Performance of I.C engine

Chapter - 1

Indicated Power (IP)

The energy available to the piston due to expansion of gas.

Brake Power (BP)

It is the energy available at the end of engine shaft. It can be determine by using the break mechanism

Frictional Power (FP)

The energy lost during the converting of indicated power into brake power

$$FP = IP - BP$$

Mechanical efficiency (η_{mech})

$$\eta_m = \frac{\text{Brake Power}}{\text{Indicated power}}$$

It is the ratio of Brake power to indicated power.

Thermal efficiency

It is are of two types.

1. Brake thermal efficiency η_{bth}
2. Indicated thermal efficiency η_{ith}

① Brake thermal efficiency (η_{bth}, $\eta_{overall}$, η_{engine})

$$\eta_{bth} = \frac{\text{Brake Power}}{\text{Heat input per sec}}$$

Indicated thermal efficency.

$$\eta_{ith} = \frac{\text{Indicated power}}{\text{Heat input per sec.}}$$

Heat input per sec

$$= \dot{M}_f \times C.V$$

unit

$$\frac{kg}{sec} \times \frac{kJ}{kg} = \frac{kJ}{sec} = kW$$

where $\dot{M}_f$ = Mass flow rate

C.V = Calorific value of the fuel

Brake thermal efficiency is the over all efficiency or engine efficiency.

Relative efficiency

Relative efficiency of the Ic engine can be defined as the ratio of indicated thermal efficiency to the air standard efficiency

Air standard efficiency means the efficiency of air standard cycle that is otto cycle, diesel cycle and duel cycle.

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Volumatic efficiency

It is the ratio of actual volume of air that entered into the cylinder to the theoritical swept volume.

$$\eta_v = \frac{\text{actual volume}}{\text{Swept volume}} = \frac{V_a}{V_s}$$

V_a can be calculated from ideal gas equation $P_1 V_a = M_a R T_1$

Theoritical swept volume

$$V_s = \frac{\pi}{4} \times d^2 \times L \times K \times \frac{N}{60} \times a$$

where V_s = theoritical swept volume

d = diameter of the cylinder

L = Length of the cylinder

N = speed in rpm

a = depend on the number of stroke.

For two stroke $a = 1$

4 " $a = \frac{1}{2}$

6 " $a = \frac{1}{3}$

8 " $a = \frac{1}{4}$

Air fuel ratio. (AFR)

It is defined as the ratio of mass of air to the mass of fuel enter into the cylinder $AFR = \frac{1}{FAR}$ $\boxed{AFR = \frac{m_a}{m_f}}$

Fuel air ratio (FAR)

The ratio of mass of fuel enter into the cylinder to the mass of air

Dt 20.1.2020

Mean effective pressure

It is an imaginary pressure which will remain constant to gives same workdone as by the actual cycle for the same change in volume.

Assignment - I

How to find molecular mass of air.

Equivalency Ratio (ϕ)

It is defined as the ratio of actual fuel air ratio to the theoritical fuel air ratio

* If $\phi > 1$ then it is rich AFM

$\phi = 1$ then it is perfect AFM

$\phi < 1$ then it is lean AFM

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AFM = Air fuel mixture

Specific fuel consumption

Mathematically

x specific $y = \frac{y}{x}$

Brake specific fuel consuption

$= \frac{\dot{M}F}{BP}$

Indicated specific fuel consuption

$= \frac{\dot{M}_f}{IP}$

→ Brake specific fuel consupation

(B.S.F.C)

It is the ratio between mass of fuel consume to the brake power

→ Indicated specific fuel consuption

(I.S.F.C)

It is the ratio between mass of fuel consume to the indicated power.

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Dt - 22.01.2020

During the test on single cylinder engine working on four stroke cycle, the following readings are taken

Effective diameter of break wheel - 630 mm

Dead load on break - 200 N

Spring balance reading - 30 N

Speed - 450 rpm

Area of indicater diagrame = 420 mm^2

length of indicater diagram = 60 mm

spring scale = 1.1 bar/mm

diameter of cylinder = 100 mm

Strooke = 150mm

quantity of oil used = 0.815 kg/h

calorific value of oil = 42000 KJ/kg

Calculate break power, indicated power, mechanical efficiency, breake thermal efficiency, break specific fuel consumption.

~~breadth~~ ~~width~~ width of indicater diameter

$$= \frac{Area}{length} = \frac{420}{60}$$

$$= 7 \text{ mm}$$

Mean effective pressure

= width × spring scale 7 × 1.1 = 7.7 bar

Brake Power

$$= 2\pi NT = \frac{2\pi N \times wl}{60} \text{ watt} = \frac{2\pi Nwl}{60000} \text{ kW}$$

or $2\pi NT$ watt

N in rps

w = break load in newton

L = length of arm in meter

N = speed of rpm

T = Torque

2π = angle turn in radians through one revolution

Dynamometer is basically torque measuring device. It is used to absorb ~~and~~ power during the period in which engine is tested.

In case of rope brake

without considering the diameter of rope

$$B.P = \frac{(w-s)\pi DN}{60} \text{ watt}$$

Consider the diameter of rope

$$B.P = \frac{(w-s)\pi (D+d) \times N}{60} \text{ watt}$$

$$B.P = \frac{(200-30)\pi 0.630 \times 450}{60}$$

$= 2523.4843$ W

$= 2.523$ kW

Indicated power

$$I.P = \frac{P_m \times LAn \times 10^5 \times k}{60} \text{ watt} = \frac{P_m \times LAn \times 10^2 \times k}{60} \text{ kW}$$

P_m = mean effective pressure in bar

L = length of stroke in meter

A = Area of the piston cylinder

n = Number of working stroke per minute

K = number of cylinder

when P_m is in N/m^2 or Pa

$$I.P = \frac{P_m \times LAn \times k}{60} \text{ watt}$$

$$= \frac{7.7 \times 0.15 \times 7.85 \times 10^{-3} \times \frac{N}{2} \times 1}{60}$$

$$= \frac{7.7 \times 0.15 \times 7.85 \times 10^{-3} \times \frac{450}{2} \times 1}{60}$$

= 3401.75 watt

mechanical efficiency

$$= \frac{B.P}{I.P}$$

$$= \frac{2523.48}{3401.75} = 0.7418 \times 100$$

= 74.18 %

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Brake thermal efficiency

$$= \frac{B.P}{\text{Heat in put per sec}} = \frac{B.P \times 3600}{m_f \times C_v}$$

$$= \frac{2.5232e48 \times 3600}{0.815 \times 42000}$$

~~= 0.265~~ 0.26539

$= 26.539\ \%$

Brake specific fuel consumption

$$= \frac{M_f}{B.P} = \frac{0.815}{2.52} = 0.323\ kg/_{B.P}$$

Dt 27.01.2020

Q1 If the engine diamention of a two cylinder ~~stroke~~ two stroke from the following ~~engine~~

Engine speed - 4000 rpm

volumatic efficiency 0.77

mechanical efficiency = 0.75

mass fuel consumption = 10 lit/h

Sp. gr. = 0.73

air fuel ratio = 18:1

Piston speed = 600 m/min

indicated mean effective = 5 bar

Take R for gas mixture = 281 J/kg K and

s t p = 15 °C NTP = 25 °C

1 bar

Q2 A four stroke petrol engine with a compression ratio of 6.5 to 1 and total piston displacement 5.2×10^{-3} m^3 developes 100 kW break power and consumes 33 kg of petrol per hour of cal. value of 44300 kJ/kg and 3000 rpm.

Find

1. Break mean effective pressure
2. Break thermal efficancy η_{bth}
3. Air standard efficancy ($\gamma = 1.4$)
4. Air fuel ratio by mass

Assume a volumetric efficancy of 80%. 1 kg of petrol vapours occupy 0.26 m^3 at 1.013 bar and 15 °C. take R for air 287 J/kg K

(1 Ans)

Given

$N = 4000$ rpm

$\eta_v = 0.77$

$\eta_m = 0.75$

$M_f = 10$ ltrs/hr $= 10 \times 0.73 = 7.3$ kg/hr

sp. gr. $= 0.73$

AFR $= 18:1$

piston speed

$= 2L \times N$

$600 = 2 \times L \times 4000$

$L = \frac{600}{2 \times 4000}$

$= 0.075$ m

$= 75$ mm

$\eta_v = \frac{V_a}{V_s}$

$V_a = \frac{M_a R T}{P} = \frac{2.19 \times 281 \times 288}{10^5}$

$= 1.77 \; m^3/min$

$AFR = \frac{M_a}{M_f} = \frac{18}{1}$

$M_a = 18 \times M_f$

$= 18 \times 7.3$

$= 131.4$ kg/h $= \frac{131.4}{60}$ kg/min

$= 2.19$ kg/min

$V_s = \frac{\pi}{4} D^2 \times L \times k \times \frac{N}{60} \times a$

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$$V_s = \frac{\pi}{4}(D)^2 \times 0.075 \times 2 \times \frac{4000}{60} \times 1$$

$$V_s = 7.85\,(D)^2 \ m^3/sec$$

$$= 7.85 \times 60$$

$$= 471\,D^2 \ m^3/min$$

$$\eta_v = \frac{V_a}{V_s}$$

$$V_s = \frac{V_a}{\eta_v}$$

$$471\,D^2 = \frac{1.77}{0.77}$$

$$D^2 = \frac{2.29}{471}$$

$$D = \sqrt{4.88 \times 10^{-3}}$$

$$= 0.069857 \ m$$

$$= 69.857 \ mm$$

$$I.P = \frac{P_m \times L A n \times 100 \times k}{60} \ kW$$

$$= \frac{2.5 \times 10^5 \times 0.075 \times 0.003739 \times 2 \times 4000 \times 2}{60}$$

$$= 18.69 \ kW$$

$$\eta_m = \frac{B.P}{I.P}$$

$$A = \frac{\pi}{4} \times D^2 \quad \cancel{}$$

$$= 0.0037\,39\,m^2$$

$$BP = 18.69 \times 0.75$$

$$= 14.0175$$

Chapter -2

Air Compressor

Air compressor

It is a machine which compress the air and raise it's pressure. Compressed air is used for

1. Pneumatic drills
2. Paint spraying
3. In starting and supercharging of internal combustion engines.
4. Jet engines

Classification of air compressors

According to working

1. Reseprocating 2. Rotary

According to number of stages.

1. single stage 2. multi stage

According to action

1. single acting 2. Double acting

Termenology

Inlet Pressure

It is the pressure at which air enter into the compressor.

Outlet / discharge pressure

It is the pressure at which air exit from the compressor.

Compression Radio or Pressure Radio

* The radio must be greater then one

Pressur radio my be defined as the radio of discharge pressure to inlet pressure.

Compresser Capacity

It can be defined as the volume of air delivered by the compresser.

unit m^3/min or m^3/sec

Free air delivery

It is the actual volume delivered by the compresser at NTP (Normal Temperature and pressure)

Swept volume

It is the volume of air sucked by the compresser.

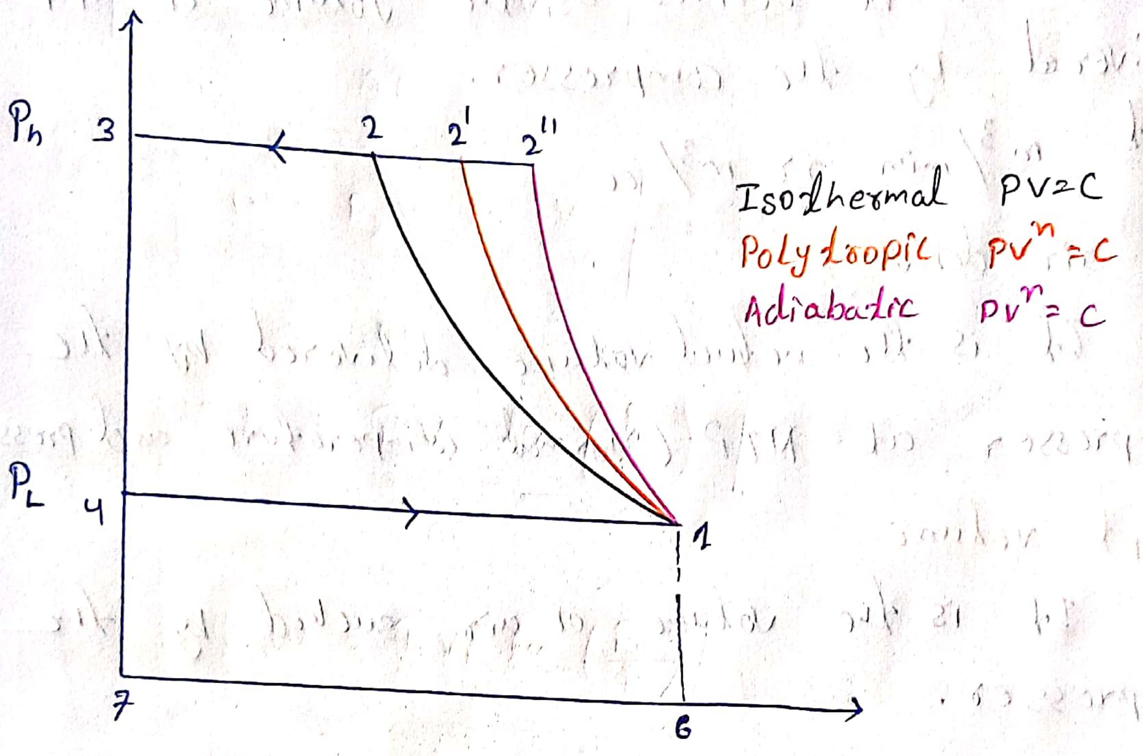
$\frac{\pi}{4} d^2 \times l$ $a^2 \times l$ $ab \times l$

cylinderical   square   rectangular.

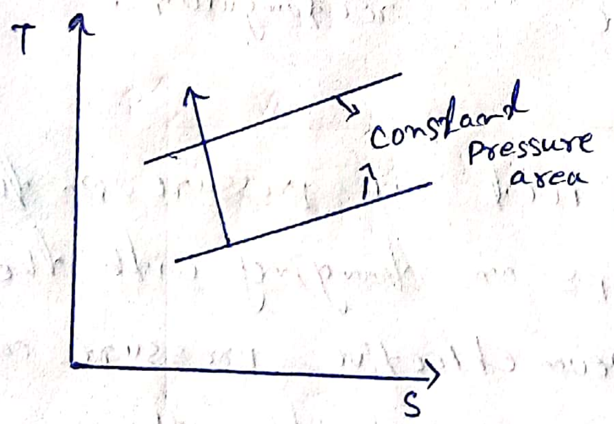
Mean effective pressure

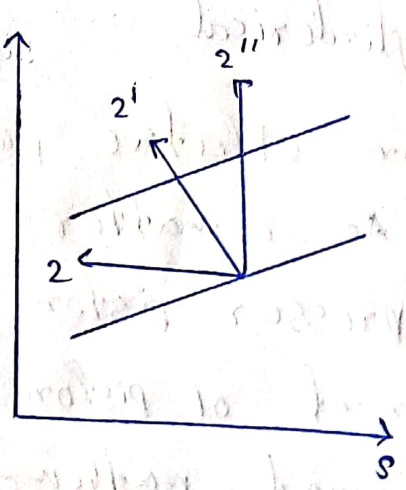
As a matter of fact air pressure on the compresser piston keeps on changing with the moment of piston. Mean effective pressure can be found mathematicaly by dividing the work done per cycle to the swept volume or stroke volume.

Work done of a single stage Reciprocating Compressor without clearance volume   03.02.2020



Area under the PV digram = Work done

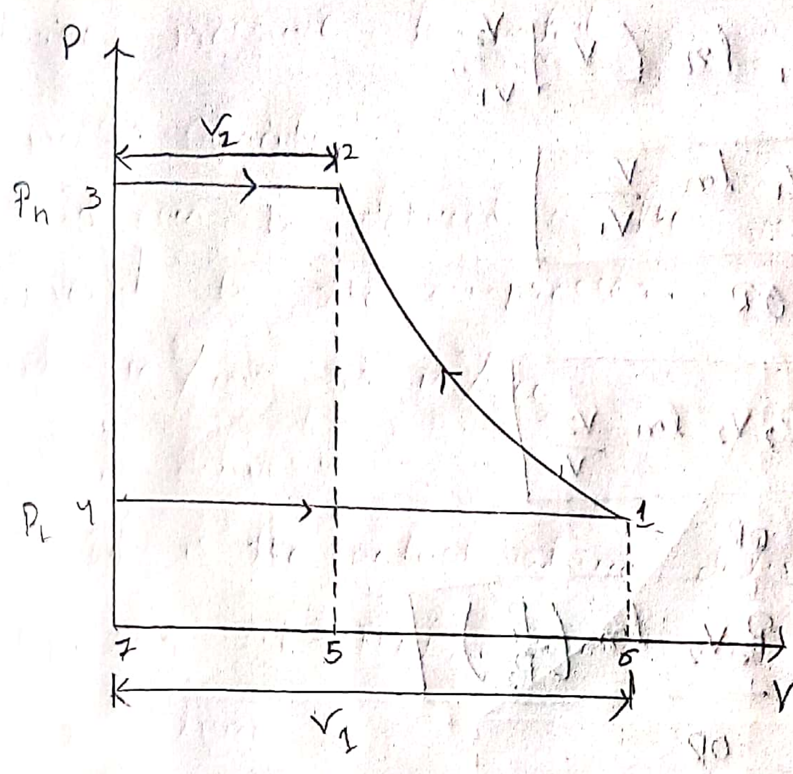




Work done in isothermal process

W = Area 12341

= Area 234752 + Area 25612 − Area 147561



$P_L = P_1 = P_4$

Pressure before compression

$P_h = P_2 = P_3$

Pressure after compression

$P_2 > P_1$

V_1 = volume before compression

V_2 = volume after compression

$$W = P_2 V_2 + P_2 V_2 \ln\left(\frac{V_2}{V_1}\right) - P_1 V_1$$

$$P_1 V_1 = P_2 V_2 = PV = C$$

$$\Rightarrow P_1 V_1 = PV$$

$$\Rightarrow P = P_1 \left(\frac{V_1}{V}\right) \qquad \left[\frac{V_2}{V_1} = \frac{P_1}{P_2}\right]$$

$$W = \int P\,dv$$

$$= P_1 \int \frac{V_1}{V}\,dv$$

$$= P_1 V_1 \int \frac{dv}{V}$$

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$$w = P_1 V_1 \ln [V]_{V_1}^{V_2}$$

$$\boxed{W = P_1 V_1 \ln \frac{V_2}{V_1}}$$

OR

$$\boxed{W = P_2 V_2 \ln \frac{V_2}{V_1}}$$

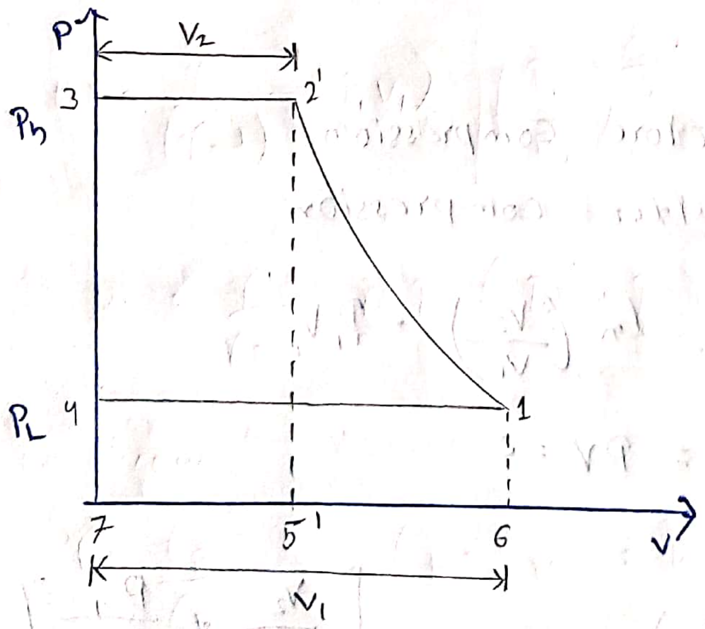
OR

$$\boxed{W = P_2 V_2 \ln \left(\frac{P_1}{P_2}\right)}$$

OR

$$\boxed{W = P_1 V_1 \ln \left(\frac{P_1}{P_2}\right)}$$

Polytropic Process



W = Area 12'341

= Area 2'3475'2' + Area 2'5'612'

- Area 1475'61

$$W = P_2V_2 + \frac{P_2V_2 - P_1V_1}{n-1} - P_1V_1$$

$$= \frac{P_2V_2(n-1) + P_2V_2 - P_1V_1 - (n-1)P_1V_1}{(n-1)}$$

$$= \frac{n(P_2V_2) - n(P_1V_1)}{n-1}$$

$$\boxed{W = \frac{n}{(n-1)}(P_2V_2 - P_1V_1)}$$

$$W = \frac{n}{(n-1)} P_1V_1 \left(\frac{P_2V_2}{P_1V_1} - 1\right)$$

we know

$$P_1V_1^n = P_2V_2^n$$

$$\frac{T_2}{T} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}$$

$$\Rightarrow \left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} = \frac{V_1}{V_2}$$

$$W = \frac{n}{n-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)\left(\frac{P_2}{P_1}\right)^{\frac{1}{2}} - 1\right]$$

$$\boxed{W = \frac{n}{n-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]}$$

$$W = \frac{n}{n-1}(mRT)\left[\frac{T_2}{T_1} - 1\right]$$

$$\boxed{W = \frac{n}{n-1}(mR(T_2 - T_1)}$$

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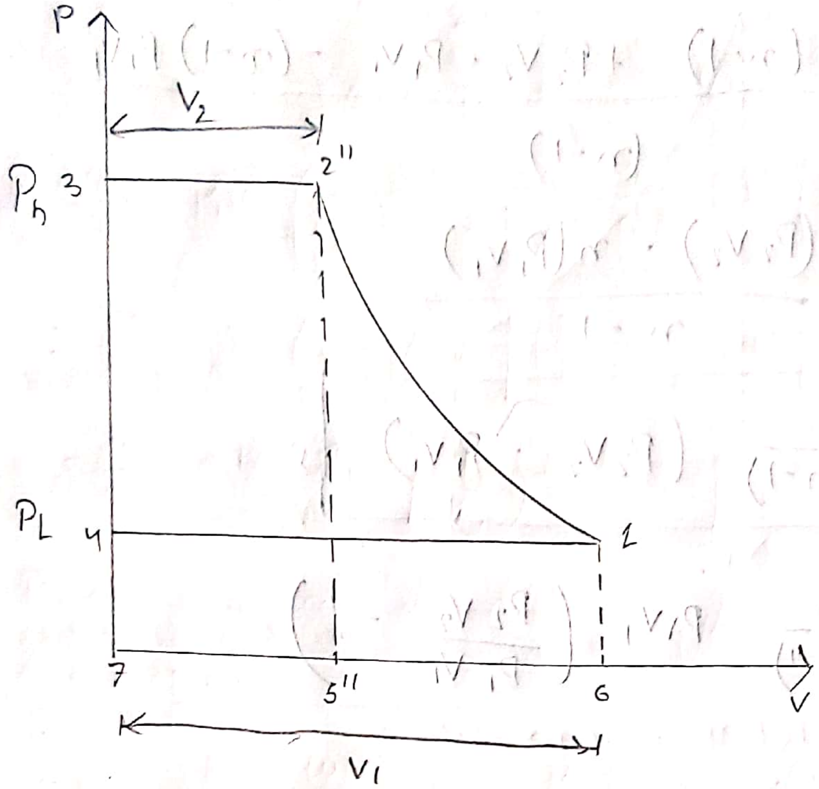
For Isoentropic Compression



$$W = \frac{\gamma}{(\gamma-1)}(P_2V_2 - P_1V_1)$$

$$W = \frac{\gamma}{(\gamma-1)}(P_1V_1)\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$W = \frac{\gamma}{\gamma-1} mR(T_2 - T_1)$$

we know

$$\gamma = \frac{C_p}{C_v} \qquad C_p - C_v = R$$

$$C_p\left(1 - \frac{C_v}{C_p}\right) = R$$

$$C_p\left(1 - \frac{1}{\gamma}\right) = R$$

$$C_p\left(\frac{\gamma-1}{\gamma}\right) = R$$

$$w = \frac{\gamma}{\gamma - 1} \, m C_p \left(\frac{\gamma - 1}{\gamma} \right) (T_2 - T_1)$$

$$w = m C_p (T_2 - T_1)$$

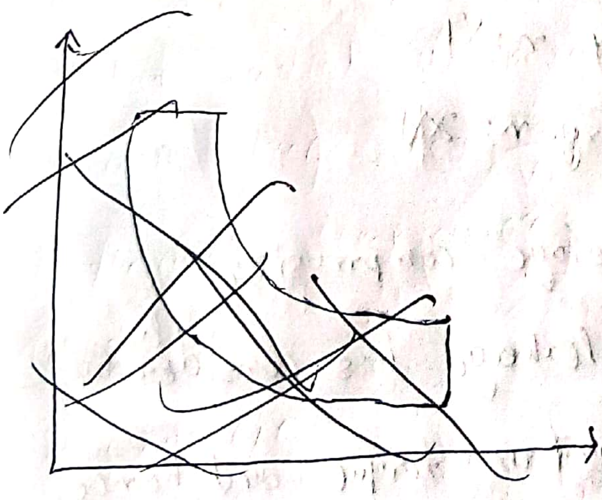
work done during isoentropic compression is equal to the heat required to raise the temperature from T_1 to T_2

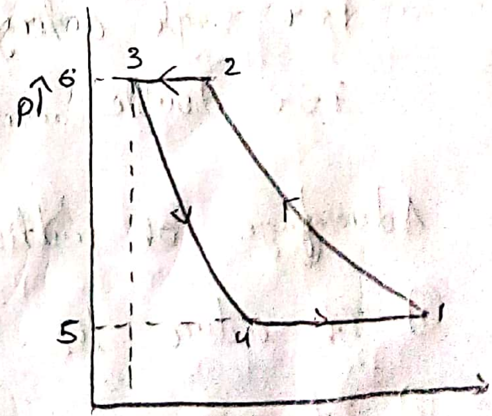
So the work done is minimum when compression process is isothermal

work done is maximum when compression process is adiabatic or isoentropic.

Dt 10.02.2020

work done by reciprocating air compressor with clearance volume





$$Pv^n = c$$

$n = 1 \rightarrow$ Isothermal

$n = \gamma \rightarrow$ adiabatic

Effective swept volume $= V_1 - V_4$

clearance volume $= V_3$

work done = Area under the 1-2-3-4-1

= Area (1-2-3-6-5-4-1)

- Area (3-6-5-4-3)

$$= \frac{n}{n-1} P_1V_1 \left(\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right) - \frac{n}{n-1} P_4V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} P_1 (V_1 - V_4) \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} \times m R T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Power required to drive single stage receprocating compressor

$$P = \frac{w \times n}{60}$$ Unit is watt

where n = no. of working stroke per minite

w = ~~load~~ work done

For single acting n = N

For double acting n = 2N

Advantage of multistage compressior

① It reduce the leakage loss considerably

② It gives more uniform torque and hence a small size flywheel is required

③ It reduces the cost of compressor.

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Chapter - 3 Dt 17.02.2020

Properties of steam

A gas referes to a substance that has a single define thermodynamic state at room temperature.

Vapour

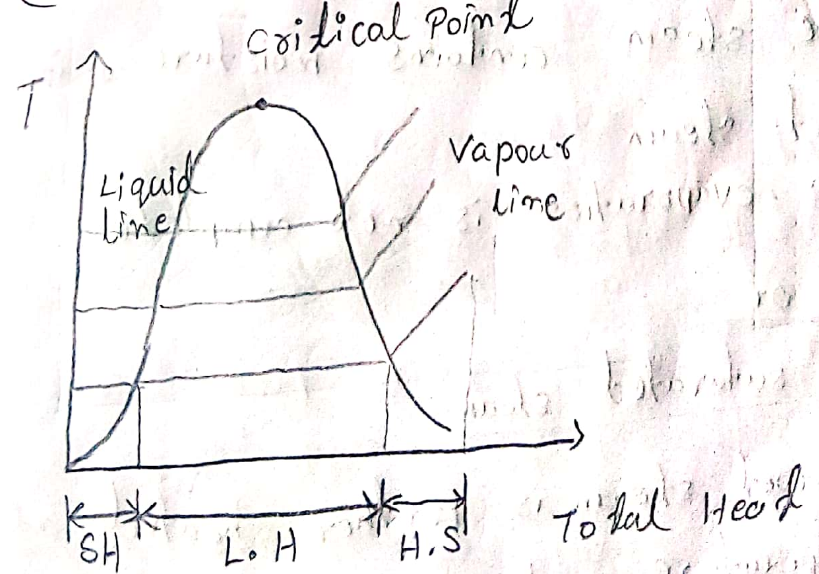
Vapour referes to a substance that is a mixture of two phase at room temperature

Boling temperature of water is 100°C at atmospheric pressure (Atmospheric pressure - 1.01325 bar)

steam

The vapour into which water is converted when heated forming a white mist of minute water droplete or partices in the air.

steam does not obey the ideal gas equation
$(PV = MRT)$



Dt 19.02.2020

Suturated liquid line

The line which forms boundary line between water and steam.

Suturated vapour line

The line which forms boundary line between wet and superheated steam.

Critical point

It is the that point or pressure and temp^r were liquid flashes into vapour or vice-versa

Sensiable heat

Latent heat

heat of super heating

→ **wet steam**

when the steam contains moisture, it is known as wet steam

It mean evaporation is not complete

→ **Dry steam or Dry suturated steam**

when the wet steam is further heated at constant temperature and pressure, it does not contain any moisture or water partical then it is known as dry steam

If mean evaporation is complete and the total latent heat is absorb.

Super heated steam

when the dry steam is forthere heated at constant pressure, it is known as super heated steam. It increase the temperature.

Dryness fraction

$$x = \frac{mg}{mp + mg} = \frac{mg}{m}$$

where

M_f = mass of water in suspention / mass of water particle present in the steam.

x = dryness fraction

M_g = mass of actual dry steam

m = mass of wet steam

$= mg + M_f$

It is the ratio of the mass of the actual dry steam to the mass of same quantity of wet steam It denoted by 'x'. It ranges from 0 to 1.

DA - 26.07.2020

Sensible heat of water

It is the amount of heat absorb by one kg of water when heated at a constant pressure from the freezing ~~point~~ point to the temperature of formation of steam. It is also known as liquid heat.

sensible heat = mass x specific heat x Rise in temperature

$$= 1 \times 4.2 \left[(t+273) - (0+273)\right]$$

$\boxed{\text{4.2 is Specific heat of water}}$

Latent heat of vaporization

It is the amount of heat absorb to evaporate one kg of water at it's ~~boiling~~ boil point or saturation temperature with out change in temperature

It is denoted by $h_{fg} = (h_g - h_f)$ and it depends upon pressure, As pressure increases h_{fg} decreases and it vise versa

If the steam is wet with a dryness fraction 'x' then latent heat of vaporisation

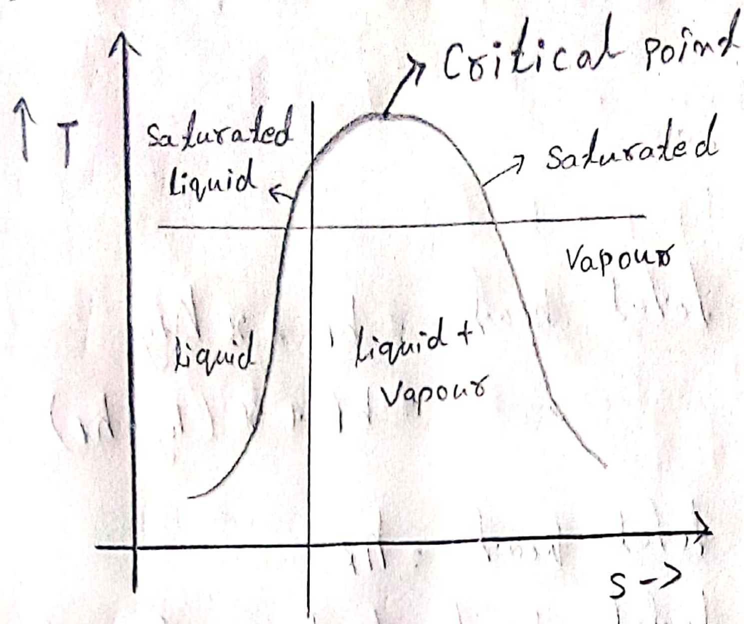
$$= x h_{fg}$$
$$= x(h_g - h_f)$$

Enthalpy or total heat of steam

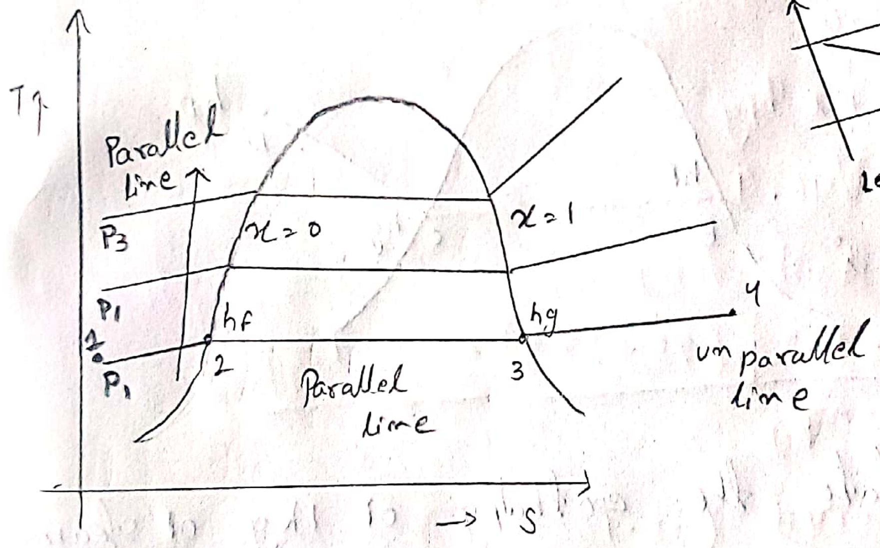
Amount of heat is absobe from freezing point to saturation temprature plus the heat absorve during to evaporation

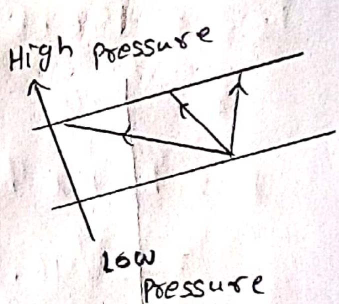
Total heat = sensible heat + Lartent heat

T-s digram



horizontal lines are isothermal lines
vertical lines are isotropic lines or adiabatic line





→ Constant pressure line are parallel in liquid and liquid + vapour region

→ In vapour region constant pressure line are diverging in nature

→ Liquid + vapour region is also known as vapour dome

→ At critical point $h_{fg} = 0$

$h_2 = h_f$

$h_3 = h_g$

wet steam total heat $= h_f + x h_{fg}$

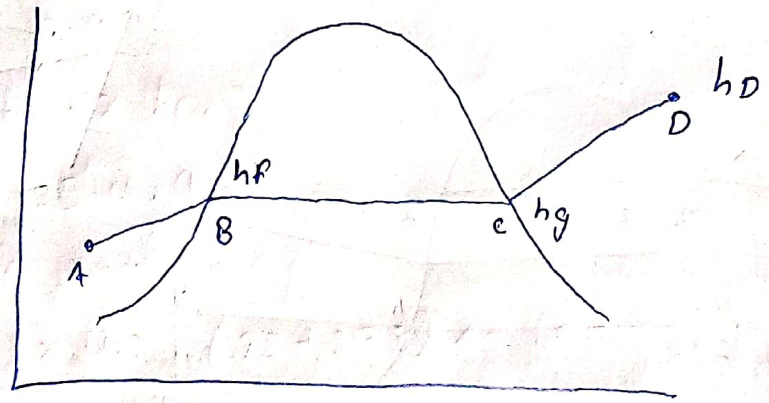
$= h_f + x(h_g - h_f)$

for $x = 0$ total heat $= h_f$

$x = 1$ total heat that is dry steam

$= h_f + h_{fg}$

Dt 2.03.2020



Q Calculate the enthalpy of 1kg of steam at a pressure of 8 bar and dryness fraction of 0.8 how much heat would be required to raise 2kg of steam from water at 20°c

Ans Given

At pressure 8 bar

$h_f = 720.9$ kJ/kg

$h_{fg} = 2046.5$ kJ/kg

$x = 0.8$

$h = h_f + x\, h_{fg}$

$= 720.9 + 0.8 \times 2046.5$

$= 2358.1$ kJ/kg

Sensible $= 1 \times 4.2\ [(20+273)-(0+273)]$

$= 84$

Sensible heat of water

0 - 100

For 1kg $= 2358.1$

sensible heat of water

0 - 20 $= 84$

For 2kg $= 84 \times 2$

$= 166$

For

2kg $= 2358.1 \times 2$

$= 4716.2$ kJ/kg

$(0-100) - (0-20)$

For 2kg $= 4716.2 - 166$

$= 4550.2$ kJ/kg

NB Change in temperature in K scale and calsious scale is same

Q Determine the quantity of heat required to produce 1kg of steam at a pressure of 6 bar at a temperature of 25°c under the following condition.

① when the steam is wet having a $x = 0.9$

② when the steam is dry saturated.

③ when it is super heated at a constant pressure at 250°c assuming the mean specific heat of super heated steam to be 2.3 kJ/kg K

Given

At 6 bar

$h_f = 670.4$ kJ/kg

$h_{fg} = 2085$ kJ/kg

$T_{sat} = 158.8°$

$x = 0.9$

$h = h_f + x\,h_{fg}$

$= 2546.9$

Sensible heat

$= 1 \times 4.2\,[(25+273) - (0+273)]$

$= 105$ kJ

heat required (25-100)

(0-100) - (0-25)

2546.9 - 105

= 2441.9 kJ

(ii) $h_{fg} = (h_g - h_f)$

$h_g = h_{fg} + h_g$

$= 2755.4$ kJ/kg

heat required $(25 - 158.8)$

$= 2755.4 - 105$

$= 2650.4$ KJ

(iii) $h_p = h_g + C_{p\,vap}(T_{sup} - T_{sat})$

$= 2755.4 + 2.3(250 - 158.8)$

$= 2965.16$ KJ

heat required $(25 - 250)$

$= 2965.16 - 105$

$= 2860.16$ Kg

Q steam enter an engine at a pressure of 12 bar with a 67°C super heat it is exhusted at a pressure of 0.15 bar and $x = 0.95$ find the drop in enthalpy of the steam.

Given

$h_f = 798.4$ kJ/kg

$h_{fg} = 1984.3$ kJ/kg

$(T_{sup} - T_{sat}) = 67°C$

$C_{p\,vap} = 2.3$

Entry

$h_D = h_f + h_{fg} + C_{p\,vap}(T_{sup} - T_{sat})$

$= 2936.8$ kJ/kg

Exhusted at (0.15)

$h_f = 226$ kJ/kg

$h_{fg} = 2373.2 \ kJ/kg$

$x = 0.95$

$h = h_f + x h_{fg}$

$= 2480.54 \ kJ/kg$

Drop in enthalpy

$= 2936.8 - 2480.54$

$= 456.26 \ kJ/kg$

Advantage of super heating the steam

→ as it contains more heat the capacity to do work is increased with out increasing the pressure

→ The high temp^r of super heated steam help in increasing the thermal efficancy

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STEAM GENERATOR

1.0. Overview

A boiler is an enclosed vessel in which water is heated and circulated, either as hot water or steam, to produce a source for either heat or power. A central heating plants may have one or more boilers that use gas, oil, or coal as fuel. The steam generated is used to heat buildings, provide hot water, and provide steam for cleaning, sterilizing, cooking, and laundering operations. Small package boilers also provide steam and hot water for small buildings.

1.1. STEAM GENERATION THEORY

To acquaint you with some of the fundamentals underlying the process of steam operation, suppose that you set an open pan of water on the stove and turn on the heat. You find that the heat causes the temperature of the water to increase and, at the same time, to expand in volume. When the temperature reaches the boiling point (212°F or 100°C at sea level), a physical change occurs in the water; the water starts vaporizing. When you hold the temperature at the boiling point long enough, the water continues to vaporize until the pan is dry. A point to remember is that the temperature of water does not increase beyond the boiling point. Even if you add more heat after the water starts to boil, the water cannot get any hotter as long as it remains at the same pressure.

Now suppose you place a tightly fitting lid on the pan of boiling water. The lid prevents the steam from escaping from the pan and this results in a build-up of pressure inside the container. However, when you make an opening in the lid, the steam escapes at the same rate it is generated. As long as water remains in the pan and as long as the pressure remains constant, the temperature of the water and steam remains constant and equal.

The steam boiler operates on the same basic principle as a closed container of boiling water. By way of comparison, it is as true with the boiler as with the closed container that steam formed during boiling tends to push against the water and sides of the vessel. Because of this downward pressure on the surface of the water, a temperature in excess of 212°F is required for boiling. The higher temperature is obtained simply by increasing the supply of heat; therefore, the rules you should remember are as follows:

1. All of the water in a vessel, when held at the boiling point long enough, will change into steam. As long as the pressure is held constant, the temperature of the steam and boiling water remain the same.
2. An increase in pressure results in an increase in the boiling point temperature of water.

A handy formula with a couple of fixed factors will prove this theory. The square root of steam pressure multiplied by 14 plus 198 will give you the steam temperature. When you have 1 psig (pounds per square inch gauge) of steam

pressure, the square root is one times 14 plus 198 which equals 212°F which is the temperature that the water will boil at 1 psig.
The equation for figuring out the steam temperature is:
Let P = Steam Pressure, T = Steam Temperature

$$\sqrt{P} \times 14 + 198 = T$$

There are a number of technical terms used in connection with steam generation. Some
of these commonly used terms you should know are as follows:

- Degree is defined as a measure of heat intensity.
- Temperature is defined as a measure in degrees of sensible heat. The term sensible heat refers to heat that can be measured with a thermometer.
- Heat is a form of energy measured in ***British thermal units (BTU)***. One Btu is the amount of heat required to raise 1 pound of water 1degree Fahrenheit at sea level.
- Steam means water in a vapor state. Dry ***saturated*** steam is steam at the saturation temperature corresponding to pressure, and it contains no water in suspension. Wet saturated steam is steam at the saturation temperature corresponding to pressure, and it contains water particles in suspension.
- The quality of steam is expressed in terms of percent. For instance, if a quantity of wet steam consists of 90 percent steam and 10 percent moisture, the quality of the mixture is 90 percent.
- Superheated steam is steam at a temperature higher than the saturation temperature corresponding to pressure. For example, a boiler may operate at 415 psig (pounds per square inch gauge). The corresponding saturation temperature for this pressure is 483°F, and this will be the temperature of the water in the boiler and the steam in the drum. This steam can be passed through a super-heater where the pressure remains about the same, but the temperature will be increased to some higher figure.

2.0.0 BOILER FITTINGS and ACCESSORIES

A sufficient number of essential boiler fittings (*Figure 9-1*) and accessories are discussed in this section to provide a background for further study. As a reminder, and in case you should run across some unit or device not covered here, check the manufacturer's manual for information on the details of its construction and method of operation.

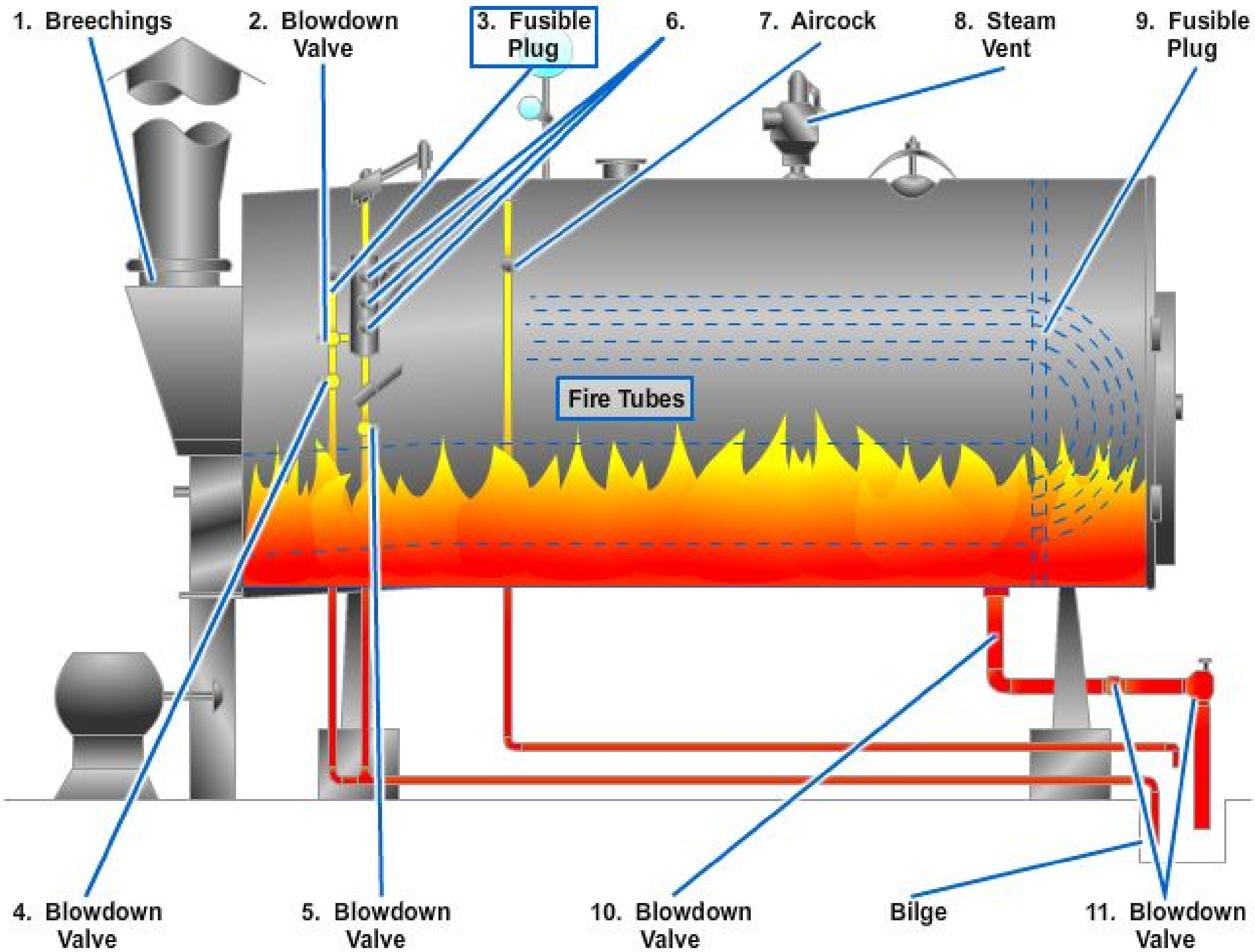


Figure 9-1—Boiler fittings.

The term “fittings” includes various control devices on the boiler. Fittings are vitally important to the economy of operation and safety of personnel and equipment. You must understand fittings if you are to acquire skill in the installation, operation, and servicing of steam boilers.

All boilers require boiler fittings to operate safely. The American Society of Mechanical Engineers (ASME) requires all boiler fittings to be made of materials that withstand the pressure and temperatures that boilers are subject to. All of the boiler fittings discussed are important and must be operated and maintained properly to operate a boiler safely.

2.1.0 Air Cock

An air cock is located in the uppermost steam space of a boiler, as shown in *Figure 9-2*. This design allows for air to enter and escape during filling and draining of the boiler. Before firing a cold boiler with no steam pressure, open the air cock to allow air to escape during the heating of the water. When steam begins to come out of the air cock piping, close the valve.

2.2.0 Chimneys, Draft Fans, and Breechings

Chimneys are necessary for discharging the products of combustion at an elevation high enough to comply with health requirements and to prevent a nuisance because of low-flying smoke, soot, and ash. A boiler needs a draft to mix air correctly with the fuel supply and to conduct the flue gases through the complete setting. The air necessary for combustion of fuel cannot be supplied normally by a natural draft. Therefore, draft fans may be used to ensure that the air requirements are properly attained. Two types of draft fans used on boilers are forced-draft and induced-draft fans. They are damper controlled and usually are driven by an electric motor.

Figure 9-2 — Aircock.

The forced draft fan forces air through the fuel bed, or fuel oil burner, and into the furnace to supply air for combustion. The induced draft fan draws gases through the setting, thus facilitating their removal through the stack. Breechings (see Item 1 in *Figure 9-1*) are used to connect the boiler to the stack. They are usually made of sheet steel with provision for expansion and contraction. The breeching may be carried over the boilers, in back of the setting, or even under the boiler room floor. Keep breechings as short as possible and free from sharp bends and abrupt changes in area. The cross-sectional area should be approximately 20 percent greater than that of the stack to keep draft loss to a minimum. A breeching with a circular cross section causes less draft loss than one with a rectangular or square cross section.

2.3.0 Blowdown Valves

Blowdown valves on boilers are located on the water column and on the lowest point of the water spaces of the boiler (*Figure 9-3*). The blowdown valves on a boiler installed at the bottom of each water drum and header are used to remove scale and other foreign matter that have settled in the lowest part of the water spaces. Boilers are also blown down to control concentration of dissolved and suspended solids in boiler water. The water column blowdown permits removal of scale and sediments from the water column. Additionally, some boilers have what is called a surface blowdown. The surface blowdown is located at the approximate water level so as to discharge partial steam and water. The surface blowdown removes

Figure 9-3 — Blowdown valve.

foaming on the top of the water surface and any impurities that are on the surface of the water.

2.4.0 Fusible Plugs

Fusible plugs are used on some boilers to provide added protection against low water. They are constructed of bronze or brass with a tapered hole drilled lengthwise through the plug. They have an even taper from end to end. This tapered hole is filled with a low-melting alloy consisting mostly of tin. There are two types of fusible plugs—fire actuated and steam actuated.

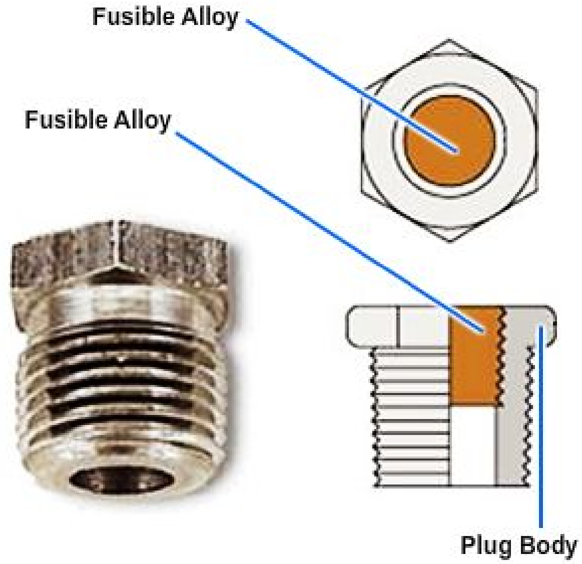


Figure 9-4 — Fusible plug.

The fire-actuated plug is filled with an alloy of tin, copper, and lead with a melting point of 445°F to 450°F. It is screwed into the shell at the lowest permissible water level. One side of the plug is in contact with the fire or hot gases, and the other side is in contact with the water (*Figure 9-4*). As long as the plug is covered with water, the tin does not melt. When the water level drops below the plug, the tin melts and blows out. Once the core is blown out, a whistling noise will warn the operator. The boiler then must be taken out of service to replace the plug.

The steam-actuated plug is installed on the end of a pipe outside the drum. The other end of the pipe, which is open, is at the lowest permissible water level in the steam drum. A valve is usually installed between the plug and the drum. The metal in the plug melts at a temperature below that of the steam in the boiler. The pipe is small enough to prevent water from circulating in it. The water around the plug is much cooler than the water in the boiler as long as the end of the pipe is below the water level. However, when the water level drops below the open end of the pipe, the cool water runs out of the pipe and steam heats the plug. The hot steam melts and blows the tin out, allowing steam to escape from the boiler warning the operator. This type of plug can be replaced by closing the valve in the piping. It is not necessary to take the boiler out of service to replace the plug.

Fusible plugs should be renewed regularly once a year. Do NOT refill old casings with new tin alloy and use again. ALWAYS USE A NEW PLUG.

2.5.0 Water Column

A water column is a hollow vessel having two connections to the boiler (*Figure 9-5*). Water columns come in many more designs than the two shown in *Figure 9-5*; however, they all operate to accomplish the same principle. The top connection enters the steam drum of the boiler through the top of the shell or drum. The water connection enters the shell or head at least 6 inches below the lowest permissible water level. The purpose of the water column is to steady the water level in the gauge glass through the reservoir capacity of the column. Also, the column may eliminate the obstruction on small diameter, gauge-glass connections by serving as a sediment chamber.

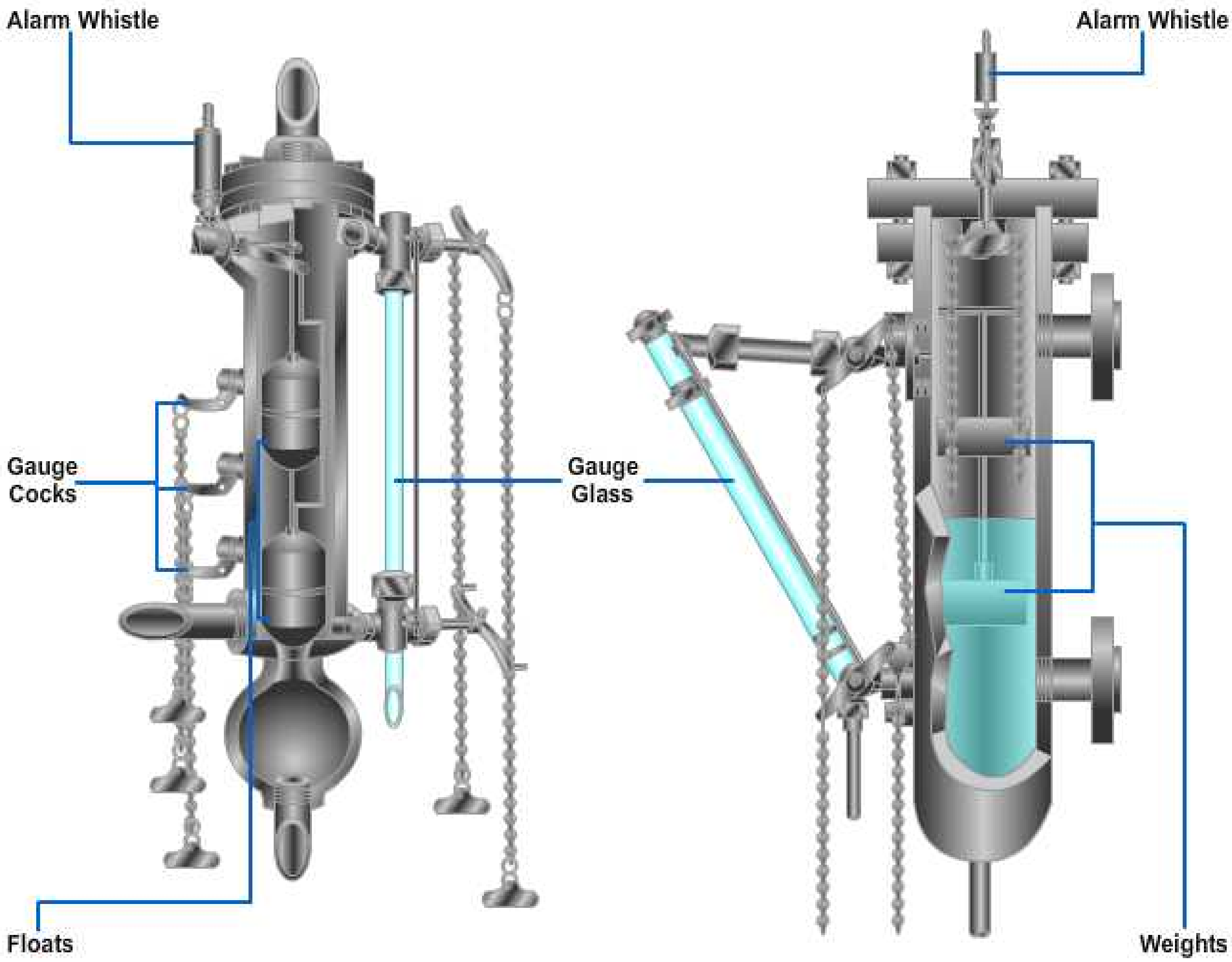


Figure 9-5—Typical water columns.

The water columns shown are equipped with high- and low-water alarms that sounds a whistle to warn the operator. The whistle is operated by either of the two floats or the solid weights shown in *Figure 9-5*.

2.5.1 Water Level Control

The water level control not only automatically operates the boiler feed pump but also safeguards the boiler against low water by stopping the burner. Various types of water level controls are used on boilers. At Seabee activities, boilers frequently are equipped with a float-operated type, a combination float and mercury switch type, or an electrode probe type of automatic water level control. Each of these types is described below.

The float-operated type of feedwater control, similar in design to the feedwater control shown in *Figure 9-6*, is attached to the water column. This control uses a float, an arm, and a set of electrical contacts. As a low-water cutoff, the float rises or lowers with the water level in an enclosed chamber. The chamber is connected to the boiler by two lines, a setup which allows the water and steam to have the same level in the float chamber as in the boiler. An arm and linkage connects the float to a set of electrical contacts that operate the feedwater pump when the water lowers the float. When the water supply fails or the pump becomes inoperative and allows the water level to continue to drop, another set of contacts operates an alarm bell, buzzer, or whistle, and secures the burners.

The combination float and mercury switch type of water level control shown in *Figure 9-6, Frame 1* reacts to changes made within a maintained water level by breaking or making a complete control circuit to the feedwater pump. It is a simple two-position type control, having no modulation or differential adjustment or setting. As all water level controllers should be, it is wired independently from the programmer. The control is mounted at steaming water level and consists of a pressurized float, a pivoted rocker arm, and a cradle-attached mercury switch. The combination float and mercury switch type of water-level control functions as follows: As the water level within the boiler tends to drop, the float lowers. As the float lowers, the position of the mercury switch changes. Once the float drops to a predetermined point, the mercury within the tube runs to its opposite end. This end contains two wire leads, and when the mercury covers both contacts, a circuit is completed to energize the feedwater pump. The pump, being energized, admits water to the boiler. As the water level within the boiler rises, the float rises. As the float rises, the position of the mercury switch changes. Once the float rises to a predetermined point, the mercury runs to the opposite end of its tube, breaking the circuit between the wire leads and securing the feedwater pump. The feedwater pump remains off until the water level again drops low enough to trip the mercury switch.

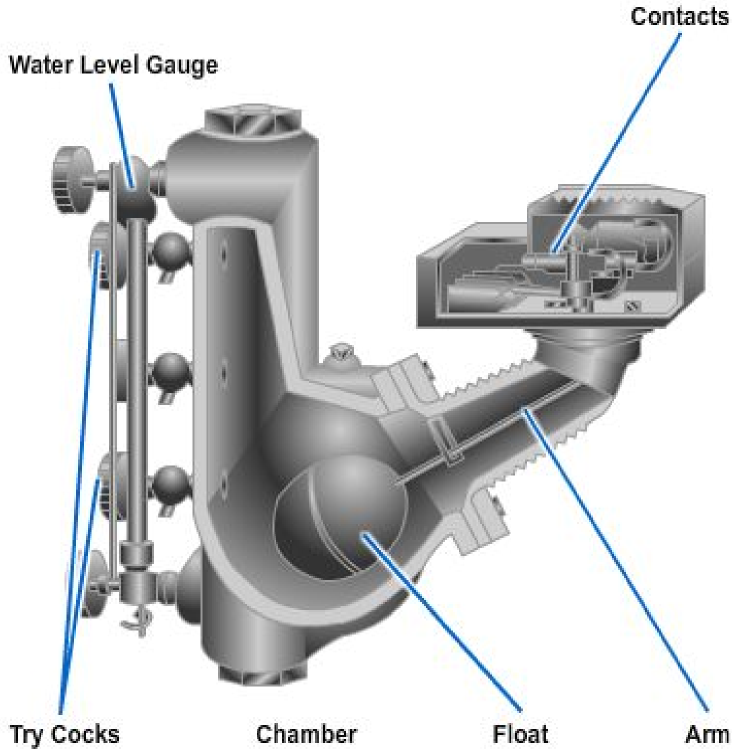


Figure 9-6 — Combination float and mercury switch type of feedwater control.

Because of the hazards associated with mercury, these switches are being phased out. The electrode probe type of feedwater control and low-water cutoff and the solid state (*Figure 9-6, Frame 2*) type of switches are replacing them. The solid state components are controlled by a ground wire connected to the side of the reservoir and a probe that extends into the water column. When the water is at the acceptable level, current is available and the switch remains closed. When the water level drops, the current is reduced and the switch is activated thus turning on the water pump. If the water level drops too far down the probe, the burner cutout switch is activated and the burner will not come on until the water reaches the appropriate level.

The electrode probe type of feedwater control and low-water cutoff consists of an electrode assembly and a water level relay (*Figure 9-7*). The electrode assembly contains three electrodes of different lengths corresponding to high, low, and burner cutout in the boiler drum.

To understand the operation of a boiler circuit, refer to *Figures 9-7*and *9-8* as you read the information in *Table 9-2*. Although this information is not complete, it is presented here to acquaint you with the operation of the electrode type of boiler water-level control.

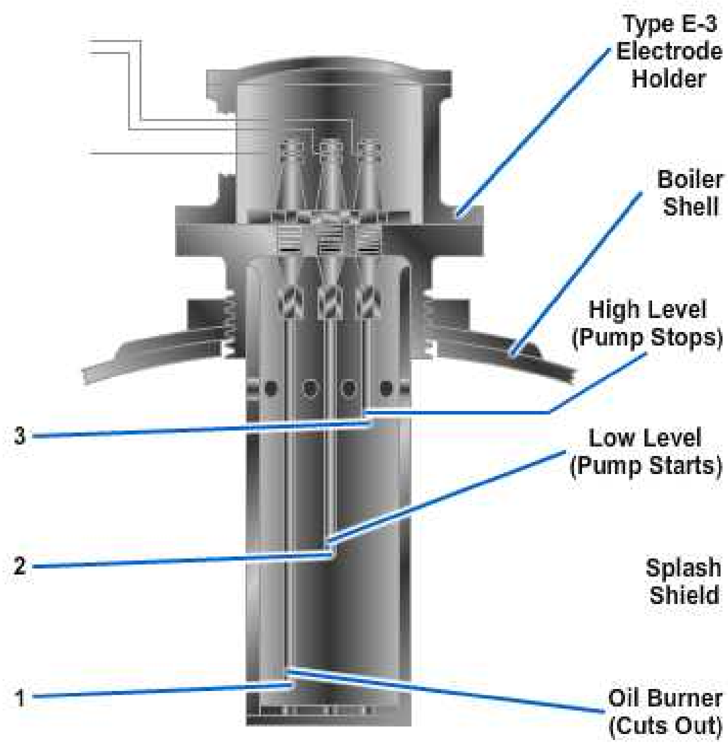


Figure 9-7 — Electrode type of water-level control.

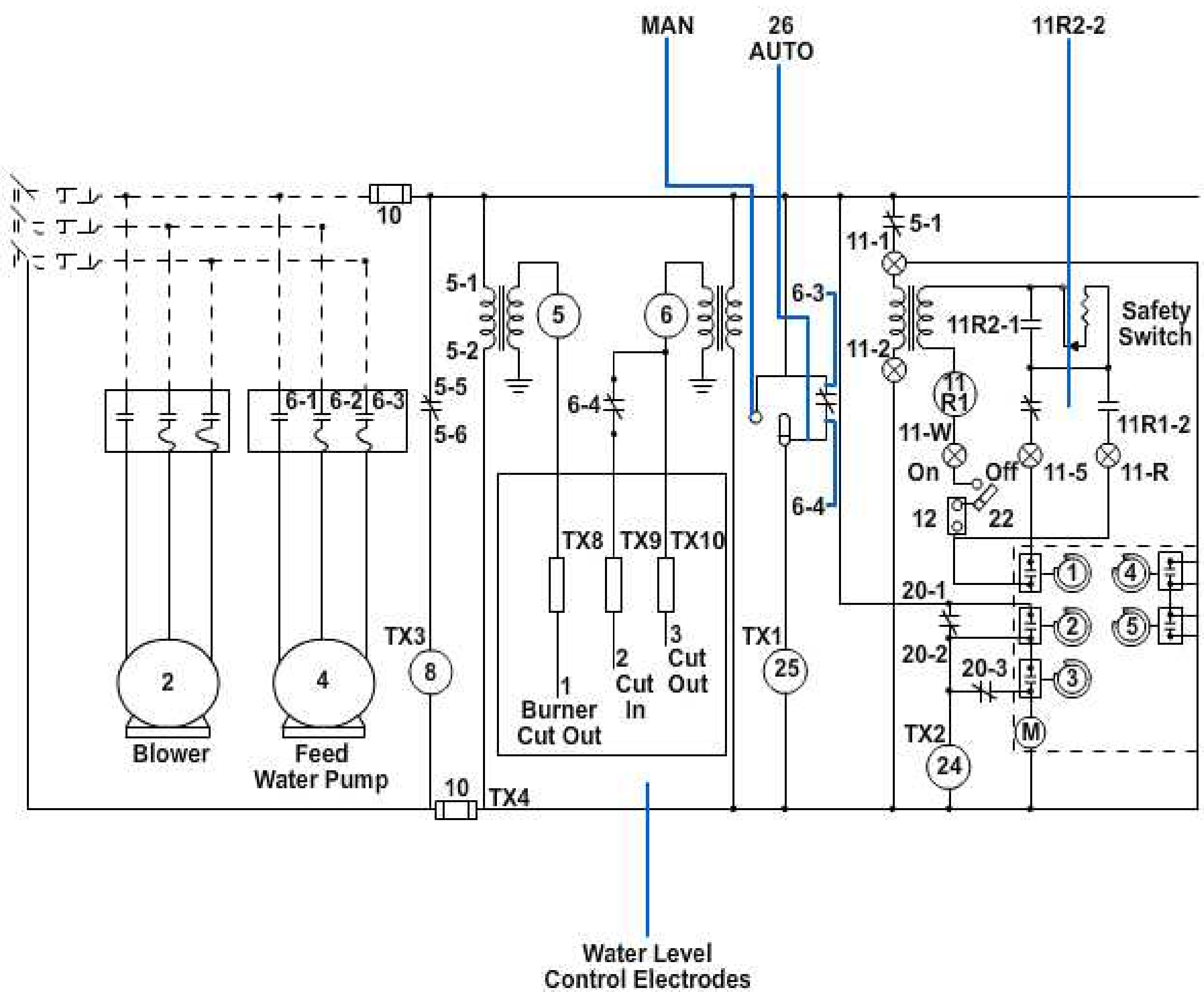


Figure 9-8—Typical boiler circuit.

Table 9-2 — Operation of a boiler circuit.

Operation	Action	Results
When the feed pump switch is in the auto position.	The feed pump motor is energized.	The feed pump will operate under control of the water-level relay.
When the water level in the boiler reaches the level of electrode #3.	The circuit through the electrode is grounded and this completes the circuit.	All of the contacts labeled #6 change positions. The three feed pump contacts that are normally closed, open, and contact 6-4 closes which maintains the grounded circuit through electrode #2.
When the water level falls below electrode #2.	The circuit through relay #6 will no longer be grounded because the water is not in contact with the electrode.	This de-energizes relay #6, so all of the contacts labeled #6 return to their normal positions. Contacts 6-1 through 6-3 close and 6-4 opens. The feedwater pump is energized and water is pumped into the boiler.
When the water level rises again to electrode #3.	Relay #6 will energize again.	The cycle continues and the water level in the boiler is maintained.
When the water level falls below electrode #1.	Relay #5 will be de-energized.	Contact 5-1 will open. This action de-energizes the entire control circuit. The boiler is now shut down and the low-water alarm is sounded.

2.5.2 Try Cocks

The purpose of the try cocks is to prove the water level in the boiler. You may see water in the gauge glass, but that does not mean that the water level is at that position in the boiler. If the gauge glass is clogged up, the water could stay in the glass, giving a false reading. The try cocks, on the other hand, will blow water, steam, or a mixture of steam and water out of them when they are manually opened. When steam is discharged from the lowest try cock, you have a low-water condition.

WARNING

When the water level is proved using the try cocks, personnel should stand off to the side of the try cocks away from the discharge. The discharged steam or scalding water can cause severe burns.

2.5.3 Gauge Glass

The gauge glass allows the boiler operator to see the water level in the boiler. Normally there are two valves associated with the gauge glass. One valve is located at the top and one is located at the bottom of the gauge glass. These two valves, named gauge cock valves, secure the boiler water and steam from the gauge glass. Another valve located in line with the gauge glass is used to blow the gauge glass down.

2.6.0 Safety Valve

The safety valve shown in *Figure 9-9* is the most important of boiler fittings. It is designed to open automatically to prevent pressure in the boiler from increasing beyond the safe operating limit. The safety valve is installed in a vertical position and attached directly to the steam space of the boiler. Each boiler has at least one safety valve; when the boiler has more than 500 square feet of heating surface, two or more valves are required.

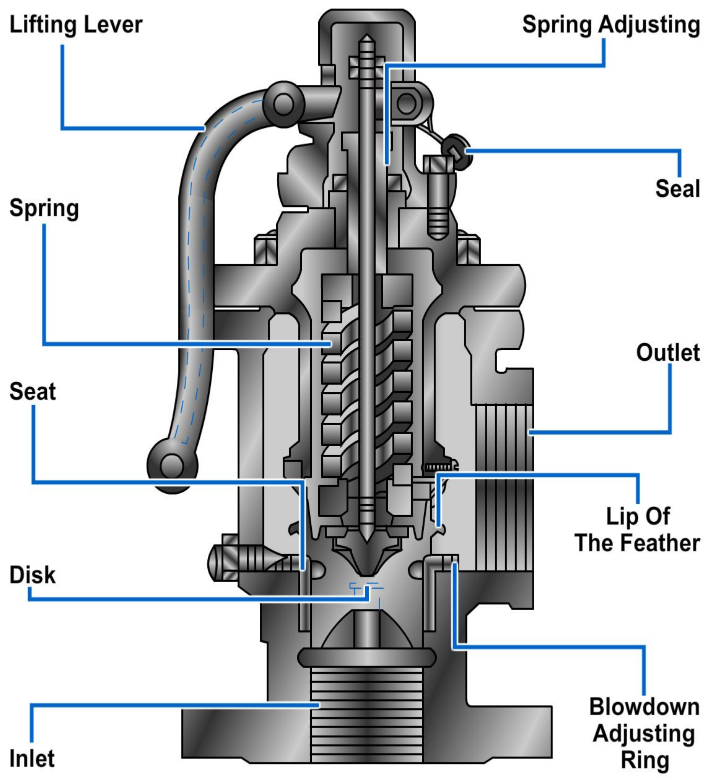


Figure 9-9 — Spring-loaded safety valve.

There are several different types of safety valves in use, but all are designed to open completely (POP) at a specific pressure and to remain open until a specified pressure drop (BLOWDOWN) has occurred. Safety valves must close tightly, without chattering, and must remain tightly closed after seating.

To understand the difference between boiler safety valves and ordinary relief valves is important. The amount of pressure required to lift a relief valve increases as the valve lifts, because the resistance of the spring increases in proportion to the amount of compression. When a relief valve is installed on a steam drum, it opens slightly when the specified pressure is exceeded, a small amount of steam is discharged, and then the valve closes again. Thus a relief valve on a steam drum is constantly opening and closing; this repeated action pounds the seat and disk and causes early failure of the valve. Safety valves are designed to open completely at a specified pressure to overcome this difficulty.

Several different types of safety valves are used on boilers; however, they all lift on the same general principle. In each case, the initial lift of the valve disk, or feather, is caused by static pressure of the steam acting upon the disk, or feather. As soon as the valve begins to open, however, a projecting lip, or ring, of the larger area is exposed for the steam pressure to act upon. The resulting increase in force overcomes the resistance of the spring, and the valve pops, that is, it opens quickly and completely. Because of the larger area now presented, the valve reseats at a lower pressure than that which caused it to lift originally.

Lifting levers are provided to lift the valve from its seat (when boiler pressure is at least 75 percent of that at which the valve is set to pop) to check the action and to blow away any dirt from the seat. When the lifting lever is used, raise the valve disk sufficiently to ensure that all foreign matter is blown from around the seat to prevent leakage after being closed.

The various types of safety valves differ chiefly as to the method of applying compression to the spring, the method of transmitting spring pressure to the feather, or disk, the shape of the feather, or disk, and the method of blowdown adjustment. Detailed information on the operation and maintenance of safety valves can be found in the instruction books furnished by the manufacturers of this equipment.

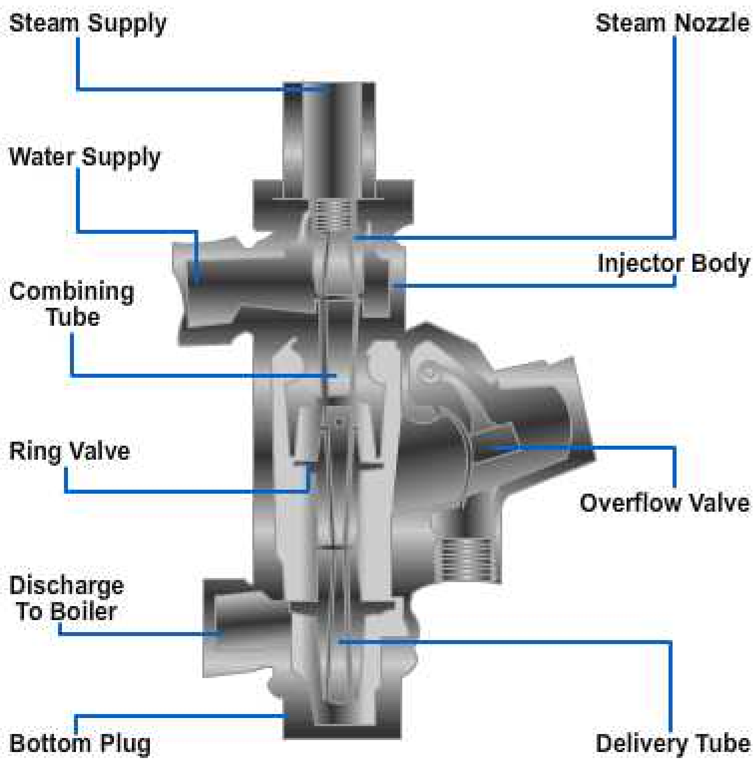


Figure 9-10 — Cross-sectional view of a steam injector.

2.7.0 Steam Injector Feed System

The steam injector is a boiler feed pump that uses the velocity and condensation of a jet of steam from the boiler to lift and force a jet of water into the boiler (*Figure 9-10*). This injection of water is many times the weight of the original jet of steam.

The injector is used to some extent in boiler plants as an emergency or standby feed unit. It does not feed very hot water. Under the best conditions, it can lift a stream of water having a temperature of 120°F about 14 feet.

The installation of an injector is not a difficult operation because the unit is mounted on the side of the boiler. The four connections to the injector are as follows (*Figure 9-11*):

1. The discharge line to the boiler feedwater inlet
2. The steam supply line from the boiler
3. The water overflow line
4. The water supply line from the reservoir.

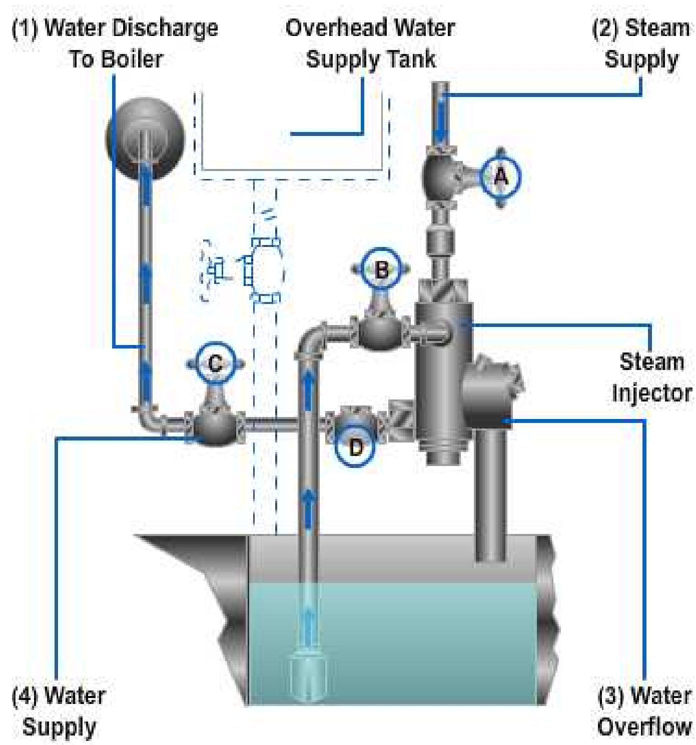


Figure 9-11 — Injector piping.

The controls for the injector include the following (*Figure 9-11*):

A. Steam supply valve

B. Water supply valve

C. Discharge valve to the boiler

D. Check valve in the discharge line

As you might expect, some degree of skill is needed to start the injector. After the injector begins to operate, however, it continues automatically until shutdown by the operator.

When starting the injector, first open the water supply valve (*Figure 9-11B*) about one full turn. Next quickly turn the steam supply valve (*Figure 9-11A*) all the way open. At this point, steam rushes into the combining tube of the injector. As the steam speeds past the water supply opening, it creates a suction that draws water through the opening into the combining tube. Water and steam are now mixed together inside the injector, and the pressure opens a valve that leads to the boiler. Meanwhile, there is an excess of water in the injector; this excess is discharged through the overflow valve. As the next step of the procedure, slowly turn the water supply valve (*Figure 9-11B*) toward the closed position until the overflow stops. The overflow valve has now closed, and all of the water being picked up from the supply line is going into the boiler. Remember, this feedwater system is used on boilers only as a standby method for feeding water.

For the injector to operate, the water supply should not be hotter than 120°F. When several unsuccessful attempts are made to operate the injector, it will become very hot and cannot be made to prime. When you encounter this problem, pour cold water over the injector until it is cool enough to draw water from the supply when the steam valve is opened.

2.8.0 Handholes and Manholes

Handholes and manholes provide maintenance personnel access into a boiler to inspect and clean it internally as needed. These handholes and manholes will be covered in depth when boiler maintenance is discussed later in this chapter.

2.9.0 Boiler Accessories

Figure 9-12 provides a graphic presentation of important boiler accessories. Refer to it as you study *Table 9-3*, which gives a brief description of each accessory, its location, and function.

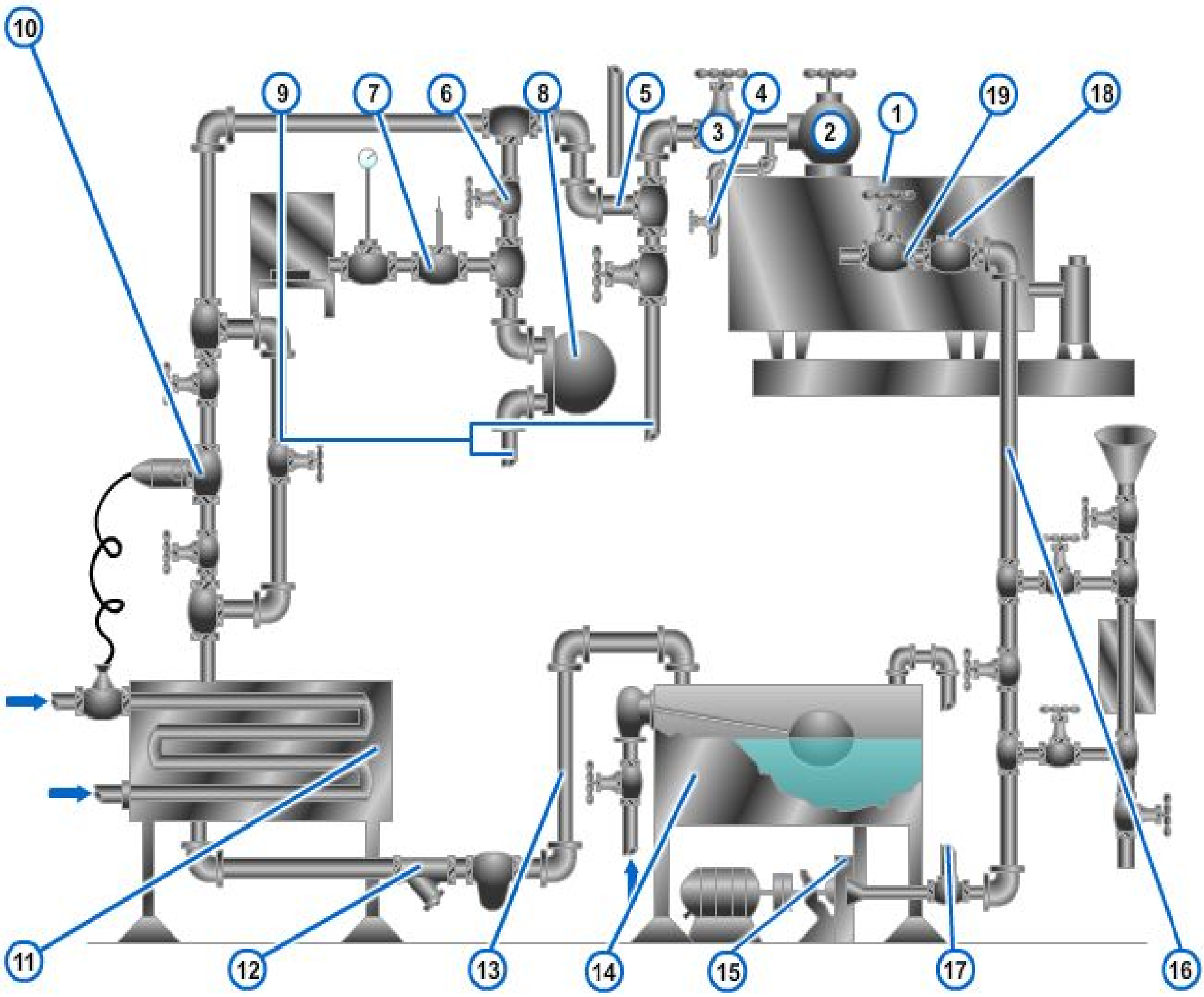


Figure 9-12 — Boiler accessory equipment.

Table 9-3 — Boiler accessories, location, and function.

Item	Accessory	Location	Function
1	Boiler	Boiler room	Generate steam or hot water in a closed vessel.
2	Main steam stop	On the steam outlet of a boiler	Place the boiler on line or off line.
3	Guard valve	On the steam outlet of a boiler directly following the main steam stop valve	Guard or backup to main steam stop valve.
4	Daylight (drain) valve	Between the main steam-stop valve and the guard valve	Open only when the main steam and guard valves are closed. Indicates if one of the valves is leaking through.
5	Main steam line	The line that conveys steam from a boiler to all branch or distribution lines. When a system is supplied by a bank of boilers connected into the same header, the line(s) conveying steam for the boiler(s) to the header	Carry steam from the boiler to the branches or distribution lines.
6	Root valve	Installed in branch or distribution lines just off of the main steam line	Isolate a branch or distribution line (serves as an emergency shutoff).
7	Pressure regulating valves (PRV)	Installed as close as practical (after a reducing station) to the equipment or area it serves	Equipment that requires lower pressure than main steam line pressure (coppers, dishwashers, steam chests, or turbines).
8	Steam trap	Installed on the discharge side of all steam heating or cooking equipment, dead ends, low points, or at regular intervals throughout a steam system (automatic drip legs)	Automatically drains condensate and prevents the passage of steam through equipment.
9	Drip legs	Provided throughout a system where condensation is most likely to occur, such as low spots, bottom of risers, and	Remove condensate from a system manually.

		dead ends	
10	Temperature regulating valve (TRV)	Install in the steam supply line close to equipment needing temperature regulation	Control steam flow through a vessel or heating equipment.
11	Heat exchanger	Locate as close as practical to the source for which it is going to supply heated water or oil	An unfired pressure vessel that contains a tube nest or electrical element. Used to heat oil or water.
12	Strainer	Install in steam and water lines just ahead of PRVs, TRVs, steam traps, and pumps	Prevent malfunction or costly repairs to equipment and components by trapping foreign matter such as rust, scale, and dirt.
13	Condensate line	Return line extends from the discharge side of steam traps to the condensate/makeup feedwater tank	Carry condensated steam back through piping for reuse in the boiler or heating vessel.
14	Condensate/makeup tank	Close to the boiler as practical and at a higher level than the boiler feed-pump suction line	Provide storage space for condensate and makeup/feedwater and vent noncondensable gases to the atmosphere.
15	Feed pump	Installed between the condensate/makeup/feedwater tank and the boiler shell or steam drum.	Supplies water to boiler as required.
16	Feedwater pipe	This line extends from the discharge side of the feedwater pump to the boiler shell or drum (installed below the steaming water level)	Provide feedwater to the boiler when required.
17	Relief valve	Between the feed pump and the nearest shutoff valve in the external feed line	Relieve excessive pressure should the external feed line be secured and the feed pump started accidently. A ruptured line or serious damage to the feed

			pump could occur if there were no relief valve.
18	Feed check valve	Between the feed pump and the stop valve in the feed water pipe	Prevent backflow from the boiler through the feedwater line into the condensate/feedwater tank during the off cycle of the pump.
19	Feed stop valve	In the feedwater line as close to the boiler as possible between the boiler and feed check valve	Permit or prevent the flow of water to the boiler.

Test your Knowledge (Select the Correct Response)

2. What is the melting point of a fire-actuated fusible plug filled with an alloy of tin, copper, and lead?

   A. 415°F
   B. 425°F
   C. 435°F
   D. 445°F

3.0.0 TYPES of BOILERS

The Utilitiesman (UT) is concerned primarily with the fire-tube type of boiler, since it is the type generally used in Seabee operations. However, the water-tube type of boiler may occasionally be used at some activities. The information in this chapter primarily concerns the different designs and construction feature of fire-tube boilers.

The basis for identifying the two types is as follows:

- Water-tube boilers are those in which the products of combustion surround the tubes through which the water flows.
- Fire-tube boilers are those in which the products of combustion pass through the tubes and the water surrounds them.

3.1.0 Water-Tube Boilers

Water-tube boilers may be classified in a number of ways. For our purpose, they are classified as either straight tube or bent tube. These classes are discussed separately in succeeding sections. To avoid confusion, make sure you study carefully each illustration referred to throughout the discussion.

3.1.1 Straight Tube

The straight-tube class of water-tube boilers includes three types:

1. Sectional-header cross drum
2. Box-header cross drum
3. Box-header longitudinal drum

In the sectional-header cross drum boiler with vertical headers, the headers are steel boxes into which the tubes are rolled. Feedwater enters and passes down through the down-comers (pipes) into the rear sectional headers from which the tubes are supplied. The water is heated and some of it changes into steam as it flows through the tubes to the front headers. The steam-water mixture returns to the steam drum through the circulating tubes and is discharged in front of the steam-drum baffle that helps to separate the water and steam.

Steam is removed from the top of the drum through the dry pipe. This pipe extends along the length of the drum and has holes or slots in the top half for steam to enter.

Headers, the distinguishing feature of this boiler, are usually made of forged steel and are connected to the drums with tubes. Headers may be vertical or at right angles to the tubes. The tubes are rolled and flared into the header. A handhole is located opposite the ends of each tube to facilitate inspection and cleaning. Its purpose is to collect sediment that is removed by blowing down the boiler.

Baffles are usually arranged so gases are directed across the tubes three times before being discharged from the boiler below the drum.

Box-header cross drum boilers are shallow boxes made of two plates—a tube-sheet plate that is bent to form the sides of the box, and a plate containing the handholes that is riveted to the tube-sheet plate. Some are designed so that the front plate can be removed for access to tubes. Tubes enter at right angles to the box header and are expanded and flared in the same manner as the sectional-header boiler. The boiler is usually built with the drum in front. It is supported by lugs fastened to the box headers. This boiler has either cross or longitudinal baffling arranged to divide the boiler into three passes. Water enters the bottom of the drum, flows through connecting tubes to the box header, through the tubes to the rear box header, and back to the drum.

Box-header longitudinal drum boilers have either a horizontal or inclined drum. Box headers are fastened directly to the drum when the drum is inclined. When the drum is horizontal, the front box header is connected to it at an angle greater than 90 degrees. The rear box header is connected to the drum by tubes. Longitudinal or cross baffles can be used with either type.

3.1.2 Bent Tube

Bent tube boilers usually have three drums. The drums are usually of the same diameter and positioned at different levels. The uppermost or highest positioned drum is referred to as the steam drum, while the middle drum is referred to as the water drum, and the lowest, the mud drum. Tube banks connect the drums. The tubes are bent at the ends to enter the drums radially.

Water enters the top rear drum, passes through the tubes to the bottom drum, and then moves up through the tubes to the top front drum. A mixture of steam and water is discharged into this drum. The steam returns to the top rear drum through the upper row of tubes, while the water travels through the tubes in the lower rear drum by tubes extending across the drum, and enters a small collecting header above the front drum.

Many types of baffle arrangements are used with bent-tube boilers. Usually, they are installed so that the inclined tubes between the lower drum and the top front drum absorb 70 to 80 percent of the heat. The water-tube boilers discussed above offer a number of worthwhile advantages. For one thing, they afford flexibility in starting up. They also have a high productive capacity ranging from 100,000 to 1,000,000 pounds of steam per hour. In case of tube failure, there is little danger of a disastrous explosion of the water-tube boiler. The furnace not only can carry a high overload, it can also be modified for firing by oil or coal. Still another advantage is that it is easy to get into sections inside the furnace to clean and repair them. There are also several disadvantages common to water-tube boilers. One of the main drawbacks is their high construction cost. The large assortment of tubes required for this boiler and the excessive weight per unit weight of steam generated are other unfavorable factors.

3.2.0 Fire-Tube Boilers

There are four types of fire-tube boilers—Scotch marine boiler, vertical-tube boiler, horizontal return tubular boiler, and firebox boiler. These four types of boilers are discussed in this section.

3.2.1 Scotch Marine Boiler

The Scotch marine tire-tube boiler is especially suited to Seabee needs. *Figure 9-13* shows a portable Scotch marine tire-tube boiler. The portable unit can be moved easily and requires only a minimal amount of foundation work. A completely self-contained unit, its design includes automatic controls, a steel boiler, and burner equipment. These features are a big advantage because no disassembly is required when you must move the boiler into the field for an emergency.

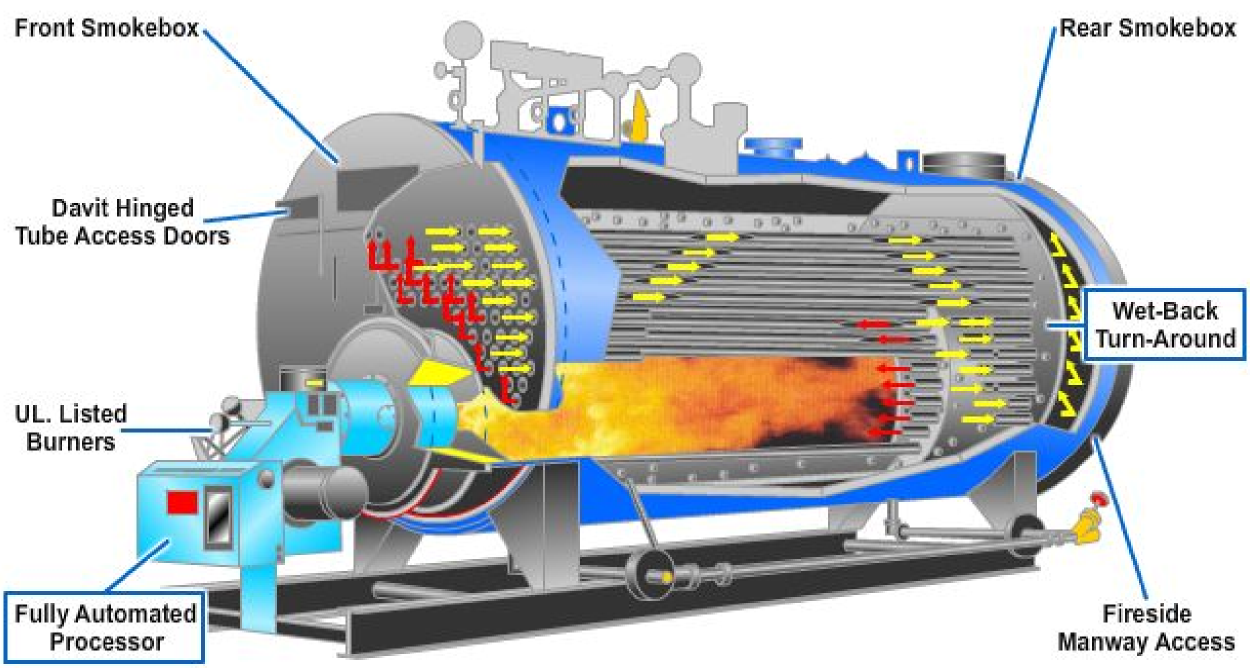


Figure 9-13 — Scotch marine type of fire-tube boiler.

The Scotch marine boiler has a two-pass (or more) arrangement of tubes that run horizontally to allow the heat inside the tubes to travel back and forth. It also has an internally fired furnace with a cylindrical combustion chamber. Oil is the primary fuel used to fire the boiler; however, it can also be fired with wood, coal, or gas. A major advantage of the Scotch marine boiler is that it requires less space than a water-tube boiler and can be placed in a room that has a low ceiling.

The Scotch marine boiler also has disadvantages. The shell of the boiler runs from 6 to 8 feet in diameter, a detail of construction that makes a large amount of reinforcing necessary. The fixed dimensions of the internal surface cause some difficulty in cleaning the sections below the combustion chamber. Another drawback is the limited capacity and pressure of the Scotch marine boiler.

An important safety device sometimes used is the fusible plug that provides added protection against low-water conditions. In case of a low-water condition, the fusible plug core melts, allowing steam to escape, and a loud noise is emitted which provides a warning to the operator. On the Scotch boiler the plug is located in the crown sheet, but sometimes it is placed in the upper back of the combustion chamber. Fusible plugs are discussed in more detail later in this chapter.

Access for cleaning, inspection, and repair of the boiler watersides is provided through a manhole in the top of the boiler shell and a handhole in the ***water leg***. The manhole opening is large enough for a person to enter the boiler shell for inspection, cleaning, and repairs. On such occasions, always ensure that all valves are secured, locked, and tagged, and that the person in charge knows you are going to enter the boiler. Additionally, always have a person located outside of the boiler standing by to aid you in case of an incident that would require assistance. The handholes are openings large enough to permit hand entry for cleaning, inspection, and repairs to tubes and headers.

Figure 9-14 shows a horizontal fire-tube boiler used in low-pressure applications. Personnel in the UT rating are assigned to operate and maintain this type of boiler more often than any other type of boiler. Refer to *Table 9-1* for equipment location.

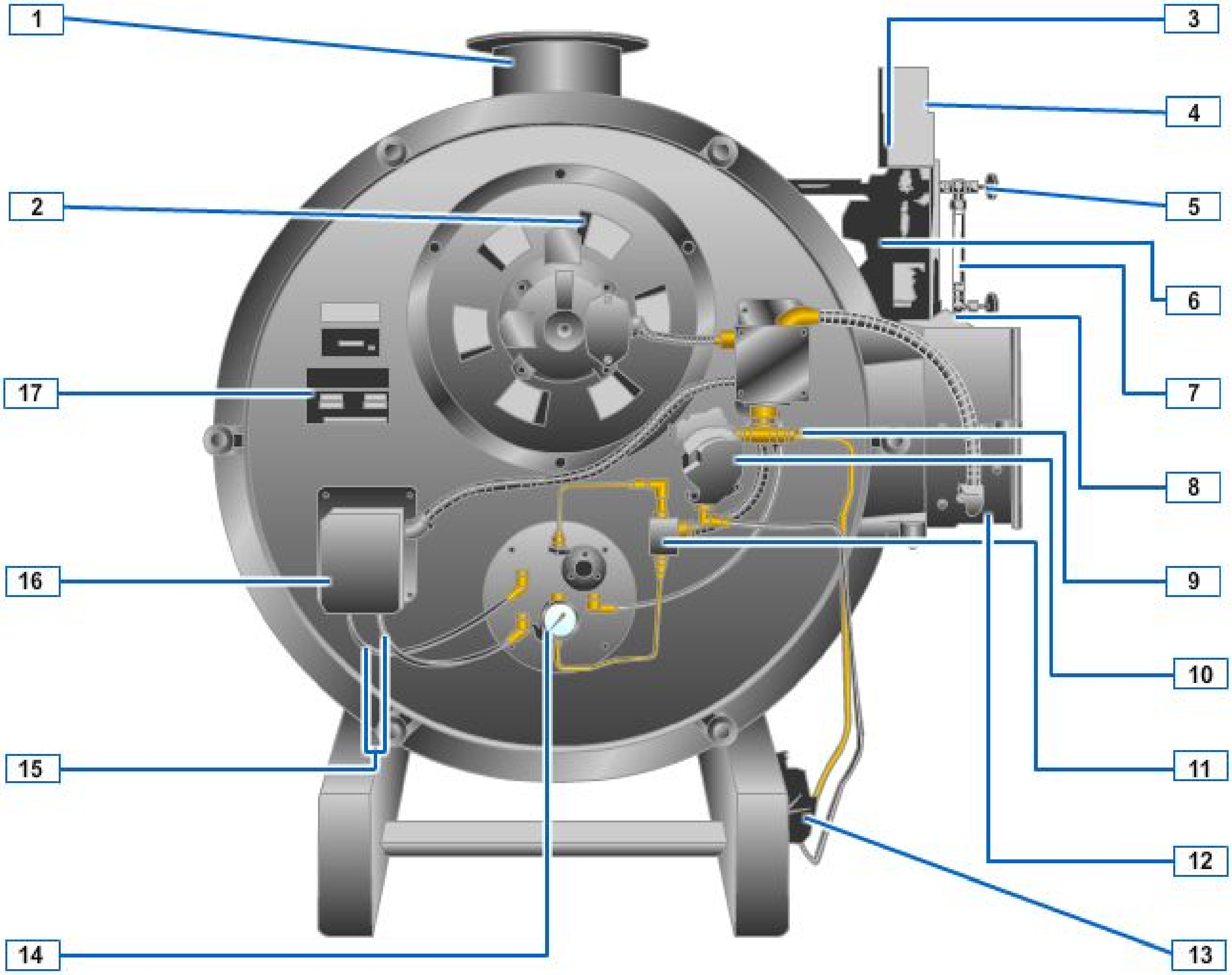


Figure 9-14—Horizontal fire-tube boiler used in low-pressure applications.

Table 9-1 — Horizontal fire-tube boiler parts location.

1. Vents	7. Water Level Gauge	13. Fuel Oil Supply Connection
2. Air Damper	8. Burner Switch	14. Fuel Oil Pressure Gauge
3. High Limit Pressure Control	9. Priming Tee	15. Ignition Cable
4. Steam Pressure Gauge	10. Oil Unit, Two Stage	16. Ignition Cable Box
5. Gauge Glass Shutoff Cock	11. Solenoid Oil Valve	17. Nameplate
6. Low Water Control	12. Service Connection Box	

3.2.2 Vertical-Tube Boiler

In some fire-tube boilers, the tubes run vertically, as opposed to the horizontal arrangement in the Scotch boiler. The vertical-tube boiler sits in an upright position *(Figure 9-15)*. Therefore, the products of combustion (gases) make a single pass, traveling straight up through the tubes and out the stack. The vertical fire-tube boiler is similar to the horizontal fire-tube boiler in that it is a portable, self-contained unit requiring a minimum of floor space. Handholes are also provided for cleaning and repairing. Though self-supporting in its setting (no brickwork or foundation being necessary), it MUST be level. The vertical fire-tube boiler has the same disadvantages as that of the horizontal-tube design—limited capacity and furnace volume.

Before selecting a vertical fire-tube boiler, you must know how much overhead space is in the building where it will be used. Since this boiler sits in an upright position, a room with a high ceiling is necessary for its installation.

The blowdown pipe of the vertical fire-tube boiler is attached to the lowest part of the water leg, and the feedwater inlet opens through the top of the shell. The boiler fusible plug is installed either (1) in the bottom tube sheet or crown sheet or (2) on the outside row of tubes, one third of the height of the tube from the bottom.

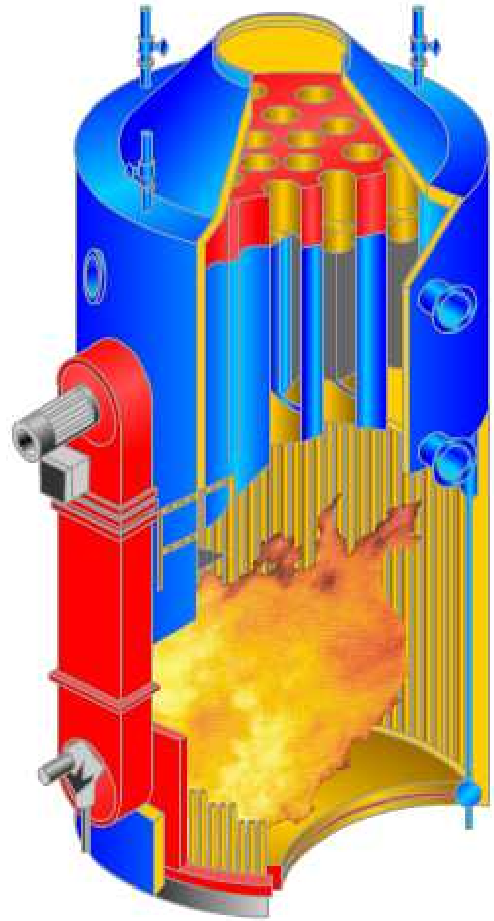


Figure 9-15—Cutaway view of a vertical fire-tube boiler.

3.2.3 Horizontal Return Tubular Boiler

In addition to operating portable boilers such as the Scotch marine and vertical fire-tube boilers, the UT must also be able to operate stationary boilers, both in the plant and in the field. A stationary boiler can be defined as one having a permanent foundation and not easily moved or relocated. A popular type of stationary fire-tube boiler is the horizontal return tubular (HRT) boiler shown in *Figure 9-16*.

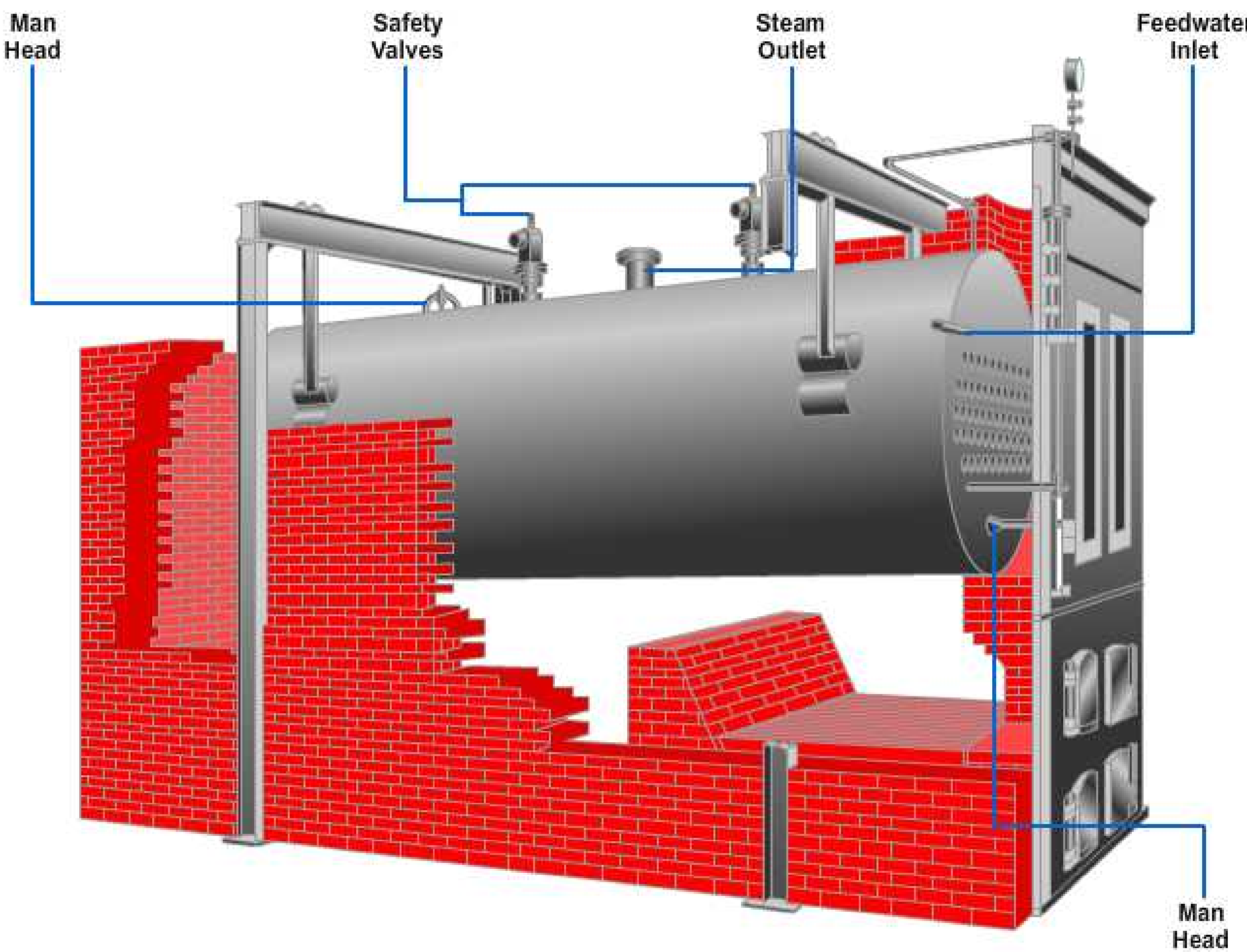


Figure 9-16—Horizontal return tubular (HRT) fire-tube boiler.

The initial cost of the HRT boiler is relatively low, and installing it is not too difficult. The boiler setting can be readily changed to meet different fuel requirements—coal, oil, wood, or gas. Tube replacement is also a comparatively easy task since all tubes in the HRT boiler are the same in size, length, and diameter.

The gas flows in the HRT boiler from the firebox to the rear of the boiler. It then returns through the tubes to the front where it is discharged to the breaching and out the stack.

The HRT boiler has a pitch of 1 to 2 inches to the rear to allow ***sediment*** to settle toward the rear near the bottom blowdown connection. The fusible plug is located 2 inches above the top row of tubes. Boilers over 40 inches in diameter require a manhole in the upper part of the shell. Those over 48 inches in diameter must have a manhole in the lower as well as in the upper part of the shell. Do not fail to familiarize yourself with the location of these and other essential parts of the HRT boiler. The knowledge you acquire will definitely help in the performance of your duties with boilers.

3.2.4 Firebox Boiler

Another type of fire-tube boiler is the firebox boiler that is usually used for stationary purposes. A split section of a small firebox boiler is shown in *Figure 9-17.*

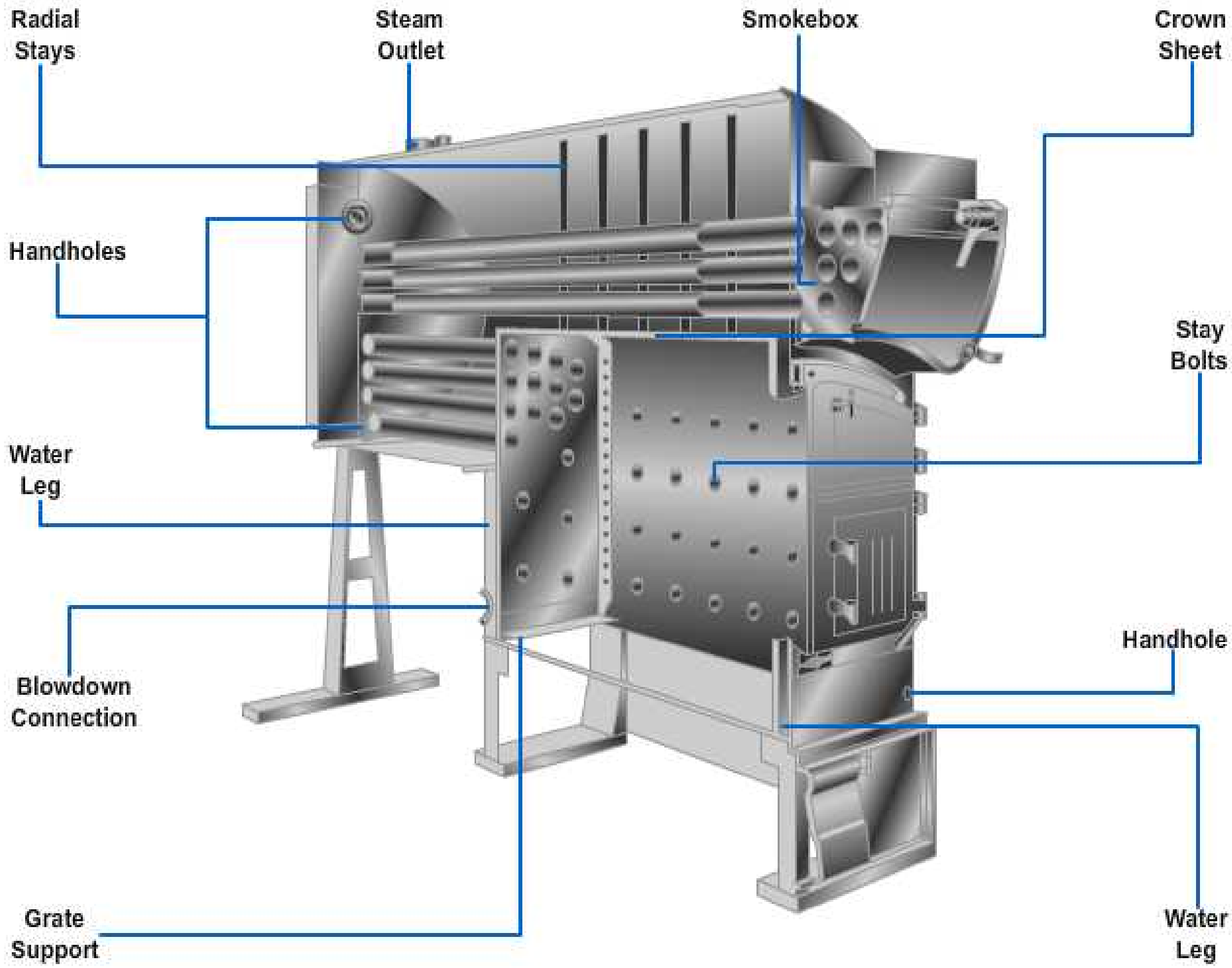


Figure 9-17—Split section of a small firebox boiler.

Gases in the firebox boiler make two passes through the tubes. Firebox boilers require no setting except possibly an ash pit for coal fuel. As a result, they can be quickly installed and placed in service. Gases travel from the firebox through a group of tubes to a reversing chamber. They return through a second set of tubes to the ***flue*** connection on the front of the boiler and are then discharged up the stack.

4.0.0 BOILER DESIGN REQUIREMENTS

A boiler must meet certain requirements before it is considered satisfactory for operation. Three important requirements for a boiler are as follows:

1. The boiler must be safe to operate.
2. The boiler must be able to generate steam at the desired rate and pressure.
3. The boiler must be economical to operate.

NOTE

Make it a point to familiarize yourself with the boiler code and other requirements applicable to the area in which you are located.

BOILER DRAUGHT: -

Draught is the pressure difference which is necessary to draw the required quantity of air for combustion and to remove the flue gases out of the system.

Thus, the object of producing draught in a boiler is:
(i) To provide sufficient quantity of air for combustion

(ii) To make the resulting hot gases, to flow through the system

(iii) To discharge these gases to the atmosphere through the chimney.

Usually this drought (pressure difference) in boiler is of small magnitude and is measured in mm of water column by means of draught gauge/manometer.

The amount of draught depends upon:
(i) Nature and depth of fuel on the grate.

(ii) Design of combustion chamber/firebox.

(iii) Rate of combustion required.

(iv) Resistance offered in the system due to baffles, tubes, superheater, economiser, air pre-heater, etc.

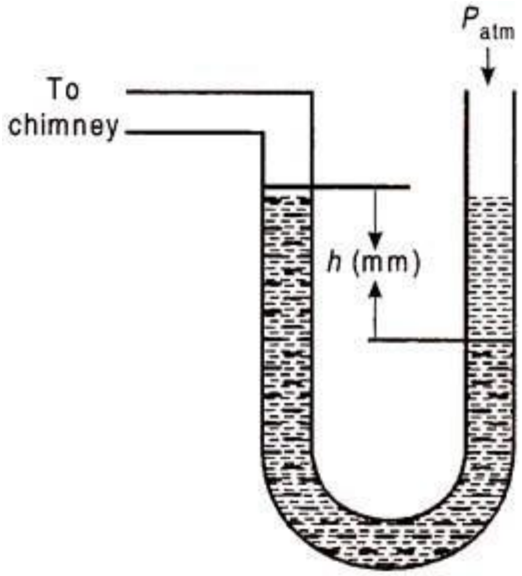


Fig. 11.22

Classification of Boiler Draught:

Draught is broadly classified into 2-types:

1. Natural or Chimney Draught:

In this case the amount of draught directly depends upon the height of chimney. It is produced due to the difference in densities between the column of hot gases in the chimney and a similar column of cold air outside the chimney.

Let us first consider the case when fires are not lighted.

Let, the atmospheric pressure at grate level be P_1 and P_2 be the atmospheric pressure at an altitude H. The pressure P_2 is lower than the pressure P_1 because with the altitude pressure goes on decreasing.

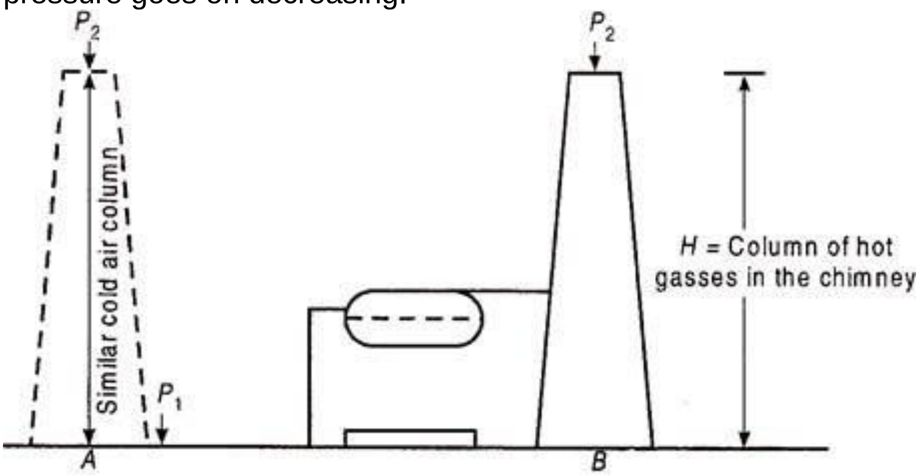


Fig. 11.23

Now let us consider the case when fires are lighted and the chimney is full of hot gases. Under these circumstances, the pressure at the base of the chimney is the sum of pressure P_2 at the top and the pressure due to hot gas column H. But pressure P_1 at grate is the sum of pressure P_2 and the pressure due to similar cold column of air H.

Since, ρ cold air > ρ hot gases

i.e., $P_A > P_B$

$\therefore$ P_2 + Pressure due to cold column H > P_2 + Pressure due to hot column H.

$\therefore$ Pressure at grate due to cold column > Pressure at the chimney base due to hot column H.

This difference is called static draught and because of the pressure difference, (draught) air will rush to the combustion chamber, where combustion of air and fuel takes place and hot gases are generated. Then these hot gases because of draught, flow through the system and finally they are exhausted to the atmosphere through the chimney.

Advantages of Natural Draught:

i. Easy to construct.

ii. No power is required for producing the draught.

iii. Long life of chimney.

iv. No maintenance is required.

Disadvantages:

i. Tall chimney is required.

ii. Poor efficiency.

iii. Decreases with increase in outside temperature.

iv. No flexibility it create more draught to take peak loads.

2. Artificial Draught:

In bigger power plants, the draught of the order of 25-350 mm of H_2O column is required. Far producing this much draught, the chimney height has to be increased considerably, which is neither convenient nor economical. Also, since the draught depends upon the climatic conditions, some mechanical equipments are used for producing the required draught and the draught so produced is called as the artificial draught.

i. Forced Draught:

In a Forced draught system, a Fan or Blower is provided is shown in figure which forces the air in the combustion chamber. In the combustion chamber combustion of air and fuel takes place and hot gases generated. These gases are forced to pass through the flues, economiser, air pre-heater and then they are exhausted after recovering heat of flue gases. This draught system is known positive draught system, since the pressure of gases throughout the system is above atmospheric pressure.

It is to be noted that, the function of chimney use is to discharge the gases high in the atmosphere to reduce air pollution and it is not much significant for producing draught.

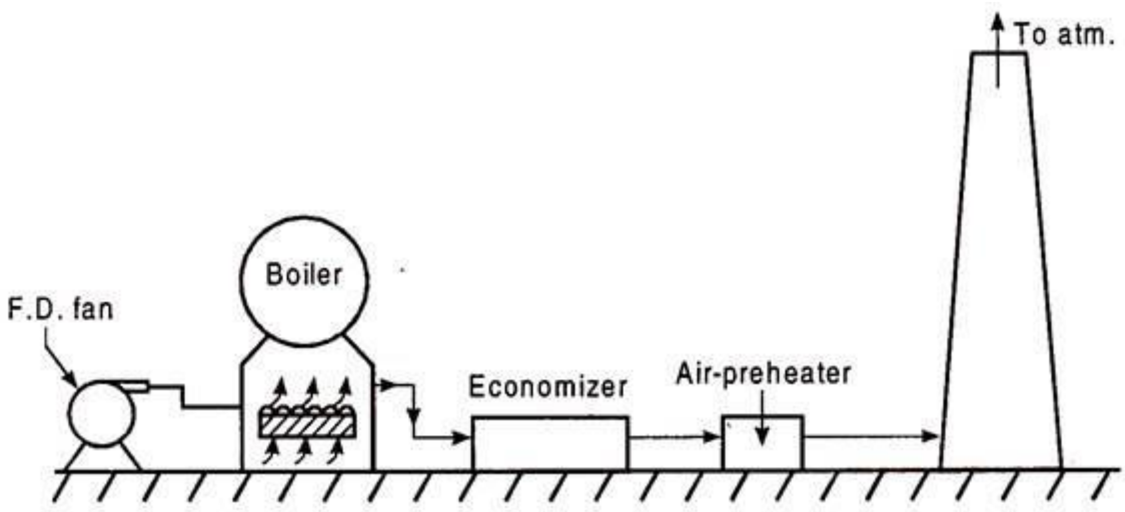


Fig. 11.24

ii. Induced Draught:

In this system, the Blower or Induced Draught fan is located near the base of chimney. The air is sucked in the system, by reducing the pressure through the system below atmosphere. The flue gases, generated after combustion are drawn through the system and after recovering heat in the economiser, air-preheater, they are exhausted through the chimney to the atmosphere.

Here it is to be noted that the draught produced is independent of the temperature of hot gases, so the gases may be discharged as cold as possible after recovering as much heat as possible.

Advantages of Forced Draught (F.D.) over Induced Draught (I.D.):

i. The size and power required by I.D. fan is more because this fan handles more gases.

ii. Since the I.D. fan handles hot gases, water cooled or air cooled bearings are to be used.

iii. F.D. fan consumes less power and normal bearing can be used.

iii. Balanced Draught:

It is always preferable to use combinations of I.D. and F.D. instead of Forced or Induced draught alone.

If Forced Draught alone is used then the furnace cannot be opened for firing or for inspection. Because the high pressure air/gases inside the furnace will try to blow out, and there is every chance of blowing out of the fire completely and the furnace may stop.

If Induced Draught fan alone is used, then also furnace cannot be opened either for firing or for inspection. Because the cold air will try to rush into the furnace, which reduces the effective draught.

To overcome both these difficulties Balanced Draught is used. In this case I.D. fan and F.D. fan are provided as shown.

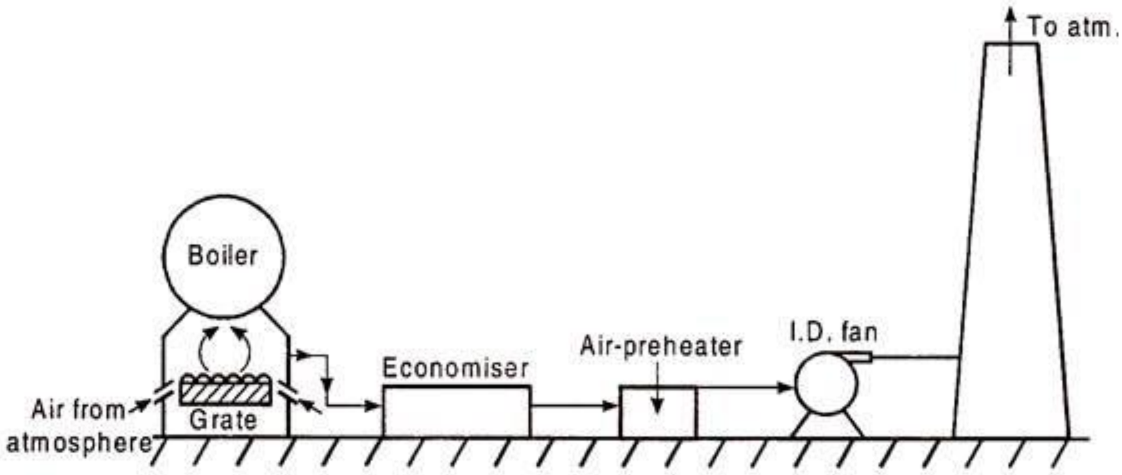
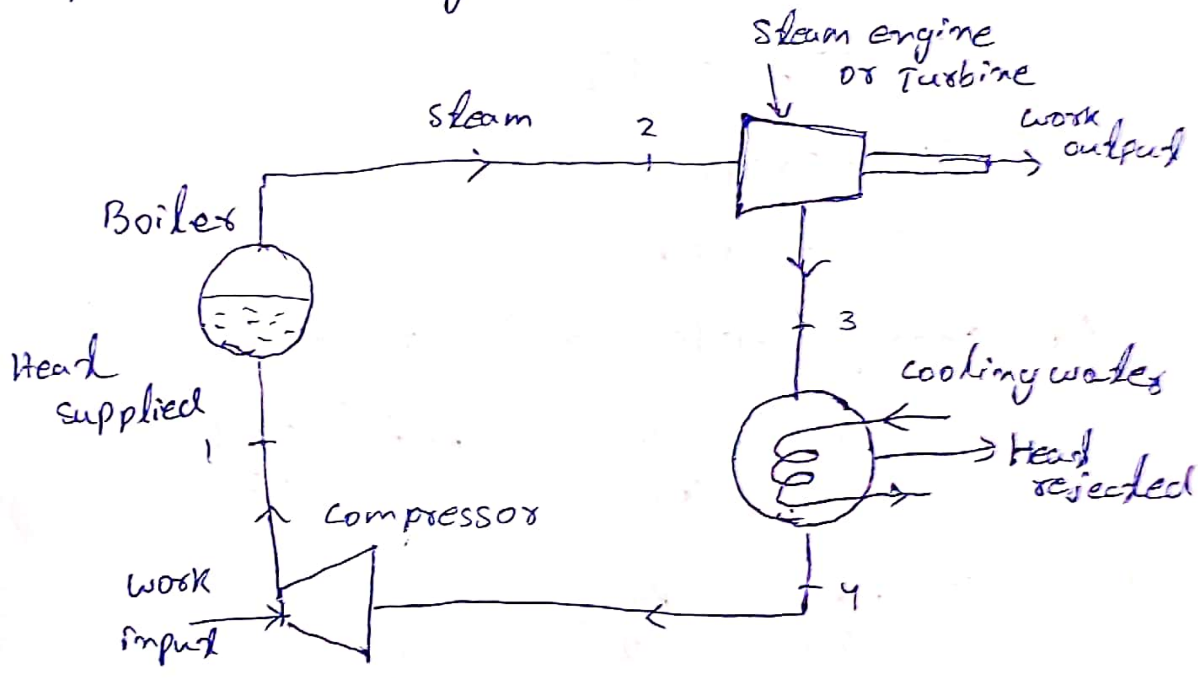


Fig. 11.25

~~Theory~~ Thermodynamic Vapour Cycle

Carnot Cycle with steam as Working Substance

The schematic diagram of the carnot ~~cycle~~ engine is shown in figure and the Carnot cycle using steam as the working substance is represented on p-v and T-S diagrams.



Schematic diagram

Consider 1 kg of saturated water at pressure p_1 and absolute temperature T_1 as represented by point 1. The cycle is completed by the following four processes.

(1) Process 1-2 The saturated water at point 1 is isothermally converted into dry saturated steam, in a boiler, and the heat is absorbed

at a constant temp. T_1 and pressure P_1. The dry state of steam is respresented by point 2. It means that the temp. T_2 and pressure P_2 is equal to temperature T_1 and pressure P_1 respectively. This isothermal process is represented by curve 1–2 on P-V and T-S diagram.

we know that the heat absorbed by the saturated water during its conversion into dry steam is its latent heat of evaporation (i.e. $h_{fg_1} = h_{fg_2}$) corresponding to a pressure P_1 and P_2 ($\because P_1 = P_2$).

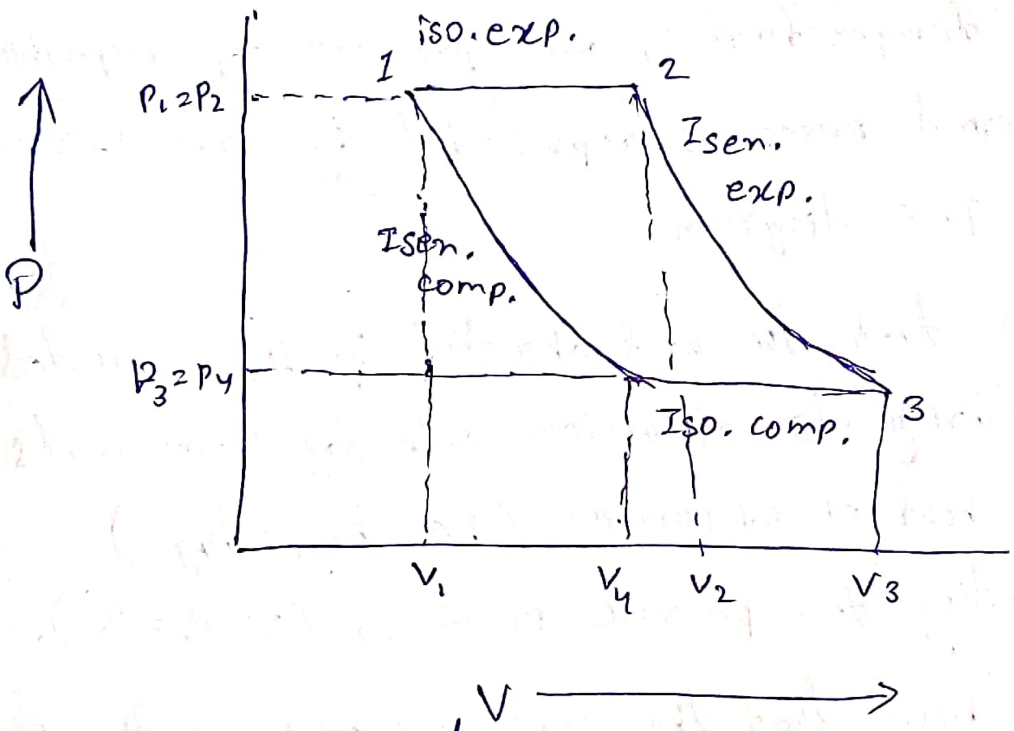
we also know that the area 1-2-b-a in the T-s diagram represents the heat absorbed to some scale, during the isothermal process.

$\therefore$ Heat absorbed during isothermal process (area 1-2-b-a),

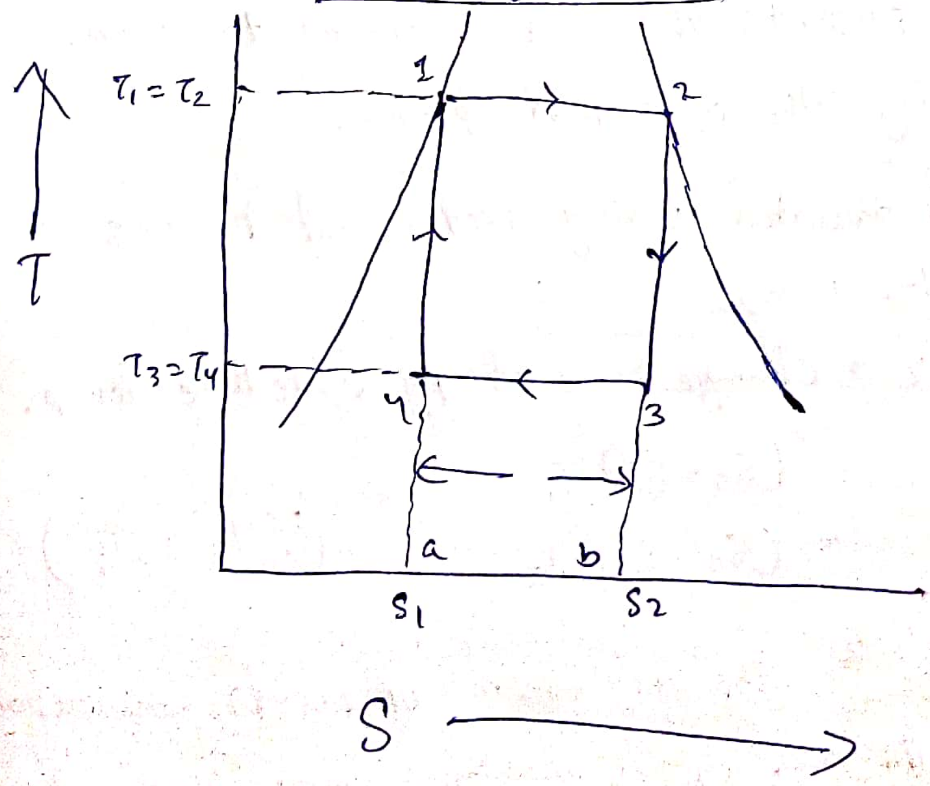
$$q_{1-2} = \text{Change in enotropy} \times \text{Absolute temp.}$$
$$= (S_2 - S_1)\, T_1$$
$$= (S_2 - S_1)\, T_2 \qquad (\because T_1 = T_2) \ldots (i)$$

(2) Process 2-3 The dry steam of point 2 now expands isentropically in a steam engine or turbine. The Pressure and temperature falls from P_2 to P_3 and T_2 to T_3 respectively. since no heat is supplied or rejected during this process, therefore

there is no change of entropy. The isentropic expansion is represented by the curve 2-3



P-V diagram



T-S diagram

(3) Process 3-4 The wet steam at point 3 is now isothermally condensed in a condenser and the heat is rejected at a constant temperature T_3 and pressure P_3. It means that the temp. T_4 and pressure P_4 is equal to the temp. T_3 and pressure P_3 respectively. This isothermal process is represented by the curve 3-4 on p-V and T-S diagrams.

We know that area 3-4-b-a in the T-S diagram represents the heat rejected to some scale during the isothermal process.

∴ Heat rejected during isothermal compression (area 3-4-a-b)

$$q_{3-4} = (S_2 - S_1) T_3 = (S_2 - S_1) T_4$$

$$(\because T_3 = T_4) \quad \ldots (ii)$$

(4) Process 4-1

The wet steam at point 4 is finally compressed till it returns back to its orignal state. The pressure and temperature rise from P_4 to P_1 and T_4 to T_1 respectively. The isentropic compression is represented by the curve 4-1 as shown in figure since no heat is absorbed or rejected during this process, therefore entropy remains constant.

This completes the cycle.

we know that work done during the cycle

$= $ Heat absorbed $-$ Heat rejected

$= (S_2 - S_1) T_1 - (S_2 - S_1) T_3$

$= (S_2 - S_1)(T_1 - T_3)$

Efficiency of the carnot cycle.

$$\eta = \frac{\text{work done}}{\text{Heat absorbed}}$$

$$= \frac{(S_2 - S_1)(T_1 - T_3)}{(S_2 - S_1) T_1}$$

$$= \frac{T_1 - T_3}{T} = 1 - \frac{T_3}{T_1}$$

T_1 = Highest temp. corresponding to the boiler pressure where $P_1 = P_2$

T_3 = lowest temp. corresponding to the condenser pressure where $P_3 = P_4$

Performance Criterial for Thermodynamic vapour cycle

Though, theoretically, the carnot cycle is the most efficient cycle, yet it is not considered as a standard of referance for the comparison of Performance of thermodynamic vapour cycle.

The following terms, in addition to the efficiency, are commonly used for the comparison

Of performance of thermodynamic vapour cycle.

① Efficiency ratio

It is also known as relative efficiency. It is defined as the ratio of thermal efficiency (or actual cycle efficiency) to Rankine efficiency (or ideal cycle efficiency) mathematically.

$$\text{Efficiency ratio} = \frac{\text{Thermal efficiency}}{\text{Rankine efficiency}}$$

Thermal efficiency:

$$= \frac{\text{Heat equivalent to one kilowatt hour (kWh)}}{\text{Total heat supplied to the steam per kWh}}$$

$$= \frac{3600 \times P}{m_s(h_2 - h_{f3})}$$

m_s = mass of steam supplied in kg/h and

P = power developed in kW

② work ratio

It is defined as the ratio of net work output to the gross (engine or turbine) output. mathematically

$$\text{work ratio} = \frac{\text{Net work output}}{\text{Gross output}}$$

$$= \frac{\text{Turbine work} - \text{Compressor work}}{\text{Turbine work}}$$

③ Specific steam consumption

It is also known as steam rate or specific rate of flow of steam. It is defined as the mass of steam that must be supplied to a steam engine or turbine in order to develop a unit amount of work or power output. The amount of work or power output is usually expressed in killowatt hour (kWh), mathematically

Specific steam consumption

$$= \frac{1\,kWh}{w} = \frac{3600}{w} = \frac{3600}{h_2 - h_3}\ kg/kWh$$

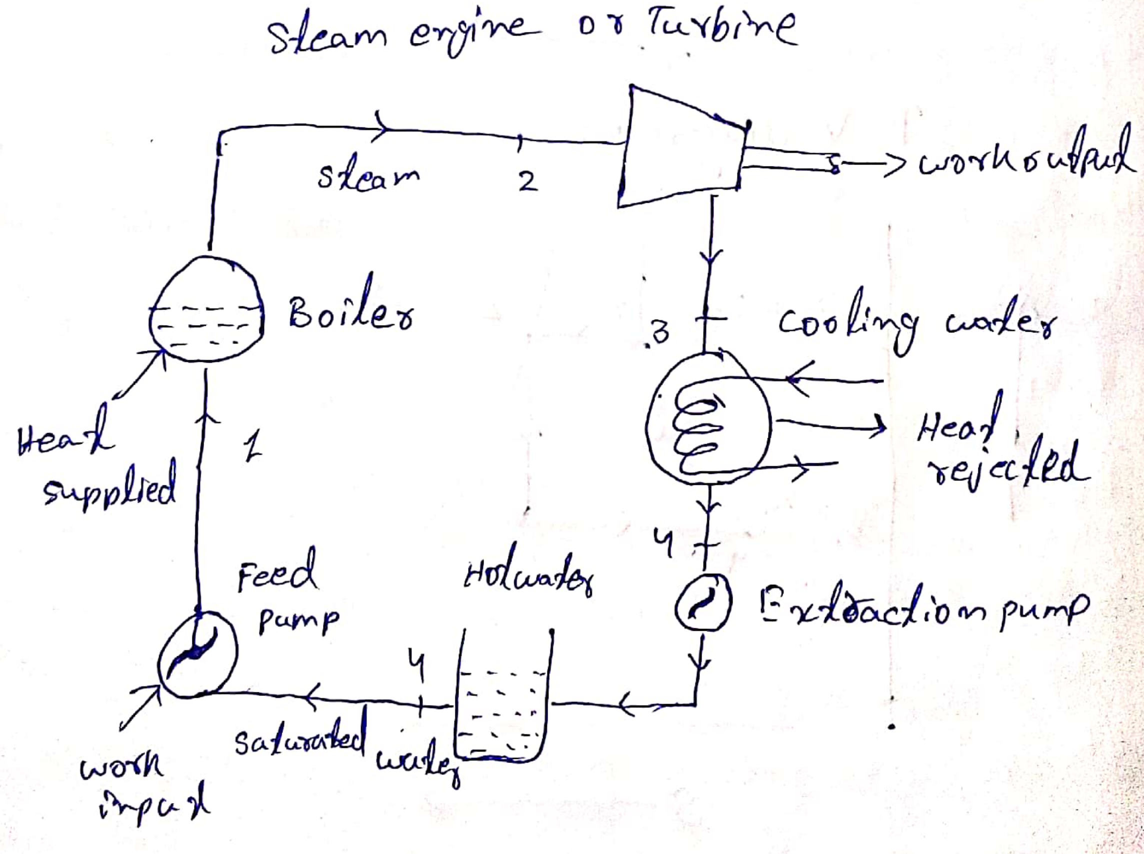
$(\because 1\,kWh = 3600\,kJ)$

w = Net workdone or power output

$= (h_2 - h_3)\ kJ/kg$

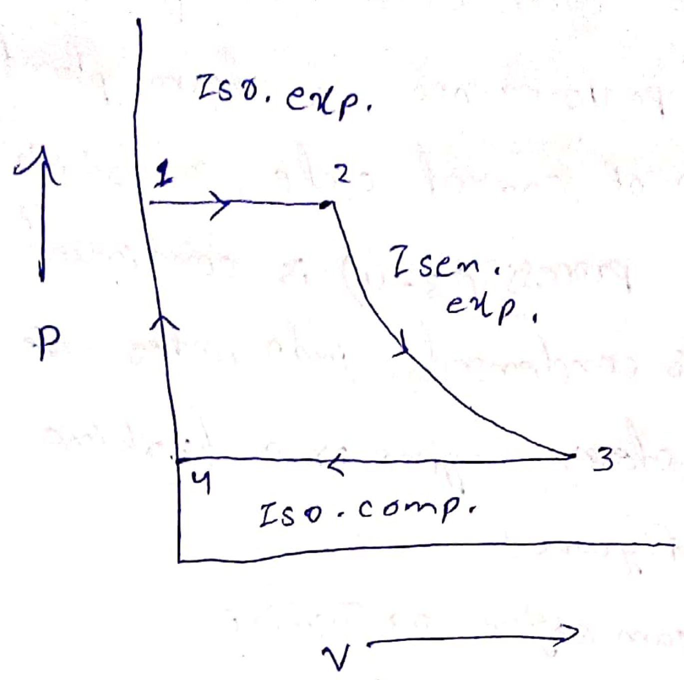
Rankine cycle

The Rankine cycle is an ideal cycle for comparing the performance of steam plants. It is modified form of carnot cycle, in which the condensation process (3-4) is continued until the steam is condensed into water. The schematic diagram of a steam engine or a turbine plant is shown in figure.

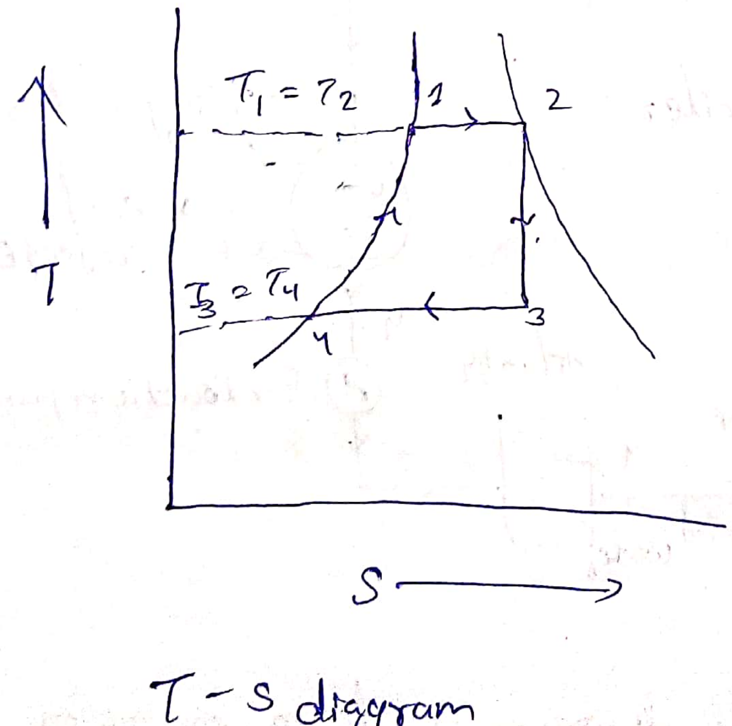


schematic diagram of steam engine or turbine plant

A Rankine cycle, using steam as a working substance is represent on p-V and T-S diagrams as shown in figure



P-V diagram



T-S diagram

consider 1 kg of saturated water at pressure P_1 and absolute temperature T_1 as represented by point 1. The cycle is completed by the following four processes.

(1) Process 1-2 The saturated water at point 1 is isothermally converted into dry saturated steam in a boiler, and the heat is absorbed at a constant temperature T_1 and pressure P_1. The dry state of steam is represented by point 2. It means that the temp. T_2 and pressure P_2 is equal to temp. T_1 and pressure P_1 respectively. This isothermal process is represented by curve 1-2 on p-v and T-s diagrams

we know that the heat absorbed during isothermal process by water during its conversion into dry ~~steam~~ steam is its latent heat of vaporisation (i.e. $h_{fg1} = h_{fg2}$), corresponding to a pressure P_1 or P_2 ($\because P_1 = P_2$).

(2) Process 2-3 → The dry saturated steam at point 2 now expand isentropically in an engine or turbine The pressure and temperature fall from P_2 to P_3 and T_2 to T_3 respectively with a dryness fraction x_3. since no heat is supplied or rejected during this process, therefore there is no change of entropy. The isentropic expansion is represented by the curve 2-3

(3) Process 3-4 The wet steam at point 3 is now isothermally condensed in a condenser and the heat is rejected at constant temperature T_3 and pressure P_3 until the whole steam is condensed into water. It means that the temp. T_4 and pressure P_4 is equal to the temperature T_3 and pressure P_3 respectively. The isothermal compression is represent by curve 3-4 on P-V and T-S diagrams The heat rejected by steam is its latent heat (equal to $x_3 h_{fg3}$).

(4) Process 4-1 The water at point 4 is ~~~~ now warmed in a boiler at constant volume from temp. T_4 to T_1. Its pressure also rises from P_4 to P_1. This warming operation is represented by the curve 4-1 on P-V and T-S diagram. The heat absorbed by water during this operation is equal to the sensible heat or liquid heat corresponding to the pressure P_1 i.e. equal to sensible heat at point 1 minus sensible heat at point 4

Let $h_{f1} = h_{f2}$ = sensible heat or enthalpy of water at point 1 corresponding to a Pressure of P_1 or P_2 ($\because P_1 = P_2$)

$h_{f4} = h_{f3}$ = sensible heat or enthalpy of water at point 4 corresponding to the pressure of P_4 or P_3 ($\because P_4 = P_3$)

$\therefore$ Heat absorbed during warming operation 4-1

$= h_{f1} - h_{f4}$

$= h_{f2} - h_{f3}$

and heat absorbed during the complete cycle

= Heat absorbed during isothermal operation 1-2
+ Heat absorbed during warming operation 4-1

$= h_{fg2} + (h_{f2} - h_{f3}) = h_{f2} + h_{fg2} - h_{f3} = h_2 - h_{f3}$

(for dry steam, $h_2 = h_{f2} + h_{fg2}$) ....(i)

we know that heat rejected during the cycle

$= h_3 - h_{f4} = h_{f3} + x_3 h_{fg3} - h_{f4} = x_3 h_{fg3}$

$(\because h_{f3} = h_{f4})$

$\therefore$ work done during the cycle

= Heat absorbed − Heat rejected

$= (h_2 - h_{f3}) - x_3 h_{fg3}$

$= h_2 - (h_{f3} + x_3 h_{fg3})$

$= h_2 - h_3$ $\quad (\because h_3 = h_{f3} + h_{fg3})$ ....(ii)

and efficiency (Rankine efficiency)

$$\eta_R = \frac{\text{work done}}{\text{Heat absorbed}}$$

$$= \frac{h_2 - h_3}{h_2 - h_{f3}}$$

Noted down

(i) The difference of enthalpies $(h_2 - h_3)$ is known as isentropic heat drop.

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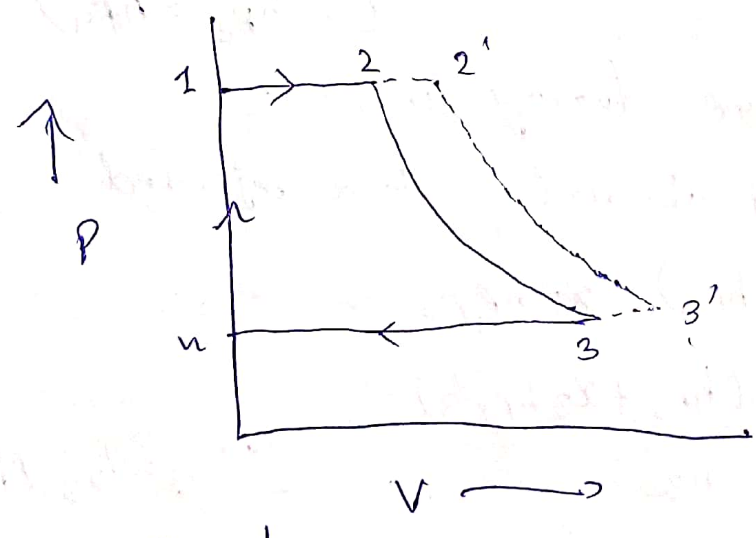
(3) If the expension of steam (2-3') is not isentropic and follows the general law pv^n = constant, then work done during the process will not be $(h_2 - h_3)$. The work done in this case will be given by the relatively

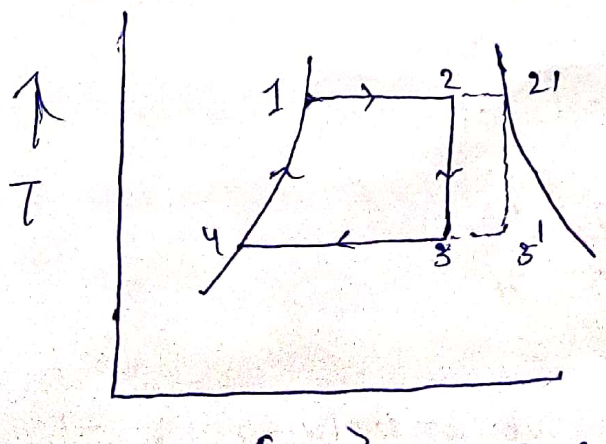
$$W = P_2V_2 + \frac{P_2V_2 - P_3V_3}{(n-1)} - P_3V_3$$

$$= \frac{n\,(P_2V_2 - P_3V_3)}{n-1}$$

Rankine cycle with Incomplete Evaporation



P-V diagram

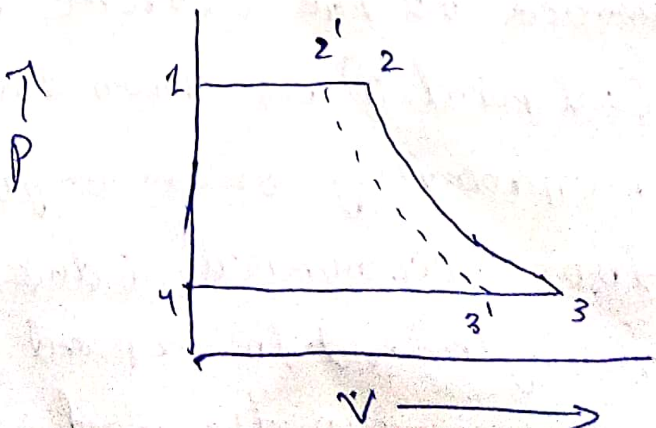


T-s diagram

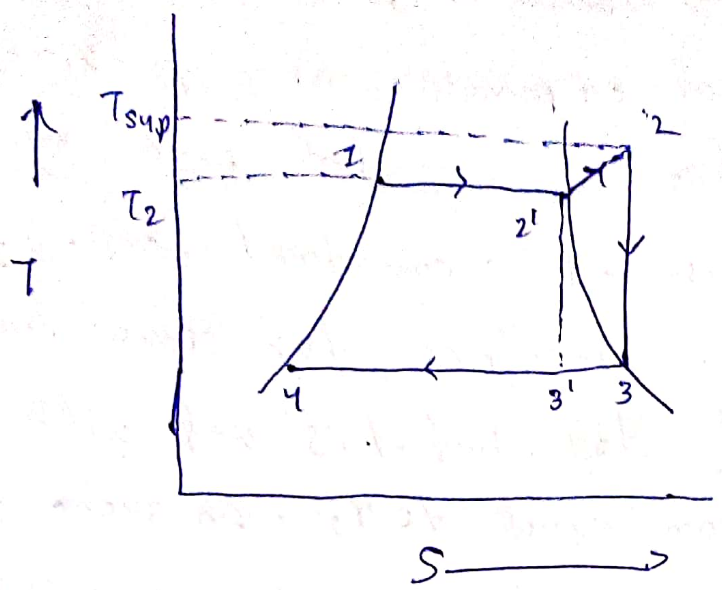
we have already discussed in the last ~~at~~ article that in isothermal expansion of a Rankine cycle, the water is converted into dry saturated steam at a constant temp. T_1 and pressure P_1. Sometimes, the steam produced is not completely dry, but it is wet with dryness fraction equal to x_2. In such a a case, the Rankine cycle may be represented on p-V and T-S diagram as shown in the figure

Rankine cycle with superheated steam

we have already discussed, in the last article, the case of a Rankine cycle where the ~~steam~~ steam produced is wet with dryness fraction x_2. But sometimes, the steam produced is superheated. In such a case, the Rankine cycle may be shown on p-V and T-S diagrams as shown in figure.



P-V diagram.



T-s diagram

In may be noted from the above figure, that 1-2-3-4 ~~cycle~~ represents the Ranking cycle with superheated steam, where as 1-2'-3'-4 represents the cycle with complete evaporation. In such a case heat absorbed during isothermal expansion

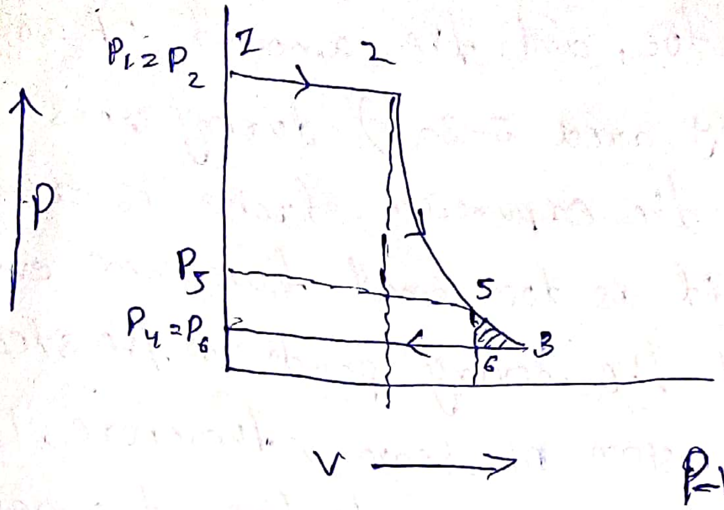
$$h_2 = h_{sup} = h_{g2} + C_p (T_{sup} - T_2)$$

Modified Rankine cycle

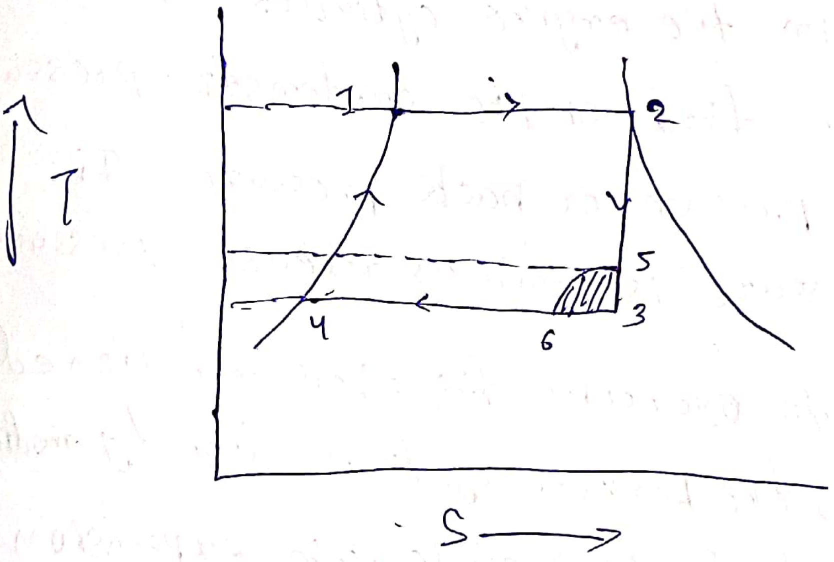
we have seen in the Rankine cycle, that the steam is expanded to the extreme toe of P-V diagram (at point 3) as shown in figure. But in actual reciprocating steam engines, it is found to be too uneconomical (due to large size of the cylinder) to expand steam to the full limit (i.e. upto the point 3)

It may be noted that the diagram is very narrow at the toe, and the amount of workdone (represented by area 5-3-6) during this final portion of the expansion stroke is extremely small. In fact, it is too small to overcome even the friction of the moving parts in the steam engine. The expansion of steam, therefore, is carries on in the engine cylinder, and a pressure higher than that of the condenser pressure or exhaust pressure or back pressure. This higher pressure is know as release pressure (P_5)

In order to overcome the above mentioned difficulty, the Rankine cycle is slightly modified. In a modified Rankine cycle, the expansion stroke of the piston is stopped at point 5 by cutting the toe of Rankine cycle, and the steam is exhausted from the cylinder at a constant volume. This causes a sudden drop of pressure from P_5 to P_6. The expansion of steam is, therefore, completed by a constant volume line 5-6 as shown in P-V diagram and T-S diagram as shown in figure. By doing so, the size of the cylinder and stroke length is considerable reduced.



P-V diagram



T-S diagrame

Efficiency of Modified Rankine Cycle

Consider a modified Rankine cycle whose process are shown in figure

Let $P_1 = P_2$ = Pressure of steam at point 2

V_2 = volume of steam at point 2.

h_2 = Enthalpy or total heat of steam at point 2,

U_2 = Internal energy of steam at point 2.

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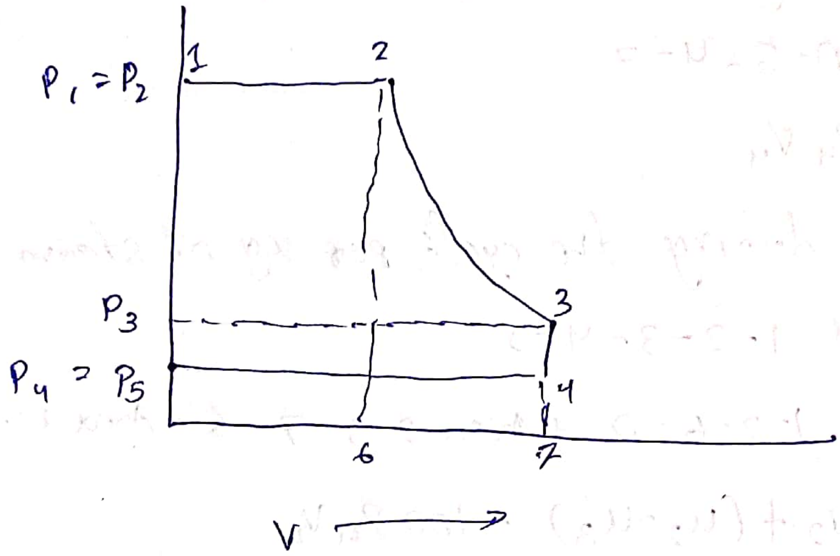
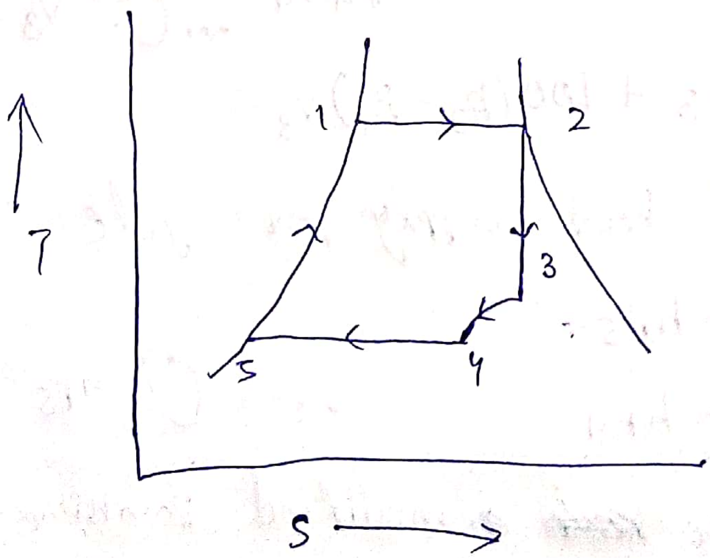
P_3, V_3, h_3, u_3 = corresponding value of steam at point 3

P_4 = Back pressure of steam at point 4

h_{f4} = sensible heat or enthalpy of water at point 4



P - V diagram



T - S diagram

we know that work done during constant pressure process = Area 1-2-6-0 = $100 P_2 V_2$

we know also that work done during isentropic expansion 2-3

$= \text{Area } 2\text{-}3\text{-}7\text{-}6$

$=$ change in internal energy

$= u_2 - u_3$

work done during constant pressure process 4-5

$= \text{Area } 0\text{-}5\text{-}4\text{-}7$

$= 100\, P_4 V_4$

$\therefore$ work done during the cycle per kg of steam

$W = \text{Area } 1\text{-}2\text{-}3\text{-}4\text{-}5$

$= \text{Area } 1\text{-}2\text{-}6\text{-}0 + \text{Area } 2\text{-}3\text{-}7\text{-}6 - \text{Area } 0\text{-}5\text{-}4\text{-}7$

$= 100 P_2 V_2 + (u_2 - u_3) - 100 P_4 V_4$

$= 100 P_2 V_2 + [(h_2 - 100 P_2 V_2) - (h_3 - 100 P_3 V_3)]$

$- 100 P_4 V_4 \quad \ldots (\because V_3 = V_4)$

$= h_2 - h_3 + 100 (P_3 - P_4) V_3$

We know that heat supply per cycle

$= h_2 - h_{f5}$

$= h_2 - h_{f4} \quad \text{----} (\because h_{f5} = h_{f4})$

Efficiency of the ~~[illegible]~~ modified Rankine cycle

$$\eta_{MR} = \frac{\text{work done}}{\text{Heat supplied}}$$

$$= \frac{(h_2 - h_3) + 100 (P_3 - P_4) V_3}{h_2 - h_{f4}}$$

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Reheat cycle

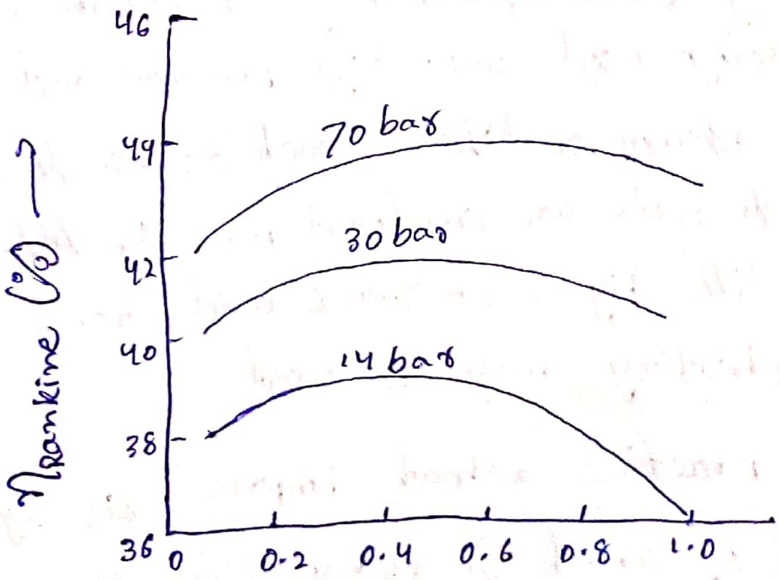
For attaining greater thermal efficiencies when the initial pressure of steam was raised beyond 42 bar it was found that resulting condition of steam after, expansion was increasingly wetter and exceeded the safe limit of 12 per cent condensation. It, therefore, become necessary to reheat the steam after part of expansion was over so that the resulting condition after complete expansion fell within the region of permissible wetness.

The reheating or resuperheating of steam is ~~not~~ now universally used when high pressure and temperature steam conditions such as 100 to 250 bar and 500°c to 600°c are employed for throttle. For Plants of still higher pressures and temperatures, a double reheating may be used.

In actual practice reheat improve the cycle efficientey by about 5% for a 85/15 bar cycle. A second reheat will give a much less gain while the initial cost involved would be so high as to prohibit use of two stage reheat except in case of very high initial throttle conditions. The cost of reheat equipment consisting of boiler, piping and controls may be 5% to 10%

more than of the conventional boilers and this additional expenditure is justified only if gain in thermal efficiency is sufficient to promise a return of this investment. Using a plant with a base load capacity of 5000 kW and initial steam pressure of 42 bar would economically justify the extra cost of reheating.

The improvement in thermal efficiency due to reheat is greatly dependent upon the reheat pressure with respect to the original pressure of steam.

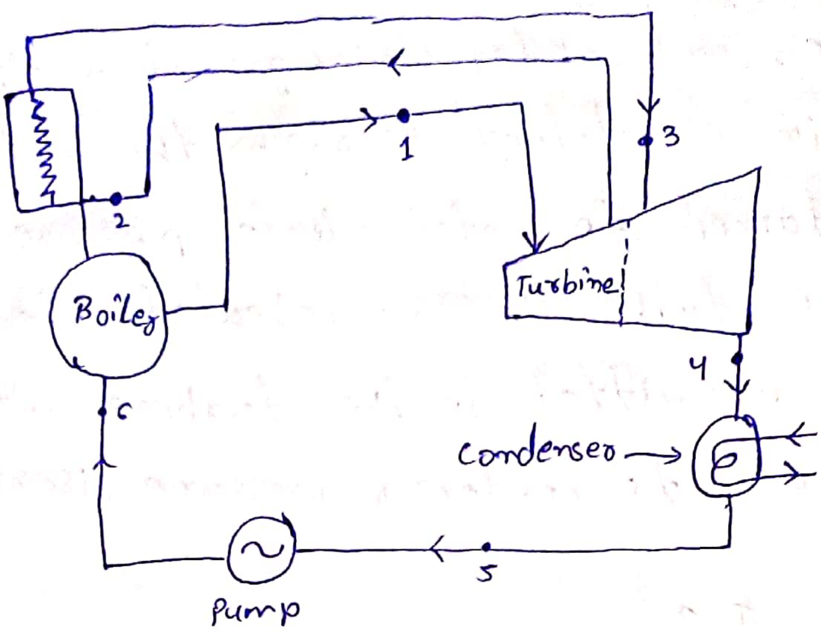


$\dfrac{\text{Reheat pressure}}{\text{Throttle pressure}} \longrightarrow$

Condenser pressure : 12.7 mm Hg

Temperature of throttle and heat 1427°C

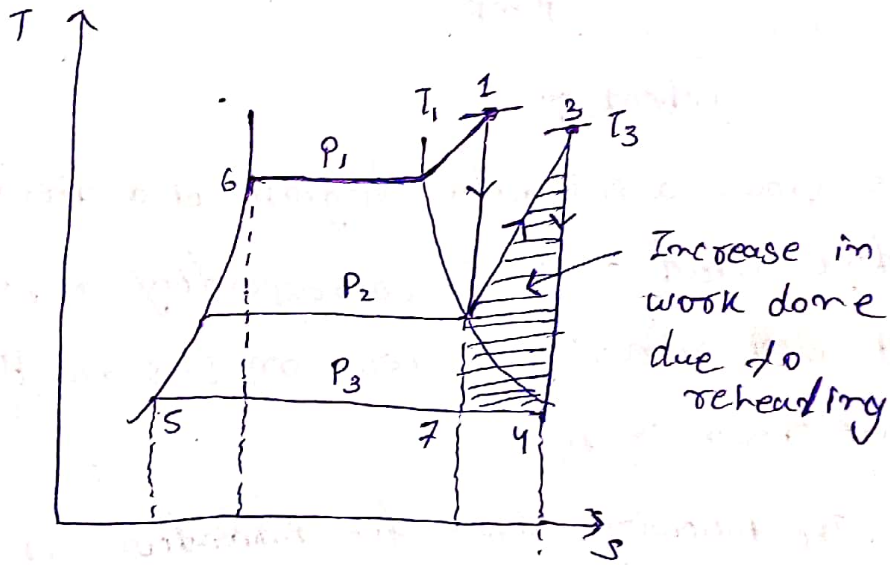
Effect of reheat pressure selection on cycle efficiency.



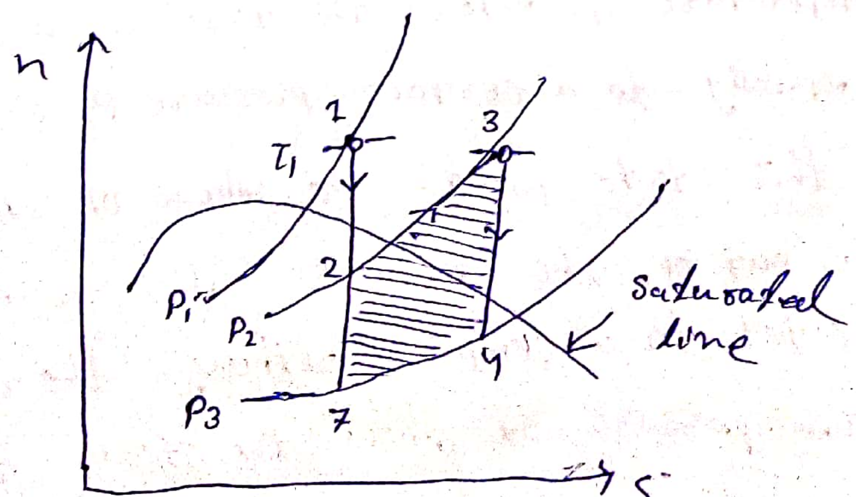
Reheat cycle

As shown a schematic diagram of a theoretical single stage reheat cycle. The corresponding representation of ideal reheating process on T-S and H-S chart ~~are~~ are shown in figure

The following shows the formation of steam in the boiler. The steam as at state point 1 (i.e. pressure P_1 and temperature T_1) enters the turbine and expands isentropically to a certain pressure P_2 and temp. T_2. From this state point 2 the whole of steam is drawn out of the turbine and is reheated in a reheated to a temp T_3. (Although there is an optimum pressure at which the steam should be removed for reheating, if the highest return is to be obtained, yet, for simplicity, the whole steam is removed from the high pressure exhaust, where the pressure is about one-fifth of boiler pressure, and after underground a 10% pressure drop, in circulating through the heater, it is returned to intermediate pressure or low pressure turbine). This reheated steam is then readmitted to the turbine where it is expanded to condenser pressure isentropically.



T-S chart



h-S chart

Thermal efficiency with Reheating (neglecting Pump work):

Heat supplied $= (h_1 - h_{f4}) + (h_3 - h_2)$

Heat rejected $= h_4 - h_{f4}$

work done by the turbine = Heat supplied - Heat rejected

$$= (h_1 - h_{f4}) + (h_3 - h_2) - (h_4 - h_{f4})$$

$$= (h_1 - h_2) + (h_3 - h_4)$$

Thus, theoretical thermal efficiency of reheat cycle is

$$\eta_{thermal} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f4}) + (h_3 - h_2)}$$

If pump work

$$W_p = \frac{V_f (P_1 - P_b)}{1000} \text{ kJ/kg}$$ is considered,

the thermal efficiency is given by:

$$\eta_{thermal} = \frac{[(h_1 - h_2) + (h_3 - h_4)] - W_p}{[(h_1 - h_{f4}) + (h_3 - h_2)] - W_p}$$

W_p is usually small and neglected

Thermal efficiency without reheating is

$$\eta_{thermal} = \frac{h_1 - h_2}{h_1 - h_{f4}} \quad (\because h_{f4} = h_{f2})$$

Advantages of Reheating

1. There is an increased output of the turbine
2. Erosion and corrosion problem in the steam turbine are eliminated.
3. There is an improvement in the thermal efficiency of the turbines.
4. Final dryness fraction of steam is improved.
5. There is an increase in the nozzle and blade efficiencies.

Disadvantage

1. Reheating required more maintenance.
2. The increase in thermal efficiency is not appreciable in comparison to the expenditure incurred in reheating.

Superheating of Steam:-

The primary object of superheating steam and supplying it to the primemovers is to avoid too much wetness at the end of expansion. Use of inadequate degree of superheat in steam engines would cause greater condensation in the engine cylinder; while in case of turbines the moisture content of steam would result in undue blade erosion. The maximum wetness in the final condition of steam that may be tolerated without any appreciable harm to the turbine bleeder is about 12%. Broadly each 1% of moisture in steam reduces the efficiency of that part of the turbine is which wet steam passes by 1% to 1.5% and in engines about 2 percent.

Regenerative cycle

In the Rankine cycle it is observed that the condensate which is fairly at low temperature has an irreversible mixing with hot boiler water and this result in decrease of cycle efficiency. Methods are, therefore, adopted to heat the feed water from the hot well of condenser irreversibly by interchange of heat within the system and thus improving the cycle efficiency. This heating method is called regenerative feed heat and the cycle is called regenerative cycle.

The principle of regeneration can be practically utilised by extracting steam from the turbine at several locations and supplying it to the regenerative heaters. The resulting cycle is known as regenerative or bleeding cycle. The heating arrangement comprises of: (i) for medium capacity turbines - not more than 3 heaters.

ii) for high pressure high capacity turbines - not more than 5 to 7 heaters; and

iii) for turbines of super critical parameters 8 to 9 heaters.

The most advantageous condensate heating temperature is selected depending on the turbine throttle conditions and this determines the number of heaters to be used. The final condensate heating temperature is kept 50 to 60°C below the boiler saturated steam temperature so as to prevent evaporation of water in the feed mains following a drop in the boiler drum pressure. The conditions of steam bled for each heater are selected so that the temperature of saturated steam will be 4 to 10°C higher than the final condensate temperature.

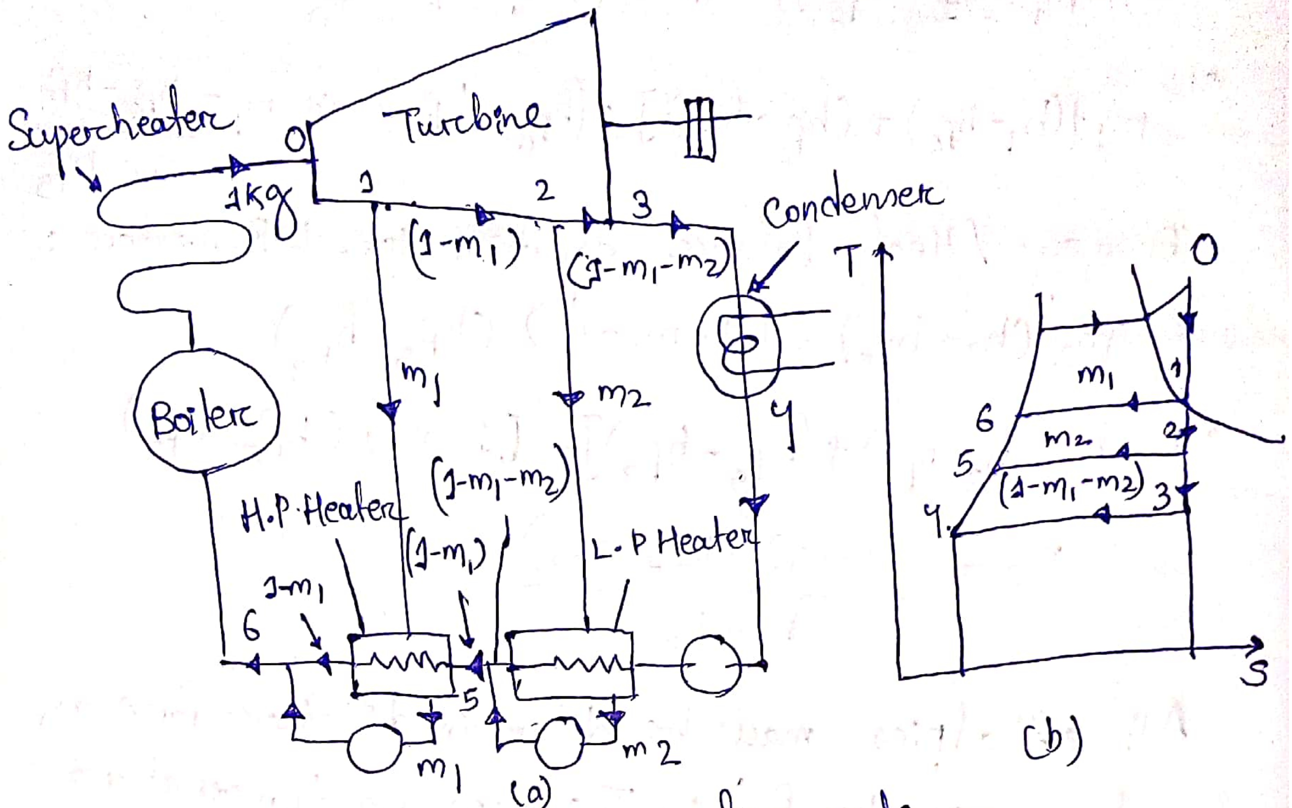


Fig. . Regenerative cycle.

Fig. (a) shows a diagrammatic layout of a surface condensing steam power plant in which a surface condenser is used to condense all the steam that is not extracted for feed water heating. The turbines is double extracting and the boiler is equipped with a superheater. The cycle diagram (T-s) would appear as shown in fig. (b). This arrangement constitutes a regenerative cycle.

Let m_1 = kg of high pressure (H.P) steam per kg of steam flow.

m_2 = kg of low pressure (L.P) steam extracted per kg of steam flow.

$1-m_1-m_2$ = kg of steam entering condenser per kg of steam flow.

$$m_1 (h_1 - h_{f6}) = (1-m_1)(h_{f6} - h_{f5})$$

or

$$m_1 [(h_1 - h_{f6}) + (h_{f6} - h_{f5})] = (h_{f6} - h_{f5}) \quad \text{or} \quad m_1 = \frac{h_{f6} - h_{f5}}{h_1 - h_{f5}}$$

Energy / Heat balance equation for L.P heater :

$$m_2 (h_2 - h_{f5}) = (1 - m_1 - m_2)(h_{f5} - h_{f3})$$

or $$m_2 [(h_2 - h_{f6}) + (h_{f5} - h_{f3})] = (1-m_1)(h_{f5} - h_{f3})$$

$$m_2 = \frac{(1-m_1)(h_{f5} - h_{f3})}{(h_2 - h_{f3})}$$

All enthalpies may be determined; therefore m_1 and m_2 may be found. The maximum temperature to which the water can be heated is dictated by that of bled steam. The condensate from the bled steam is added to feed water.

Neglecting pump work :

The heat supplied externally in the cycle.

$$= (h_0 - h_{f6})$$

Isentropic work done $= m_1 (h_0 - h_1) + m_2 (h_0 - h_2) + (1 - m_1 - m_2)(h_0 - h_3)$

The thermal efficiency of regenerative cycle is

$$\eta_{thermal} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{m_1 (h_0 - h_1) + m_2 (h_0 - h_2) + (1 - m_1 - m_2)(h_0 - h_3)}{(h_0 - h_{f6})}$$

Advantages of Regenerative cycle over simple Rankine cycle:

1- The heating process in the boiler tends to become reversible.

2- The thermal stresses set up in the boiler are minimised. This is due to the fact that temperature ranges in the boiler are reduced.

3- The thermal efficiency is improved because the average temperature of heat addition to the cycle is increased.

4- Heat rate is reduced.

5- The blade height is less due to the reduced amount of steam passed through the low pressure stages.

~~6- The blade height is less due to the~~

6- Due to may extraction there is an improvement in the turbine drainage and it reduces erosion due to moisture,

7- A small size condenser is required.

Disadvantage

1- The plant becomes more complicated.

2- Because of addition of heaters greater ~~maintaince~~ maintanance is required.

3- For given power a large capacity boiler is required.

4- The heaters are costly and the gain in thermal efficiency is not much in comparsion to the heavier costs.

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BASICS OF HEAT TRANSFER

The science of thermodynamics deals with the amount of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference to how long the process will take. But in engineering, we are often interested in the rate of heat transfer, which is the topic of the science of heat transfer.

We all know from experience that a cold canned drink left in a room warms up and a warm canned drink left in a refrigerator cool down. This is accomplished by the transfer of energy from the warm medium to the cold one. The energy transfer is always from the higher temperature medium to the lower temperature one, and the energy transfer stops when the two mediums reach the same temperature.

In thermodynamics, energy exists in various forms. Here we are primarily interested in heat, which is the form of energy that can be transferred from one system to another as a result of temperature difference. The science that deals with the determination of the rates of such energy transfers is heat transfer.

Thermodynamics deals with equilibrium states and changes from one equilibrium state to another. Heat transfer, on the other hand, deals with systems that lack thermal equilibrium, and thus it is a nonequilibrium phenomenon.

The basic requirement for heat transfer is the presence of a temperature difference. There can be no net heat transfer between two mediums that are at the same temperature. The temperature difference is the driving force for heat transfer, just as the voltage difference is the driving force for electric current flow and pressure difference is the driving force for fluid flow***. The rate of heat transfer in a certain direction depends on the magnitude of the temperature gradient (the temperature difference per unit length or the rate of change of temperature) in that direction.*** The larger the temperature gradient, the higher the rate of heat transfer.

Application Areas of Heat Transfer: -

1. The human body is constantly rejecting heat to its surroundings, and human comfort is closely tied to the rate of this heat rejection. We try to control this heat transfer rate by adjusting our clothing to the environmental conditions.
2. Many household appliances are designed, in whole or in part, by using the principles of heat transfer on the basis of minimizing heat loss in winter and heat gain in summer.
   Examples: -the electric or gas range, the heating and air-conditioning system, the refrigerator and freezer, the water heater, the iron, and even the computer, the TV, and the VCR etc.
3. Heat transfer plays a major role in the design of many other devices, such as car radiators, solar collectors, various components of power plants, and even spacecraft.
4. The optimal insulation thickness in the walls and roofs of the houses, on hot water or steam pipes, or on water heaters is again determined on the basis of a heat transfer analysis with economic consideration.

Some Terms Related to Heat Transfer: -

Thermal Conductivity :- (k)

It can be defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.

→ It is the measure of the ability of the material to conduct heat.

High value — Good heat conductor

Low value — Poor heat conductor / Insulator

- Pure crystals and metals have highest thermal conductivity and gases and insulating materials the lowest.

Unit :- W/m-K (Watt per meter kelvin)

Thermal Diffusivity (α) :-

- It is the thermal conductivity divided by density and specific heat capacity at constant pressure.
- It measures the rate of heat transfer of heat of a material from the hot end to the cold end.

Unit :→ m^2/s

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho C_p}$$

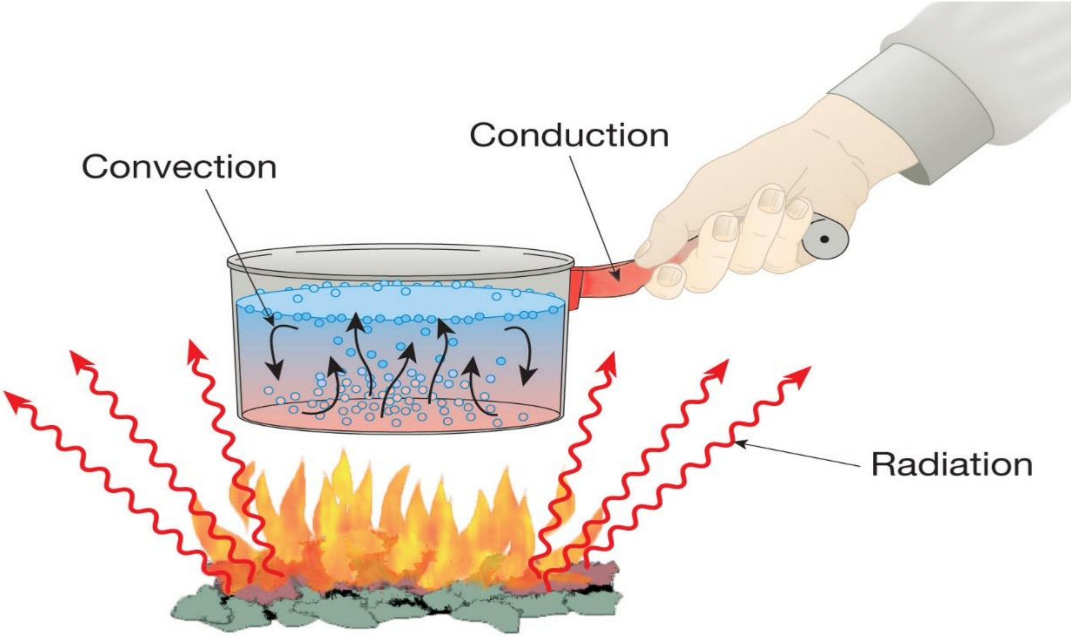
where, C_p = Specific heat capacity (J/kg-K)

ρ = density (kg/m³)

ρC_p = Volumetric heat capacity (J/m³.K)

Larger the value of 'α', the faster the propagation of heat into the medium.

Modes of Heat Transfer: -



Heat can be transferred in three different modes:

- Conduction
- Convection
- Radiation

CONDUCTION: -

Conduction is heat transfer by means of molecular agitation within a material without any motion of the material as a whole.

Conduction can take place in solids, liquids, or gases. In gases and liquids, conduction is due to the collisions and diffusion of the molecules during their random motion. In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.

The rate of heat conduction through a medium depends on the geometry of the medium, its thickness, and the material of the medium, as well as the temperature difference across the medium. We know that wrapping a hot water tank with glass wool (an insulating material) reduces the rate of heat loss from the tank. The thicker the insulation, the smaller the heat loss. We also know that a hot water tank will lose heat at a higher rate when the temperature of the room housing the tank is lowered. Further, the larger the tank, the larger the surface area and thus the rate of heat loss.

Fourier's Law

Consider steady heat conduction through a large plane wall of thickness $\Delta x = L$ and area A

Temperature difference across the wall $\Delta T = T_2 - T_1$

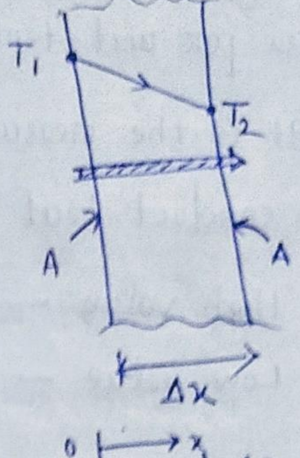


Fig:- Heat conduction through a large plane wall of thickness Δx and area A

According to experiment

$$\text{Rate of heat conduction} \propto \frac{(\text{Area}) \times (\text{Temp. difference})}{\text{Thickness}}$$

$$\Rightarrow \dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad (\text{As } \Delta T = T_2 - T_1)$$

where, k = Thermal conductivity of the material (Proportionality constant)

In differential form $\boxed{\dot{Q}_{cond} = -kA\frac{dT}{dx}}$

It is called Fourier's law of heat conduction.

Definition :- It states that the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer.

* Temperature Gradient :—

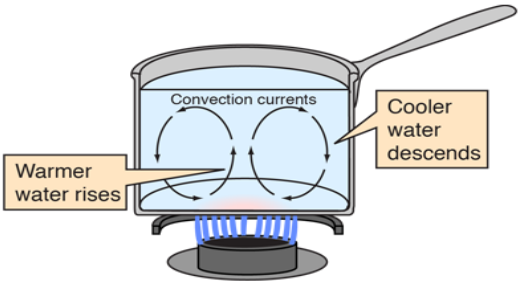
It can be defined as change in temp in a particular direction. Change may be rise or fall.

$$\frac{T_1 - T_2}{\Delta x} = \frac{\Delta T}{\Delta x} = \frac{dT}{dx}$$

CONVECTION: -

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion.

The faster the fluid motion, the greater the convection heat transfer. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates



Convection can also lead to circulation in a liquid, as in the heating of a pot of water over a flame. Heated water expands and becomes more buoyant. Cooler, more dense water near the surface descends and patterns of circulation can be formed.

Newton's Law of Cooling :-

The rate of convection heat transfer is observed to be proportional to the temperature difference.

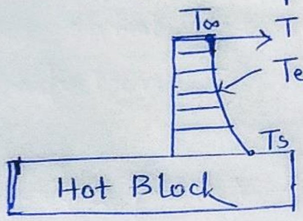
$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

where h = convection heat transfer coefficient (W/m^2K)

A_s = Surface area through which convection heat transfer takes place

T_s = Surface temperature

T_∞ = Temp. of fluid sufficiently far from the surface



Temp. variation of air → As distance increases temp. decreases

RADIATION: -

Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules. Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium. In fact, energy transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.

Here we are interested in thermal radiation, which is the form of radiation emitted by bodies because of their temperature. It differs from other forms of electromagnetic radiation such as x-rays, gamma rays, microwaves, radio waves, and television waves that are not related to temperature.

All bodies at a temperature above absolute zero emit thermal radiation. Radiation is a volumetric phenomenon, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees. However, radiation is usually considered to be a surface phenomenon for solids that are opaque to thermal radiation such as metals, wood, and rocks since the radiation emitted by the interior regions of such material can never reach the surface, and the radiation incident on such bodies is usually absorbed within a few microns from the surface.

Stefan- Boltzmann Law: -

It states that the rate of radiation that can be emitted from a surface is directly proportional to the 4th power of absolute temp. T_s.

$$\dot{Q}_{emit,max} \propto A_s T^4 \Rightarrow \dot{Q}_{emit,max} = \sigma A_s T^4$$

In terms of energy it states that the total energy radiated per unit time(second) per unit area of a surface is directly proportional to the 4th power of absolute temp. T_s.

$$\boxed{E \ \alpha \ T^4 \ => E = \sigma T^4}$$

Where σ= Stefan- Boltzmann Constant

Value of σ= $5.67\times10^{-8} \frac{W}{m^2K^4}$

The law applies only to blackbodies, theoretical surfaces that absorb all incident heat radiation.

Black body radiation :-

A black body in thermal equilibrium (i.e. at constant temperature) emits electromagnetic radiation called black-body radiation.

Black body is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. (It is idealized opaque and non-reflective body). It emits radiation at the maximum rate.

The radiation emitted by all ~~black~~ real surfaces is less than the radiation emitted by a black body at the same temperature. It can be expressed as

$$\dot{Q}_{emit} = \varepsilon \sigma A_s T_s^4$$

where ε = Emissivity of the surface

value of ε is in the range $0 \leq \varepsilon \leq 1$.

For black body $\varepsilon = 1$.

The emissivity of the surface of a material is its effectiveness in emitting energy as thermal radiation. It is the ratio of the energy radiated from a material's surface to that radiated from a perfect emitter (i.e. black body) at the same temp. and wavelength and under same viewing condition.

Absorptivity (α) :-

It is a measure of how much of the radiation is absorbed by the body.

Value ranges in $0 \leq \alpha \leq 1$.

$$\boxed{\alpha = \frac{\text{Absorbed radiation}}{\text{Incident radiation}}}$$

- Black body is a perfect absorber ($\alpha = 1$) as it is a perfect emitter.

Transmissivity (τ) :-

It is a measure of how much of the radiation is transmitted by the body.

$$\tau = \frac{\text{Transmitted radiation}}{\text{Incident radiation}}, \quad 0 \leq \tau \leq 1$$

Both ε and α of a surface depends on the temperature and wavelength of the radiation.

Kirchhoff's law of radiation states that the emissivity and absorptivity of a surface at a given temperature and wavelength are equal.