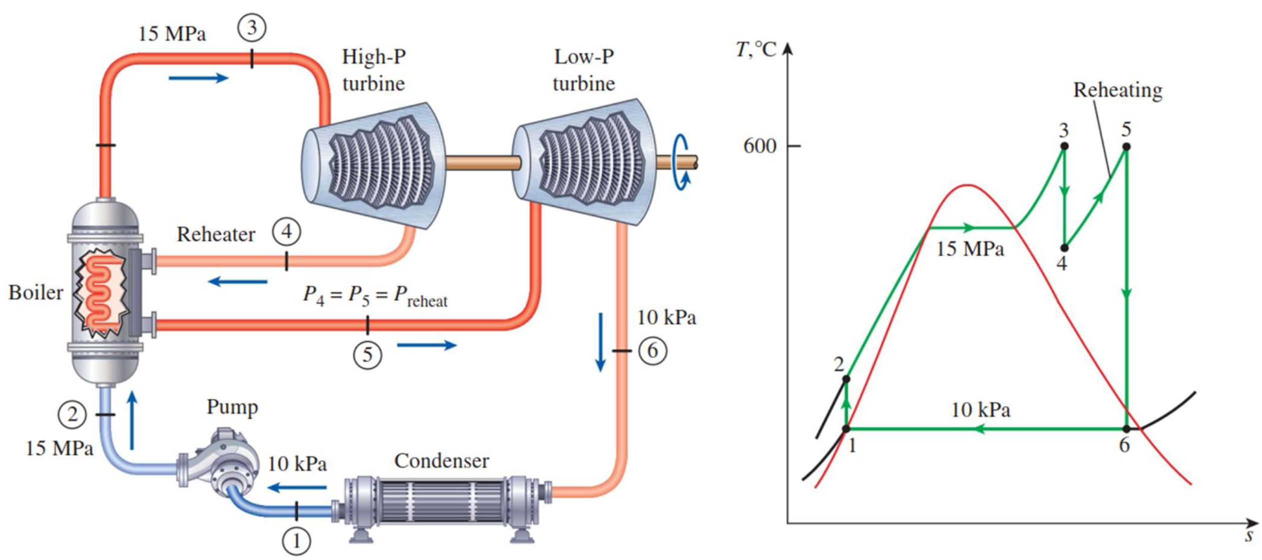
The reheat temperatures are very close or equal to the turbine inlet temperature. The optimum reheat pressure is about one-fourth of the maximum cycle pressure. For example, the optimum reheat pressure for a cycle with a boiler pressure of 12 MPa is about 3 MPa.

Remember that the sole purpose of the reheat cycle is to reduce the moisture content of the steam at the final stages of the expansion process. If we had materials that could withstand sufficiently high temperatures, there would be no need for the reheat cycle.

Example 2

Consider a steam power plant operating on the ideal reheat Rankine cycle. Steam enters the high-pressure turbine at 15 MPa and 600 °C and is condensed in the condenser at a pressure of 10 kPa. If the moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10.4 percent, determine

1. **The pressure at which the steam should be reheated and**
2. **The thermal efficiency of the cycle. Assume the steam is reheated to the inlet temperature of the high-pressure turbine.**



Solution

a. **The reheat pressure is determined from the requirement that the entropies at states 5 and 6 be the same:**

State 6 : P_6= 10 kPa= 0.1 bar

$$x_6 = 1 - \frac{10.4}{100} = 0.896$$

$$s_6 = s_f + x_6(s_{fg}) = 0.649 + 0.896\ (7.5) = 7.369\ \text{kJ/kg.K}$$

Also

$$h_6 = h_f + x_6(h_{fg}) = 192 + 0.896\ (2392) = 2335.2\ \text{kJ/kg}$$

State 5: $T_5 = 600$ °C and $S_5 = S_6 = 7.369$ kJ/ kg K, Entering Steam Table with these values we get:

$P_5 = 40$ Bar

$h_5 = 3674$ kJ/ kg

Therefore, steam should be reheated at a pressure of 40 bar or lower to prevent a moisture content above 10.4 percent.

b. To determine the thermal efficiency, we need to know the enthalpies at all other states:

State 1: Saturated liquid at $P_1 = 0.1\ bar$ then from steam table (page no. 3) at P_1

$h_1 = h_f = 192\ \ kJ/kg$
$v_1 = v_f = 0.00101\ \ m^3/kg$ [from steam table (page no. 10) at P_1]

State 2: $P_2 = 15\ Mpa = 150\ bar$ and $s_1 = s_2$

$$w_{pump} = v_1(P_2 - P_1) = 0.00101(15000 - 10) = 15.14\ \text{kJ/kg}$$

$$h_2 = h_1 + w_{pump} = 192 + 15.14 = 207.14\ \text{kJ/kg}$$

State 3: Superheated Steam at $P_3 = 150\ bar$ and $T_3 = 600\ °C$ then from steam table (page no. 3) at P_3 and T_3

$h_3 = 3581\ \ \text{kJ/kg}$

$s_3 = 6.677\ \text{kJ/kg.K}$

State 4: $P_4 = 40\ bar$ and $s_4 = s_3 = 6.677\ \text{kJ/kg.K}$

Entering Steam Table with These Values we get

T (°C)	*h* (kJ/kg)	*s* (kJ/kg.K)
350	3094	6.584
T_4	h_4	6.677
400	3214	6.769

$$\frac{T_4 - 350}{400 - 350} = \frac{6.677 - 6.584}{6.769 - 6.584}$$

$T_4 = 275.13\ °C$

$$\frac{h_4 - 3094}{3214 - 3094} = \frac{6.677 - 6.584}{6.769 - 6.584}$$

$h_4 = 3154.32\ \ \text{kJ/kg}$

Thus,

$$q_{in} = (h_3 - h_2) + (h_5 - h_4) = (3581 - 207.14) + (3674 - 3154.32) = 3893.54\ \text{kJ/kg}$$

$$q_{out} = h_6 - h_1 = 2335.2 - 192 = 2143.2\ \text{kJ/kg}$$

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

$$w_{net} = q_{in} - q_{out}$$

$$\eta_{th} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{3893.54 - 2143.2}{3893.54} = 0.4495 \; or \; \approx 45\%$$

or

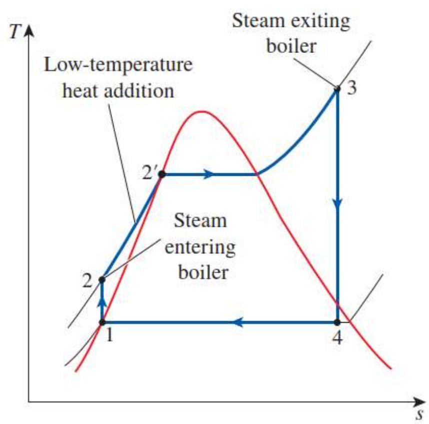
$$w_{net} = w_{turbine} - w_{pump}$$

$$w_{turbine} = (h_3 - h_4) + (h_5 - h_6) = (3581 - 3154.32) + (3674 - 2335.2) = 1765.48 \; kJ/kg$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{turbine} - w_{pump}}{q_{in}} = \frac{1765.48 - 15.14}{3893.54} = 0.4495 \; or \; \approx 45\%$$

4. The Ideal Regenerative Rankine Cycle

A careful examination of the T-s diagram of the Rankine cycle redrawn in the below Fig. reveals that heat is transferred to the working fluid during process 2-2′ at a relatively low temperature. This lowers the average heat-addition temperature and thus the cycle efficiency.



To remedy this shortcoming, we look for ways to raise the temperature of the liquid leaving the pump (called the feedwater) before it enters the boiler. One such possibility is to transfer heat to the feedwater from the expanding steam in a counterflow heat exchanger built into the turbine, that is, to use regeneration. This solution is also impractical because it is difficult to design such a heat exchanger and because it would increase the moisture content of the steam at the final stages of the turbine.

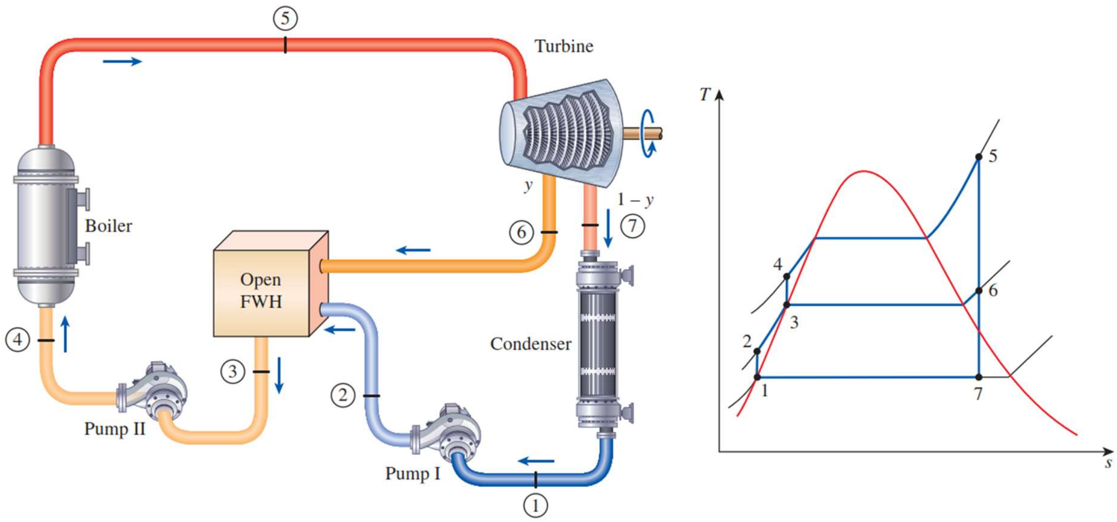
A practical regeneration process in steam power plants is accomplished by extracting, or "bleeding," steam from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead. The device where the feedwater is heated by regeneration is called a regenerator, or a feedwater heater (FWH).

Regeneration not only improves cycle efficiency, but also provides a convenient means of deaerating the feedwater (removing the air that leaks in at the condenser) to prevent corrosion in the boiler. It also helps control the large volume flow rate of the steam at the final stages of the turbine (due to the large specific volumes at low pressures). Therefore, regeneration has been used in all modern steam power plants since its introduction in the early 1920s.

A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters). Regeneration with both types of feedwater heaters is discussed next.

Open Feedwater Heaters

An open (or direct-contact) feedwater heater 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. The schematic of a steam power plant with one open feedwater heater (also called single-stage regenerative cycle) and the T-s diagram of the cycle are shown in the below Figure.



In an ideal regenerative Rankine cycle, steam enters the turbine at the boiler pressure (state 5) and expands isentropically to an intermediate pressure (state 6). Some steam is extracted at this state and routed to the feedwater heater, while the remaining steam continues to expand isentropically to the condenser pressure (state 7). This steam leaves the condenser as a saturated liquid at the condenser pressure (state 1). The condensed water, which is also called the feedwater, then enters an isentropic pump, where it is compressed to the feedwater heater pressure (state 2) and is routed to the feedwater heater, where it mixes with the steam extracted from the turbine. The fraction of the steam extracted is such that the mixture leaves the heater as a saturated liquid at the heater pressure (state 3). A second pump raises the pressure of the water to the boiler pressure (state 4). The cycle is completed by heating the water in the boiler to the turbine inlet state (state 5).

In the analysis of steam power plants, it is more convenient to work with quantities expressed per unit mass of the steam flowing through the boiler. For each 1 kg of steam leaving the boiler, y kg expands partially in the turbine and is extracted at state 6. The remaining (1 – y) kg expands completely to the condenser pressure.

Therefore, the mass flow rates are different in different components. If the mass flow rate through the boiler is $\dot{m}$, for example, it is (1 – y) $\dot{m}$ through the condenser. This aspect of the regenerative Rankine cycle should be considered in the analysis of the cycle as well as in the interpretation of the areas on the T-s diagram. In light of the above Figure, the heat and work interactions of a regenerative Rankine cycle with one feedwater heater can be expressed per unit mass of steam flowing through the boiler as follows:

$$q_{in} = h_5 - h_4$$

$$q_{out} = (1 - y)(h_7 - h_1)$$

$$w_{turbine} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

$$w_{pump} = (1 - y)w_{pump,I} + w_{pump,II}$$

Where

$$y = \frac{\dot{m}_6}{\dot{m}_5} \ \ (fraction\ of\ steam\ extracted)$$

The energy analysis of open feedwater heaters is identical to the energy analysis of mixing chambers. neglecting the kinetic and potential energies of the streams, the energy balance reduces for a feedwater heater to

$$\dot{E}_{in} = \dot{E}_{out} \rightarrow \ \textstyle\sum_{in} \dot{m}\, h = \sum_{out} \dot{m}\, h$$

Or

$$y h_6 + (1 - y) h_2 = 1(h_3)$$

$$y = \frac{h_3 - h_2}{h_6 - h_2}$$

Thus,

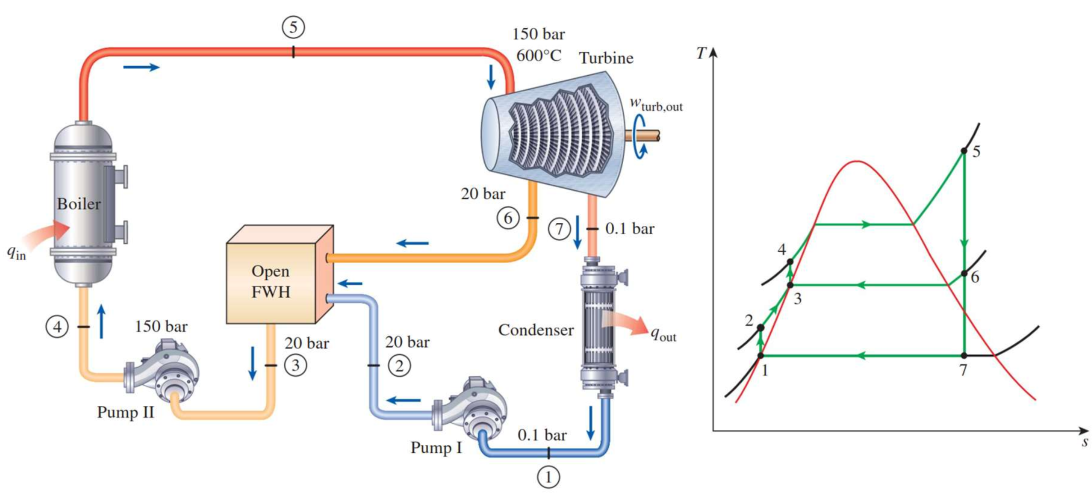
$$w_{pump,I} = v_1 (P_2 - P_1)$$

$$w_{pump,II} = v_3 (P_4 - P_3)$$

The thermal efficiency of the Rankine cycle increases as a result of regeneration. This is because regeneration raises the average temperature at which heat is transferred to the steam in the boiler by raising the temperature of the water before it enters the boiler. The cycle efficiency increases further as the number of feedwater heaters is increased. Many large plants in operation today use as many as eight feedwater heaters. The optimum number of feedwater heaters is determined from economic considerations. The use of an additional feedwater heater cannot be justified unless it saves more in fuel costs than its own cost.

Example 3

Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feedwater heater. Steam enters the turbine at 150 bar and 600°C and is condensed in the condenser at a pressure of 0.1 bar. Some steam leaves the turbine at a pressure of 20 bar and enters the open feedwater heater. Determine the fraction of steam extracted from the turbine, the thermal efficiency of the cycle, turbine and pumps works.



Solution

State 1: Saturated liquid at $P_1 = 0.1\ bar$ then from steam table (page no. 3) at P_1

$h_1 = h_f = 192$ kJ/kg

$v_1 = v_f = 0.00101$ m^3/kg [from steam table (page no. 10) at P_1]

State 2: $P_2 = 20\ bar,$ and $s_1 = s_2$

$$w_{pump,\ I} = v_1(P_2 - P_1) = 0.00101(20 - 0.1) \times 100 = 2 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{pump,\ I} = 192 + 2 = 194 \text{ kJ/kg}$$

State 3: Saturated liquid at $P_3 = 20\ bar$ then from steam table (page no. 3) at P_3

$h_3 = h_f = 909$ kJ/kg

$v_3 = v_f = 0.001176$ m^3/kg [from steam short steam table]

[*or from page no. 10 of old steam table at P_3 by interpolation*]

P (bar)	***v* (m^3/kg)**
19.08	0.001173
20	***v_3***
23.2	0.001190

$$\frac{20 - 19.08}{23.2 - 19.08} = \frac{v_3 - 0.001173}{0.00119 - 0.001173}$$

State 4: $P_4 = 150\ bar,$ and $s_1 = s_2$

$$w_{pump,\ II} = v_3(P_4 - P_3) = 0.001176(150 - 20) \times 100 = 15.288 \text{ kJ/kg}$$

$$h_4 = h_3 + w_{pump,\ II} = 909 + 15.288 = 778.792 \text{ kJ/kg}$$

State 5: $P_5 = 150\ bar,$ and $T_5 = 600\ °C$, Entering Steam Table with these values we get:

$h_5 = 3581$ kJ/kg , $s_5 = 6.677$ kJ/kg. K

State 6: $P_6 = 20\ bar,$ and $s_6 = s_5 = 6.677$ kJ/kg. K , Entering Steam Table with these values we get:

T (°C)	***h* (kJ/kg)**	***s* (kJ/kg.K)**
250	2904	6.547
T_6	***h_6***	6.677
300	3025	6.768

$$\frac{T_6 - 250}{300 - 250} = \frac{6.677 - 6.547}{6.768 - 6.547}$$

$T_6 = 279.41\ °C$

$$\frac{h_6 - 2904}{3025 - 2904} = \frac{6.677 - 6.547}{6.768 - 6.547}$$

$h_6 = 2975.176$ kJ/kg

State 7: $P_7 = 0.1\ bar,$ and $s_7 = s_6 = s_6 = 6.677$ kJ/kg. K

$s_{fg} = 7.5$ kJ/kg. K and $s_f = 0.649$ kJ/kg. K [from steam table (page no. 3) at P_7]

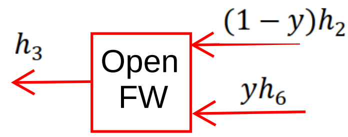
$h_{fg} = 2392$ kJ/kg and $h_f = 192$ kJ/kg [from steam table (page no. 3) at P_7]

$$s_7 = s_f + x_7(s_{fg}) \rightarrow 6.677 = 0.649 + x_7\ (7.5)$$

$$x_7 = \frac{6.677 - 0.649}{7.5} = 0.8037$$

$$\therefore\ h_7 = h_f + x_7(h_{fg}) \rightarrow h_7 = 192 + 0.8037(2392) = 2114.45 \text{ kJ/kg}$$

Energy balance for open feedwater yields:



$$yh_6 + (1-y)h_2 = 1(h_3)$$

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{909 - 194}{2975.176 - 194} = 0.257$$

$$q_{in} = (h_5 - h_4) = (3581 - 778.792) = 2802.208 \text{ kJ/kg}$$

$$q_{out} = (1-y)(h_7 - h_1) = (1 - 0.257)(2114.45 - 192) = 1428.38 \text{ kJ/kg}$$

$$\eta_{th} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{2802.208 - 1428.38}{2802.208} = 0.49\ or\ \approx 49\%$$

$$w_{turbine} = (h_5 - h_6) + (1-y)(h_6 - h_7)$$

$$w_{turbine} = (3581 - 2975.176) + (1 - 0.257)(2975.176 - 2114.45)$$

$$w_{turbine} = 1245.343 \text{ kJ/kg}$$

$$w_{pump} = (1-y)w_{pump,I} + w_{pump,II}$$

$$w_{pump} = (1 - 0.257) \times 2 + 15.288 = 16.774 \text{ kJ/kg}$$

Homework

1. Consider a 210000 kW steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 100 bar and 500°C and is cooled in the condenser at a pressure of 0.1 bar. Show the cycle on a T-s diagram with respect to saturation lines, and determine (a) the quality of the steam at the turbine exit, (b) the thermal efficiency of the cycle, and (c) the mass flow rate of the steam.

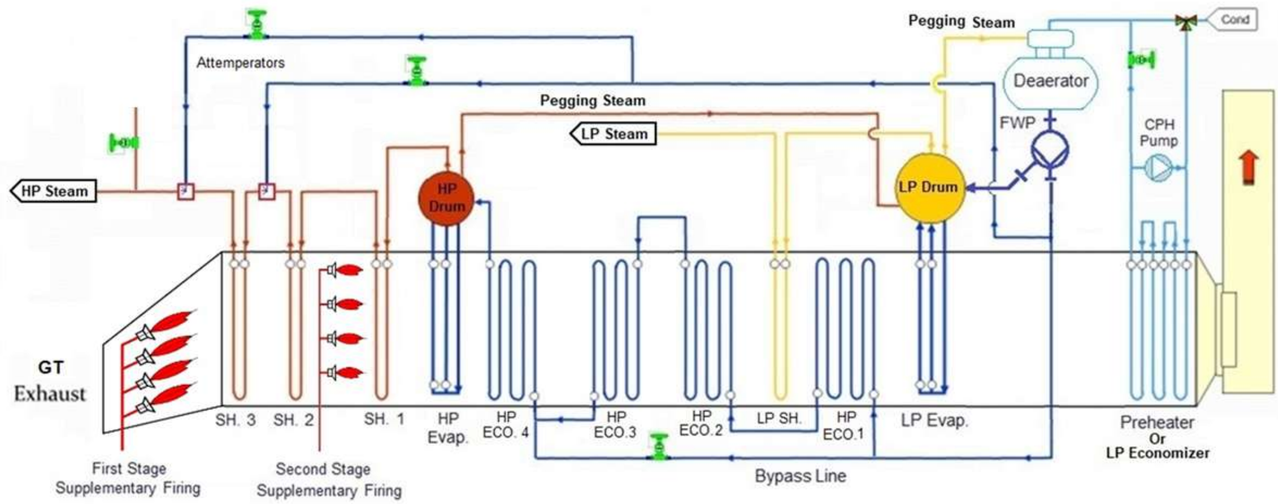
2. A steam power plant operates on the ideal reheat Rankine cycle. Steam enters the high-pressure turbine at 60 bar and 400°C and leaves at 15 bar. Steam is then reheated at constant pressure to 400°C before it expands to 0.2 bar in the low-pressure turbine. Determine the turbine work output, in kJ/kg, and the thermal efficiency of the cycle. Also, show the cycle on a T-s diagram with respect to saturation lines.

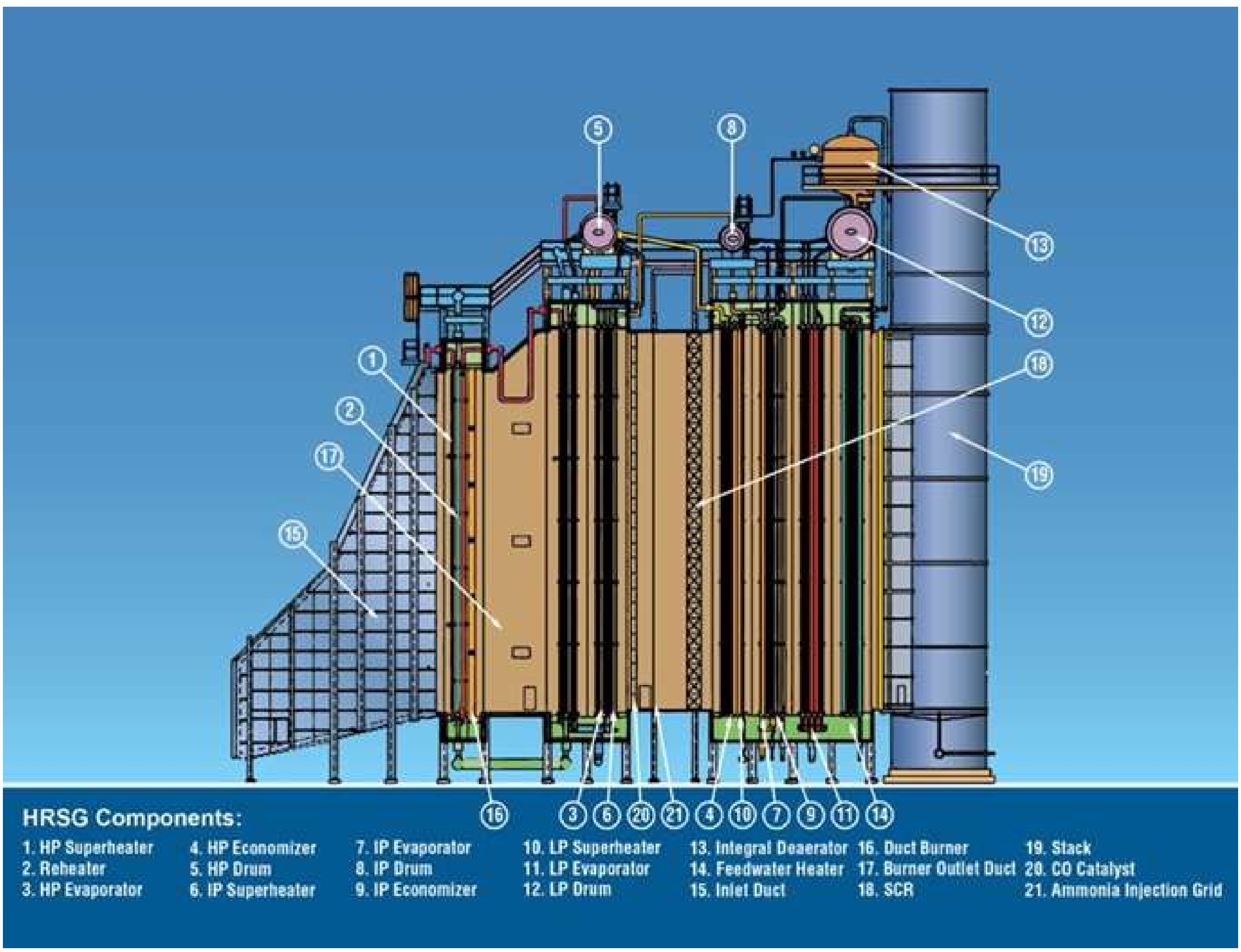
3. A steam power plant operates on an ideal regenerative Rankine cycle. Steam enters the turbine at 60 bar and 450°C and is condensed in the condenser at 0.2 bar. Steam is extracted from the turbine at 4 bar to heat the feedwater in an open feedwater heater. Water leaves the feedwater heater as a saturated liquid. Show the cycle on a T-s diagram, and determine (a) the network output per kilogram of steam flowing through the boiler and (b) the thermal efficiency of the cycle.

4. Why is the Carnot cycle not a realistic model for steam power plants?

5. Explain briefly with T-s diagram the methods of increasing the efficiency of the Rankine Cycle?

Boiler


Attemperators
Pegging Steam
LP Steam
HP Steam
Pegging Steam
Cond
Deaerator
FWP
CPH Pump
HP Drum
LP Drum
GT Exhaust
SH. 3
SH. 2
SH. 1
HP Evap.
HP ECO. 4
HP ECO.3
HP ECO.2
LP SH.
HP ECO.1
LP Evap.
Preheater Or LP Economizer
First Stage Supplementary Firing
Second Stage Supplementary Firing
Bypass Line


HRSG Components:
1. HP Superheater
2. Reheater
3. HP Evaporator
4. HP Economizer
5. HP Drum
6. IP Superheater
7. IP Evaporator
8. IP Drum
9. IP Economizer
10. LP Superheater
11. LP Evaporator
12. LP Drum
13. Integral Deaerator
14. Feedwater Heater
15. Inlet Duct
16. Duct Burner
17. Burner Outlet Duct
18. SCR
19. Stack
20. CO Catalyst
21. Ammonia Injection Grid

Functions of Boiler components

- **Deaerator:** Removes dissolved gases like oxygen and carbon dioxide from feedwater to prevent corrosion in the boiler.
- **Stack Damper:** Protect the boiler during maintenance, and reducing heat loss when the boiler is shutdown mode.
- **Continuous Blow Down System:** removing dissolved solids and maintaining water chemistry to prevent scaling and corrosion.
- **Attemperator:** Regulates steam temperature by injecting cooling water, preventing overheating and protecting turbine and superheater components.
- **Condensate Preheater Pump:** recirculate condensate water through a preheater heat exchanger to raise its temperature before entering the boiler to improving thermal efficiency and avoid sulfuric acid condensation on the outer surface of preheater tubes bundle.
- **Start-up Vent Control Valve:** Releases excess steam during boiler startup to prevent excessive pressure buildup and ensure safe operation.
- **HP Drum Safety Valve:** Protects the high-pressure steam drum by automatically relieving excess pressure to prevent overpressure conditions and potential damage.
- **Feedwater Pump:** Pumps feedwater from the deaerator or storage tank into the boiler to maintain water levels and sustain steam generation.
- **Steam Separator:** Separates moisture from steam inside the boiler drum, ensuring dry steam is delivered to the turbine.
- **Chimney (or Stack):** Expels combustion gases safely into the atmosphere, ensuring proper ventilation and reducing emissions.
- **Soot Blower:** Uses steam or compressed air to remove soot and ash deposits from boiler tubes, maintaining heat transfer efficiency and preventing blockages.
- **Steam Trap:** Removes condensate and non-condensable gases from the steam system while preventing steam loss, ensuring efficient steam usage.
- **HP Superheater:** Increases the temperature of high-pressure steam after it exits the HP evaporator, improving thermal efficiency.
- **Reheater:** Reheats steam exiting the high-pressure turbine before entering the intermediate or low-pressure turbine, enhancing efficiency and avoiding moisture issues.
- **HP Evaporator:** Converts high-pressure feedwater into saturated steam using heat from gas turbine exhaust.
- **HP Economizer:** Preheats feedwater entering the HP evaporator using exhaust heat, improving overall energy efficiency.
- **HP Drum:** Separates saturated steam from water in the high-pressure system and serves as a reservoir for recirculating water.
- **LP Superheater:** Heats low-pressure steam before it enters the LP turbine.
- **LP Evaporator:** Produces low-pressure steam by boiling water with lower temperature exhaust gases.
- **LP Drum:** Separates water from steam in the low-pressure circuit and stores water for recirculation.

Classification of Condensers

Mainly, condensers are of two types : (1) Jet condensers, (2) Surface condensers.

In ***jet*** condensers, *the exhaust steam and water come in direct contact with each other* and temperature of the condensate is the same as that of cooling water leaving the condenser. The cooling water is usually sprayed into the exhaust steam to cause rapid condensation.

In ***surface*** *condensers, the exhaust steam and water do not come into direct contact.* The steam passes over the outer surface of tubes through which a supply of cooling water is maintained. There may be single-pass or double-pass. In single-pass condensers, the water flows in one direction only through all the tubes, while in two-pass condenser the water flows in one direction through the tubes and returns through the remainder.

A jet condenser is simpler and cheaper than a surface condenser. It should be installed when the cooling water is cheaply and easily made suitable for boiler feed or when a cheap source of boiler and feed water is available.

A surface condenser is most commonly used because the condensate obtained is not thrown as a waste but returned to the boiler

The effects of air leakage in steam condenser

(a) **Reduced Efficiency:** Air leakage raises condenser pressure, lowering the turbine's output and thermal efficiency.
(b) **Poor Heat Transfer:** Air forms a barrier on condenser tubes, reducing steam condensation and heat exchange.
(c) **Corrosion Risk:** Ingress of oxygen and CO_2 accelerates rust and pitting in condenser and boiler components.
(d) **Higher Energy Use:** Air removal systems (e.g., ejectors, vacuum pumps) consume more power to maintain vacuum levels.

Thermochemistry and Fuels

Most IC engines obtain their energy from the combustion of a hydrocarbon fuel with air, which converts chemical energy of the fuel to internal energy in the gases within the engine. There are many thousands of different hydrocarbon fuel components, which consist mainly of hydrogen and carbon but may also contain oxygen (alcohols), nitrogen, and/or sulfur, etc. The maximum amount of chemical energy that can be released (heat) from the fuel is when it reacts (combusts) with a stoichiometric amount of oxygen. Stoichiometric oxygen (sometimes called theoretical oxygen) is just enough to convert all carbon in the fuel to CO_2 and all hydrogen to H_2O, with no oxygen left over. The balanced chemical equation of the simplest hydrocarbon fuel, methane CH_4, burning with stoichiometric oxygen is:

$$\boldsymbol{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

It takes two moles of oxygen to react with one mole of fuel, and this gives one mole of carbon dioxide and two moles of water vapor. If isooctane is the fuel component, the balanced stoichiometric combustion with oxygen would be:

$$\boldsymbol{C_8H_{18} + 12.5\,O_2 \rightarrow 8CO_2 + 9H_2O}$$

Molecules react with molecules, so in balancing a chemical equation, molar quantities (fixed number of molecules) are used and not mass quantities. One kgmole of a substance has a mass in kilograms equal in number to the molecular weight (molar mass) of that substance. In English units the lbm mole is used.

$$\boldsymbol{m = N \times M}$$

where: m = mass

N = number of moles

M = molecular weight

In SI units:

1 kgmole of CH_4 = 16.04 kg

1 kgmole of O_2 = 32.00 kg

1 kgmole = 6.02 x 10^{26} molecules

The components on the left side of a chemical reaction equation which are present before the reaction are called reactants, while the components on the right side of the equation which are present after the reaction are called products or exhaust.

Very small powerful engines could be built if fuel were burned with pure oxygen. However, the cost of using pure oxygen would be prohibitive, and thus is not done. Air is used as the source of oxygen to react with fuel. Atmospheric air is made up of about:

78% nitrogen by mole

21 % oxygen

1% different gases.

Nitrogen and argon are essentially chemically neutral and do not react in the combustion process. Their presence, however, does affect the temperature and pressure in the combustion chamber. To simplify calculations without causing any large error, the neutral argon in air is assumed to be combined with the neutral nitrogen, and atmospheric air then can be modeled as being made up of 21% oxygen and 79% nitrogen. For every 0.21 moles of oxygen there is also 0.79 moles of nitrogen, or for one mole of oxygen there are 0.79/0.21 moles of nitrogen. For every mole of oxygen needed for combustion, 4.76 moles of air must be supplied: one mole of oxygen plus 3.76 moles of nitrogen.

Stoichiometric combustion of methane with air is then:

$$\boldsymbol{CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 2(3.76)N_2}$$

and of isooctane with air is:

$$\boldsymbol{C_8H_{18} + 12.5\,(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 12.5(3.76)\,N_2}$$

It is convenient to balance combustion reaction equations for one kgmole of fuel. The energy released by the reaction will thus have units of energy per kgmole of fuel, which is easily transformed to total energy when the flow rate of fuel is known. Molecular weights can be found in Table 1. The molecular weight of 29 will be used for air. Combustion can occur, within limits, when more than stoichiometric air is present (lean) or when less than stoichiometric air is present (rich) for a given amount of fuel. If methane is burned with 150% stoichiometric air, the excess oxygen ends up in the products:

$$\boldsymbol{CH_4 + 3(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + O_2 + 3(3.76)N_2}$$

If isooctane is burned with 80% stoichiometric air, there is not enough oxygen to convert all the carbon to CO_2, and carbon monoxide CO is found in the products:

$$\boldsymbol{C_8H_{18} + 10\,(O_2 + 3.76N_2) \rightarrow 3CO_2 + 9H_2O + 5CO + 10(3.76)\,N_2}$$

Table 1 Molecular Weight

SUBSTANCE		MOLECULAR WEIGHT (kg/kgmole) or (Ibm/lbmmole)
Air		28.97 (≈ 29)
Argon	Ar	39.95
Carbon	C	12.01 (≈ 12)
Carbon Monoxide	CO	28.01 (≈ 28)
Carbon Dioxide	CO_2	44.01 (≈ 44)
Hydrogen	H_2	2.02 (≈ 2)
Water Vapor	H_2O	18.02 (≈ 18)
Helium	He	4.00
Nitrogen	N_2	28.01 (≈ 28)

Note: C= 12, O=16, H=1, N=14

Carbon monoxide is a colorless, odorless, poisonous gas which can be further burned to form CO2. It is formed in any combustion process when there is a deficiency of oxygen. It is also very likely that some of the fuel will not get burned when there is a deficiency of oxygen. This unburned fuel ends up as pollution in the exhaust of the engine.

Various terminology is used for the amount of air or oxygen used in combustion.

80% stoichiometric air = 80% theoretical air = 80% air= 20% deficiency of air

133% stoichiometric oxygen = 133% theoretical oxygen= 133% oxygen = 33% excess oxygen

For actual combustion in an engine, the equivalence ratio is a measure of the fuel-air mixture relative to stoichiometric conditions. It is defined as:

$$\phi = \frac{(A/F)_{stoich}}{(A/F)_{act}}$$

Where

$$A/F = m_a/m_f = \text{ air to fuel ratio}$$

$$m_a = \text{mass of air} = N_a \times M_a$$

$$m_f = \text{mass of fuel} = N_f \times M_f$$

When

$$\phi < 1 \quad \text{running lean, oxygen in exhaust}$$

$$\phi < 1 \quad \text{running rich, CO in exhaust}$$

$$\phi = 1 \quad \text{stiochiometric, maximum energy released from fuel}$$

SI engines normally operate with an equivalence ratio in the range of 0.9 to 1.2, depending on the type of operation.

Example 1:

Isooctane C_8H_{18} is burned with 120% theoretical air in small three-cylinder turbocharged automobile engine. Calculate: (a) air-fuel ratio, and (b) equivalence ratio.

Solution

Stoichiometric reaction

$$C_8H_{18} + a\left(O_2 + \frac{79}{21}N_2\right) \rightarrow b\,CO_2 + c\,H_2O + d\,N_2$$

$$C_8H_{18} + a(O_2 + 3.76N_2) \rightarrow b\,CO_2 + c\,H_2O + d\,N_2$$

Applying the conservation of mass principle to the carbon, hydrogen, oxygen, and nitrogen

$$C: \quad 8 = b$$

$$H: \quad 18 = 2c \quad \rightarrow c = 9$$

$$O: \quad 2a = 2b + c \rightarrow a = \frac{2b+c}{2} = \frac{2\times 8+9}{2} = 12.5$$

$$N: \quad 3.76 \times 2 \times a = 2d \rightarrow d = 3.76 \times a = 47$$

Stoichiometric reaction will be

$$C_8H_{18} + 12.5(O_2 + 3.76\,N_2) \rightarrow 8\,CO_2 + 9\,H_2O + 47\,N_2$$

With 20% excess air:

$$\mathbf{C_8H_{18} + 15(O_2 + 3.76\,N_2) \rightarrow 8\,CO_2 + 9\,H_2O + 56.4\,N_2 + 2.5\,O_2}$$

With 20% excess air, ail the fuel gets burned, and the same amount of CO_2 and H_2O is found in the products. In addition, there is some oxygen and additional nitrogen in the products (the excess air).

$$M_f = C \times 8 + H \times 18 = 12 \times 8 + 1 \times 18 = 114$$

$$(A/F)_{act} = \frac{m_a}{m_f} = \frac{N_a \times M_a}{N_f \times M_f} = \frac{[15 \times (1 + 3.76)] \times 29}{1 \times 114} = 18.16$$

$$(A/F)_{stoich} = \left(\frac{m_a}{m_f}\right)_{stoich} = \left(\frac{N_a \times M_a}{N_f \times M_f}\right)_{stoich} = \frac{[12.5 \times (1 + 3.76)] \times 29}{1 \times 114} = 15.136$$

$$\phi = \frac{(A/F)_{stoich}}{(A/F)_{act}} = \frac{15.136}{18.16} = 0.833$$

Example 2:

Determine the air–fuel ratio and equivalence ratio for the combustion of octane, C_8H_{18}, with (a) the theoretical amount of air, (b) 150% theoretical air, and (c) 90% theoretical air.

Solution

Stoichiometric reaction

$$\mathbf{C_8H_{18} + \mathit{a}(O_2 + 3.76N_2) \rightarrow \mathit{b}\,CO_2 + \mathit{c}\,H_2O + \mathit{d}\,N_2}$$

Applying the conservation of mass principle to the carbon, hydrogen, oxygen, and nitrogen

$$C: \quad 8 = b$$

$$H: \quad 18 = 2c \ \rightarrow c = 9$$

$$O: \quad 2a = 2b + c \ \rightarrow a = \frac{2b+c}{2} = \frac{2\times 8+9}{2} = 12.5$$

$$N: \quad 3.76 \times 2 \times a = 2d \ \rightarrow d = 3.76 \times a = 47$$

Stoichiometric reaction will be

$$\mathbf{C_8H_{18} + 12.5(O_2 + 3.76\,N_2) \rightarrow 8\,CO_2 + 9\,H_2O + 47\,N_2}$$

$$M_f = C \times 8 + H \times 18 = 12 \times 8 + 1 \times 18 = 114$$

$$(A/F)_{stoich} = \left(\frac{m_a}{m_f}\right)_{stoich} = \left(\frac{N_a \times M_a}{N_f \times M_f}\right)_{stoich} = \frac{[12.5 \times (1 + 3.76)] \times 29}{1 \times 114} = 15.136$$

$$\phi = 1$$

(a) With 150% theoretical air (50% excess air):

$$\mathbf{C_8H_{18} + 18.75(O_2 + 3.76\,N_2) \rightarrow 8\,CO_2 + 9\,H_2O + 6.25\,O_2 + 70.5\,N_2}$$

With 50% excess air, ail the fuel gets burned, and the same amount of CO_2 and H_2O is found in the products. In addition, there is some oxygen and additional nitrogen in the products (the excess air).

$$(A/F)_{act} = \frac{m_a}{m_f} = \frac{N_a \times M_a}{N_f \times M_f} = \frac{[18.75 \times (1 + 3.76)] \times 29}{1 \times 114} = 22.7$$

$$\phi = \frac{(A/F)_{stoich}}{(A/F)_{act}} = \frac{15.136}{22.7} = 0.66$$

(a) With 90% theoretical air (Deficient Air):

If isooctane is burned with 90% theoretical air, there is not enough oxygen to convert all the carbon to CO_2, and carbon monoxide CO is found in the products:

$$C_8H_{18} + 11.25\,(O_2 + 3.76N_2) \rightarrow x\,CO_2 + y\,H_2O + z\,CO + 42.3N_2$$

Applying the conservation of mass principle to the carbon, hydrogen, and oxygen.

H: $18 = 2y \rightarrow y = 9$

C: $8 = x + z$ …… (1)

O: $2x + y + z = 11.25 \times 2$

$2x + 9 + z = 22.5$

$2x + z = 13.5$ …… (2)

Subtract (1) from (2):

$x = 5.5$ **and** $z = 2.5$ **then**

$$C_8H_{18} + 11.25\,(O_2 + 3.76N_2) \rightarrow 5.5\,CO_2 + 9\,H_2O + 2.5\,CO + 42.3N_2$$

$$(A/F)_{act} = \frac{m_a}{m_f} = \frac{N_a \times M_a}{N_f \times M_f} = \frac{[11.25 \times (1 + 3.76)] \times 29}{1 \times 114} = 13.62$$

$$\phi = \frac{(A/F)_{stoich}}{(A/F)_{act}} = \frac{15.136}{13.62} = 1.11$$

Final Answers:

Case	A/F	Equivalence Ratio (ϕ)
(a) Theoretical Air	15.136	1
(b) 150% Theoretical Air	22.7	0.66
(c) 90% Theoretical Air	13.62	1.11

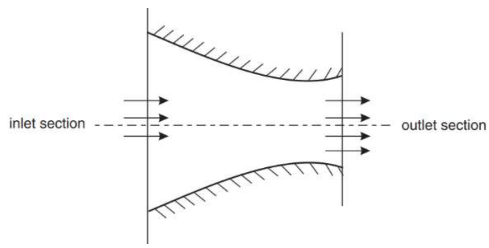
Steam Nozzles

A steam nozzle may be defined as a passage of varying cross-section, through which heat energy of steam is converted to kinetic energy. Its major function is to produce steam jet with high velocity to drive steam turbines. A turbine nozzle performs *two functions:*

I. It transforms a portion of energy of steam (obtained from steam generating unit) into kinetic energy.
II. In the impulse turbine it directs the steam jet of high velocity against blades, which are free to move in order to convert kinetic energy into shaft work. In reaction turbines the nozzles which are free to move, discharge high velocity steam. The reactive force of the steam against the nozzle produces motion and work is obtained.

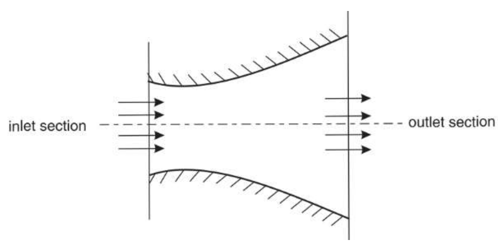
Nozzles Types

1. **Convergent Nozzle**: in the converged nozzle the cross area decreases from the inlet section to the outlet section.



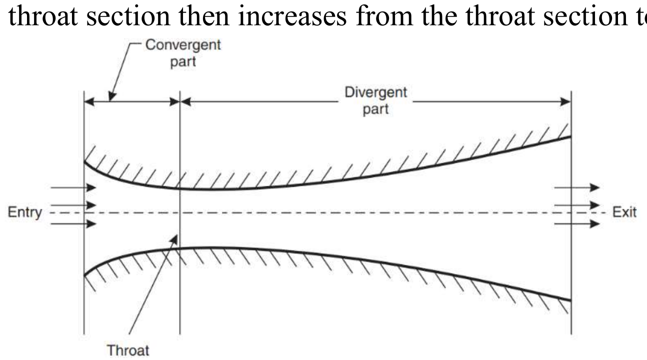
Inlet pressure > Outlet pressure

2. **Divergent Nozzle**: in the converged nozzle the cross area increases from the inlet section to the outlet section.



Outlet pressure > Inlet pressure

3. **Convergent – Divergent Nozzle**: in the converged divergent nozzle the cross area decreases from the inlet section to the throat section then increases from the throat section to the outlet section.



Inlet pressure > Outlet pressure

Throat pressure > Outlet pressure

Inlet pressure > Throat pressure > Outlet pressure

Steam Flow Through Nozzles

It is assumed as adiabatic flow since no heat is supplied or rejected by the steam, in addition not work been done during the process.

Steam Velocity:

Neglecting the initial velocity find minimum area, the outlet velocity is given as:

$$C_2 = \sqrt{2000(h_1 - h_2)} = 44.72\sqrt{(h_1 - h_2)}$$

Mass Flowrate:

it is given at any section by:

$$\dot{m} = \frac{A \times C}{v}$$

Where:

A = Cross-sectional area of nozzle (m^2)

C = Velocity of steam (m/s)

v = the specific volume of the steam (m^3/kg)

The discharge through the nozzle will be the maximum when critical pressure ratio, i.e.,

$$\frac{Throat\ pressure}{inlet\ pressure} = \frac{P_2}{P_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

For saturated steam : n = 1.135

$$\frac{P_2}{P_1} = \left(\frac{2}{1.135+1}\right)^{\frac{1.135}{1.135-1}} = 0.58$$

For superheated steam : n = 1.3

$$\frac{P_2}{P_1} = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}} = 0.546 \approx 5.5$$

For **wet steam**, the value of **n** can be calculated by **Zenner's** equation,

n = 1.035 + 0.1*x*, where ***x*** is the initial dryness fraction of steam

Example:

Steam is expanded in a set of nozzles from 10 bar and 200ºC to 5 bars. What type of nozzle is it? Neglecting the initial velocity find minimum area of the nozzle required to allow a flow of 3 kg/s under the given conditions. Assume that expansion of steam to be isentropic.

Solution:

Steam pressure and temperature at the entry to the steam nozzles, P_1 = 10 bar, T_1 = 200ºC

Steam exit pressure, P_3 = 5 bar

Since $P_1 < P_3$ the nozzle is either **convergent** or **convergent-divergent** type so we have to check the critical condition if exist or not within nozzle limit.

To check that we have to follow the following steps:

State 1) P_1 = 10 bar, and T_1 = 200ºC

T_1 (200 C) > Ts (179.9 C) so the initial condition is superheated therefore we get from steam table at P_1 and T_1 :

$$h_1 = 2829\ \text{kJ/kg}$$

$$s_1 = 6.695\ \text{kJ/kg.K}$$

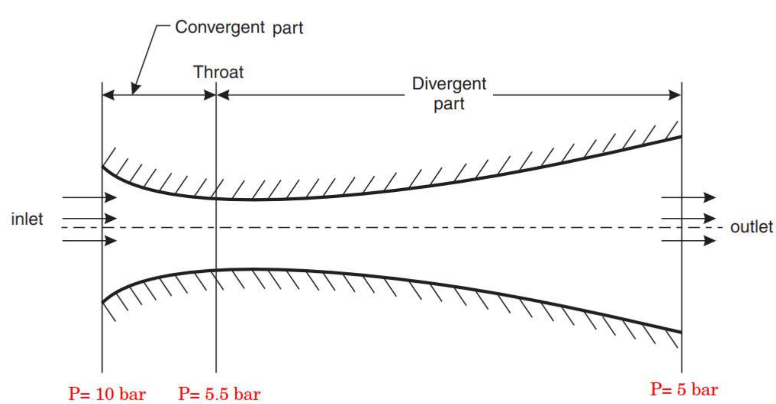
Since the condition is superheated, the value of **n** is **1.3**

We know that,

$$\frac{P_2}{P_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \rightarrow \frac{P_2}{10} = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}}$$

$$P_2 = 0.545 \approx 5.5\ \text{bar}$$

Since throat pressure (P_2) is greater than the exit pressure (P_3), the nozzle used is convergent-divergent type. The minimum area will be at throat, where the pressure is 5.5 bar.



State 2) P_2 = 5.5 bar, $s_2 = s_1$ = 6.695 kJ/kg. K

Since s_2 (6.695 kJ/kg. K) < s_g (6.790 kJ/kg. K) the condition is wet steam (Water+steam)

$s_{fg} = 4.893\ \text{kJ/kg.K}$ and $s_f = 1.897\ \text{kJ/kg.K}$ [from steam table]

$h_{fg} = 2097$ kJ/kg and $h_f = 656$ kJ/kg [from steam table]

$$v_g = 0.3427 \text{ m}^3/\text{kg}$$

$$v_f = 0.00109 \text{ m}^3/\text{kg}$$

$$s_2 = s_f + x_2(s_{fg}) \rightarrow 6.695 = 1.897 + x_2\,(4.893)$$

$$x_2 = \frac{6.695 - 1.897}{4.893} = 0.98$$

$$\therefore\ h_2 = h_f + x_2(h_{fg}) \rightarrow h_2 = 656 + 0.98(2097) = 2711.06 \text{ kJ/kg}$$

$$v_2 = v_f + x_2 v_{fg} = v_f + x_2(v_g - v_f)$$

$$v_2 = 0.00109 + 0.98(0.3427 - 0.00109) \text{ m}^3/\text{kg}$$

$$v_2 = 0.3358 \text{ m}^3/\text{kg}$$

$$C_2 = 44.72\sqrt{(h_1 - h_2)}$$

$$C_2 = 44.72\sqrt{(2829 - 2711.06)}$$

$$C_2 = 485.6 \text{ m/s}$$

$$\dot{m} = \frac{A_2 \times C_2}{v_2} \rightarrow A_2 = \frac{\dot{m} \times v_2}{C_2} \rightarrow A_2 = \frac{3 \times 0.3358}{485.6}$$

$$A_2 = 0.00021\ m^2$$