Condenser

Purpose of the condenser plant

In steam turbines, the condensation of the steam essentially has the following purposes:

- Transformation of the working medium (steam) into an state of aggregation (water) which allows a pressure increase (boiler inlet pressure) with a relative small expenditure of energy. When the steam has completed its work in the turbine and before it can be returned to the boiler, it is necessary to change it back into water. The volume of water is much less than the volume of equal quantity of steam and therefore the work involved in handling the condensate is much less than the steam. This is the duty the condenser must perform as efficiently as possible and, for this reason, it is the largest and most important of the heat exchangers in a power station. The heat in the exhaust steam, which can no longer be converted into mechanical energy, must be transferred from the steam to the cooling water. Though it is valuable energy that has to be rejected, but Thermodynamics laws dictate that to get some useful work done by a system, one would need a sink for heat rejection and therefore it becomes a necessity for the power plant.

- Expansion of the steam to as low a pressure level as possible, near vacuum, in order to exploit the thermal gradient of the steam as completely as possible. Absolute pressures of 0.03 to 0.01 bar are common, depending on cooling water condition and cooling processes.

- Removal of the condensation heat of the steam leaving the turbine and discharge of the condensate without further reduction in temperature. Only the remaining latent heat of evaporation should be extracted in the condenser plant, but the condensate temperature should not be additionally reduced. The condensate is fed to the steam generator (water/steam circuit) through a condensate extraction pump.

The increase of the thermal gradient (enthalpy gradient) can be read in the "h, s - diagram". It is achieved by the expansion of the negative pressure (as compared to outside gage pressure).
If a live steam condition of 160 bar/530 °C is presupposed, the adiabatic thermal gradient
h_{ad} = 1065 kJ/ kg at an expansion to 1.013 bar (open exhaust operation), whereas
h_{ad} = 1450 KJ/ kg at an expansion to 0.04 bar

Hence, it is possible to attain a higher output with the same quantity of steam in a condensing turbine.

Condenser types

There are two types of condensers:

- Direct – Contact condensers / jet condensers, and
- Surface condenser

Surface condensers are used almost exclusively in power plants.

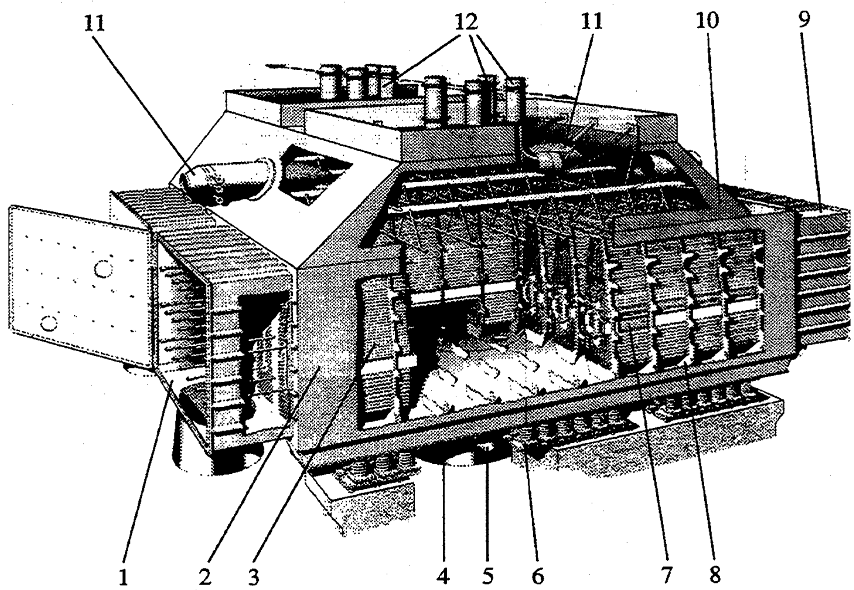
Jet condensers

Function: in a direct-contact or jet condenser, the exhaust steam is condensed by means of a jet of cold condensate. The jet heats up due to the released evaporation heat and mixes with the circuit condensate.

Condenser

Surface condenser

Function: in a surface condenser (shown in figure below), the steam does not get mixed with the cooling water. The evaporation heat of the exhaust steam is removed by the cooling agent separated from the steam (water or air are used as cooling agents). This process is called "surface cooling".



1. water chamber inlet
2. steam chamber
3. tube bundle
4. condensate receiver
5. condensate extraction
6. spring support
7. air cooler
8. support plate
9. water chamber outlet
10. exhaust steam casing
11. bypass steam inlet
12. extraction lines

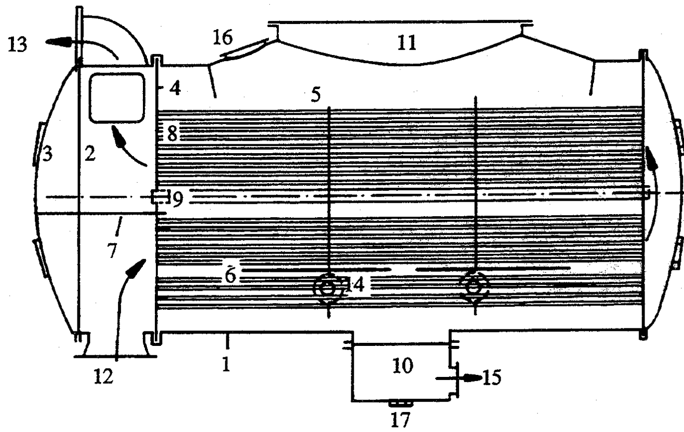
Surface Condenser

Main components of a surface condenser

- Depending on their size, surface condensers consist of a cylindrical, oval or rectangular casing.
- Inside the casing, tubes run in horizontal direction and the cooling water flows through them.
- At both ends, the condenser tubes are firmly rolled into so-called tube bottoms, or even welded-in if the tubes are made of titanium.
- In the condenser, the tubes are arranged irregularly, so that in fact wide, tube-free channels (steam channels) in steam flow direction are available.
- Over their whole length, the tubes are led at intervals through vertical support plates. The plates serve for supporting and preventing the tubes from vibrating.
- Baffle plates between the tube banks collect the dropping condensate and deliver it to the condensate collecting tank (hotwell). Thus, the condensate cannot drop on further cooling tubes, which would lead to under-cooling the condensate.

There are water chambers at both ends of the condenser, into which the cooling water tubes inside the condenser run. One of the chambers is divided horizontally into two halves: Out of the lower half, the "cold" cooling water streams into the condenser. In the upper half, the warmed-up cooling water flows back out of the condenser. The water chamber at the lower end connects both of the flows. In order to make various cooling water flow configurations possible, the water chambers can be compartmented additionally by vertical partition walls as shown in figure below.
Large condensers are generally divided into two separate systems. Thus, it is possible to inspect one half of the condenser and, if necessary, to repair it while the turbine is being operated

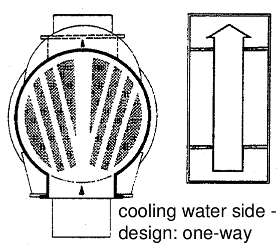
Condenser

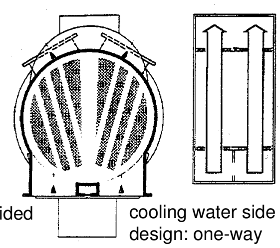


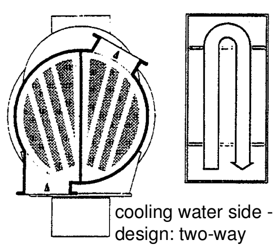
1. shell
2. water chamber
3. water box cover
4. tube plate
5. supporting plate
6. baffle plate
7. partition wall
8. cooling tubes
9. anchor
10. condensate header
11. steam inlet connection
12. cooling water inlet connection
13. cooling water outlet connection
14. air extraction connection
15. condensate outlet connection
16. manhole
17. drain connection

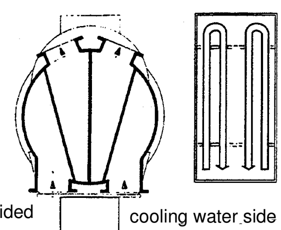
Condenser - longitudinal section

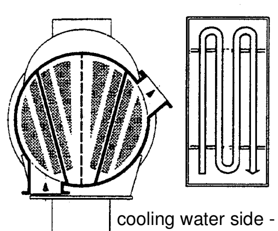
Section through the front water chamber (view direction towards tube bottom)/ Configuration of water paths (condenser in horizontal section) are shown in the figure below.

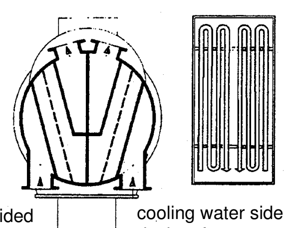

cooling water side - undivided
design: one-way


cooling water side - divided
design: one-way


cooling water side - undivided
design: two-way


cooling water side - divided
design: two-way


cooling water side - undivided
design: four-way


cooling water side - divided
design: four-way

Operating principle of a condenser

A steam turbine works with a surface condenser.
The heat exchange from steam to cooling water takes place via the surface of the cooling water tubes.

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Here, the evaporation heat is removed from the steam.

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The steam turns into liquid condensate, by which a vacuum, i.e. a negative pressure, is created in the condenser due to the different volumes.
In order to achieve the condensation effect, the air in the condenser must be extracted first. During operation, too, the air penetrating into the condenser must be extracted.
The absolute pressure in the condenser is in a fixed proportion to the specific temperature of the steam chamber and of the condensates.
This temperature depends on:

- the heat quantity, i.e. the heat content of the steam getting into the condenser,
- the cooling water inlet temperature,
- the cooling water outlet temperature resulting therefrom,
- the cooling surface,
- the heat transfer coefficient

In order to pass the heat of the steam over the cooling water, a temperature gradient is necessary, i.e. the temperature of the steam must be higher than the cooling water outlet temperature

The difference between the exhaust steam temperature or the condensate temperature and the cooling water outlet temperature is called "**terminal temperature difference**" (TTD). It is generally between 3 °C and 5 °C.
The cooling water is warmed up by approximately 8 °C. 50 to 70 times the steam quantity is taken as a basis for the cooling water quantity.
The terminal temperature difference and the warming up of the cooling water are indicators, showing whether a condenser is working flawlessly.

The following examples indicate possible malfunctions (no general values):

ϑ_{We} = 20 °C ϑ_{Wa} = 35 °C ϑ_{D} = 38 °C	The cooling water quantity is too small since the warming up is too high.
ϑ_{We} = 20 °C ϑ_{Wa} = 28 °C ϑ_{D} = 36 °C	The terminal temperature difference is too great. Possible reasons: cooling water tubes are impured at the inside or air ingress.
ϑ_{We} = 20 °C ϑ_{Wa} = 33 °C ϑ_{D} = 40 °C	The cooling water quantity is too small, the terminal temperature difference is too great.
ϑ_{k} = 18 °C ϑ_{D} = 22 °C	The condensate is undercooled, the condensate level is too high and reaches the cooling water tubes.

Protective devices for operating troubles
Increasing pressure in the condensate (e.g. collapse of vacuum):
Protection is provided by rupture disks: If all other protective devices fail and the pressure increases beyond the admissible value in the exhaust steam connection, the force acting on a shear plate bursts a membrane made of a thin flat lead foil, allowing the steam to escape.

Air extraction

In a condensing turbine, the steam pressures in the condenser and in some other sections of the plant are below the atmospheric pressure. Despite careful sealing, a certain air ingress cannot be prevented.

Effects of Air ingress:
Air in the condenser causes a deterioration of heat tranfer.
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Condenser

The terminal temperature difference increases.

⇩

The absolute pressure in the condenser increases in correspondence with the higher saturated steam temperature.

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Air must be extracted.

Ingress of non-condensable gases:
The gases come with the steam into the condenser. They must be extracted in order to prevent the pressure from rising. If they are not extracted, the turbine output drops although the same quantity of steam is supplied.

Type of Extractors:

- liquid ring compressor (water ring pumps)
- steam jet ejectors
- water jet ejectors
- or: a combination of these units

Condenser Efficiency

The condenser efficiency may be defined as the ratio of temperature rise of cooling water to the difference between the temperature corresponding to vacuum and the inlet temperature of the cooling water.

i.e. $$\eta_c = \frac{\text{Temperature rise of cooling water } (\Delta T_{c.w})}{\text{Sat. Temp. corresponding to abs. pressure - Inlet temp of c.w.}}$$

Mass of cooling water required:
For condensation of steam in condenser, weight of C.W. required may be found out as follows:
Consider total heat lost by exhaust steam in kJ per hour = total heat gained by cooling water in kJ per hour.
Let, W = mass of c.w. required per kg of steam
t_i = Inlet temp. of c.w.
t_o = Outlet temp of c.w.
t_s = Saturation temp. of the exhaust steam corresponding to the vacuum in condenser
t_c = Temp. of condensate leaving the condenser.
x = dryness fraction of entering steam.
h_{fg}= Enthalpy of evaporation of the exhaust steam
K is the specific heat of CW and condensate
Heat lost by 1 kg of steam= $x \times H_{fg} + (t_s - t_c) \times K$ kJ
Heat gained by c.w. = $W (t_o-t_i) \times K$ kJ
$\therefore \quad W (t_o-t_i) \times K = x \times H_{fg} + (t_s - t_c) \times K$
or, $\mathbf{W = \{x \times h_{fg} + (t_s - t_c) \times K\}/ (t_o-t_i) \times K}$

Vacuum Efficiency:
The maximum vacuum or the ideal vacuum in a condenser is the pressure corresponding to the temperature of the exhaust steam entering the condenser. Actual condenser pressure is higher than the ideal by an amount equal to the pressure of air present in the condenser.
The ratio of the actual vacuum to the ideal vacuum is known as vacuum efficiency of a condenser.
η_v = (Barometric Pressure – Actual pressure)/ (Barometric Pressure – ideal pressure)

Dalton's law of Partial Pressure and its application to Condensers:
Dalton's law of partial pressure states that "the total pressure exerted by a mixture of gases or a mixture of gas and vapour is equal to the sum of individual partial pressure of the constituents of the mixture”. Partial Pressure of

each constituent of the mixture is the pressure of the constituent gas if this individual mass of the constituent gas alone occupies total volume occupied by mixture having the same temp of mixture".

The total pressure in the condenser is the sum of the partial pressures of steam and air.
According to Dalton's low of partial pressure:
$\mathbf{P_c = P_s + P_a}$
V = Volume of condenser shell
T = Temperature in the condenser
P_c = Actual total pressure in the condenser
P_s = Partial pressure of steam in condenser
P_a = Partial pressure of air in condenser
m = Total mass of mixture (air steam) in the condenser shell.
m_s = Mass of steam in condenser shell
m_a = Mass of air in condenser shell
v_s = Specific volume of saturated water vapour at temp.T & pressure P_s
v_a = Specific volume of air at temp. T & pressure P_a
$V = m_s v_s = m_a v_a$
$\therefore m_a / m_s = v_s / v_a$
The mass of air per m^3 of the condenser shell
$= m_a / V = 1/ v_a$
and the Mass of Water Vapour per m^3 of the condenser shell
$= M_s/V = 1/ v_s$
The total mass of mixture in the condenser shell,
$m = m_a + m_s \quad = m_a (1 + m_s/m_a)$

$m = m_a (1+ v_a/v_s)$
or
$m = m_s (1+ v_s/v_a)$