Part II. Energy Efficiency by Sectors

# Energy Efficiency in Boilers & Steam System

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Introduction to Boiler

- **It is an enclosed Pressure Vessel**
- **Heat generated by Combustion of Fuel is transferred to water to become steam**
- **Process: Evaporation**

- **Steam volume increases to 1,600 times from water and produces tremendous force**
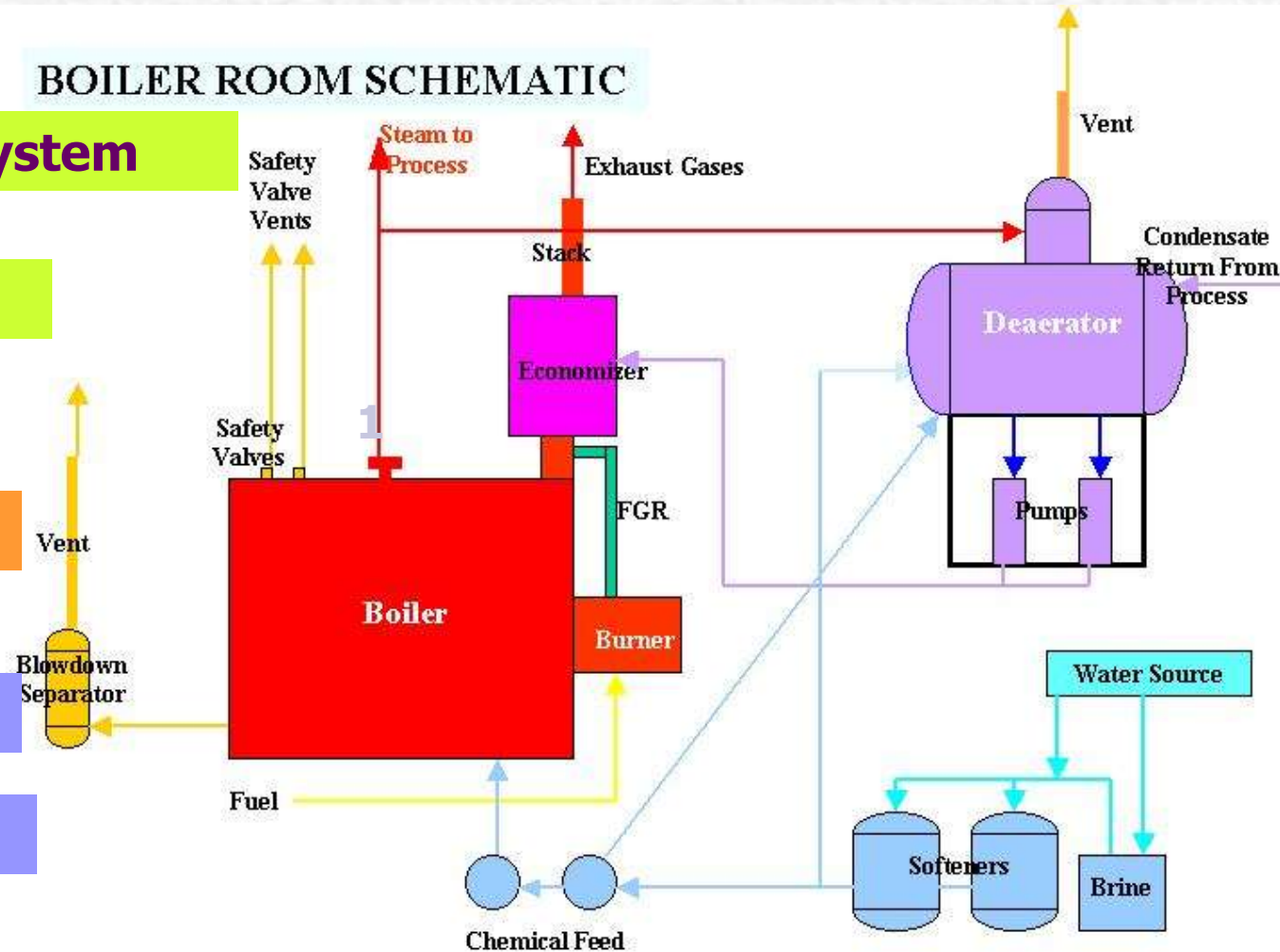- **Care is must to avoid explosion**

Sight Glass

Door Gasket

Tubes

Typical Boiler
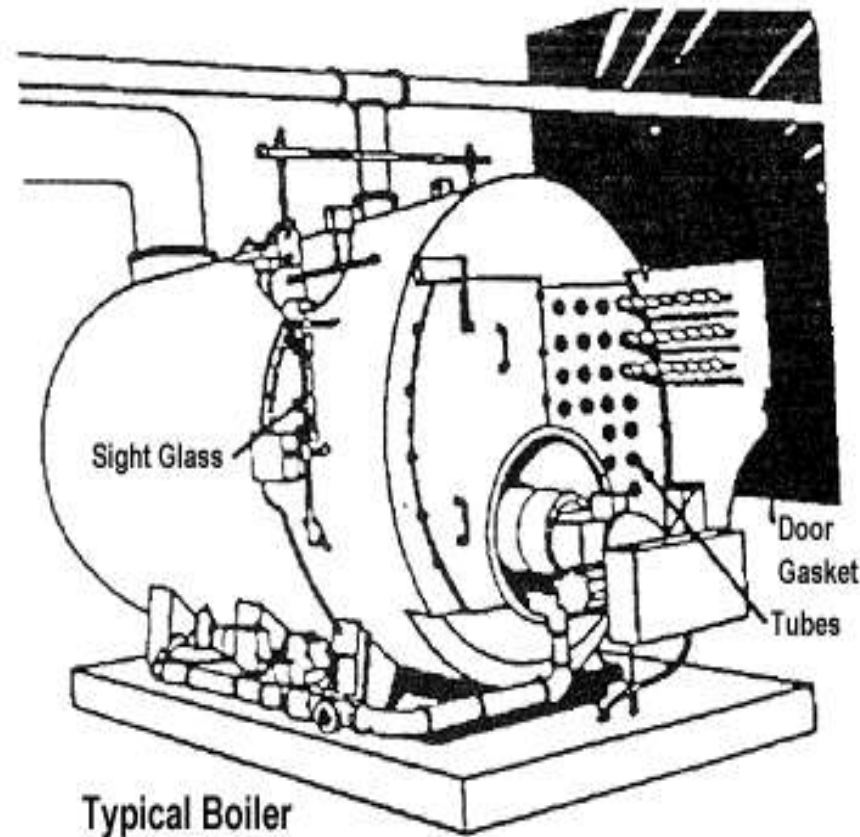
What is a boiler?

Boiler Specification

- **Boiler Make & Year** **:XYZ & 2003**

- **MCR(Maximum Continuous Rating) :10TPH (F & A 100°C)**

- **Rated Working Pressure:** **10.54 kg/cm^2(g)**

- **Type of Boiler** **:** **3 Pass Fire tube**

- **Fuel Fired** **:** **Fuel Oil**
- **Heating surface** **:** **m^2**

Boiler Systems

✓**Water treatment system**

✓**Feed water system**

✓**Steam System**

✓**Blow down system**

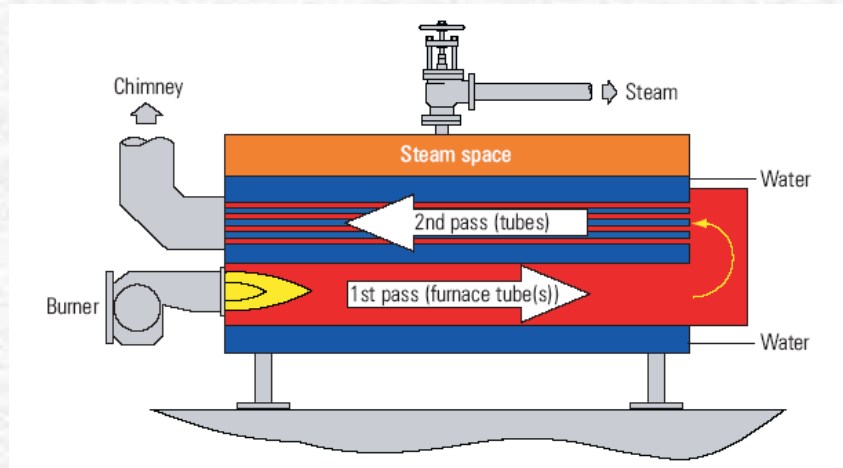✓**Fuel supply system**

✓**Air Supply system**

✓**Flue gas system**

BOILER ROOM SCHEMATIC

Boiler Types and Classifications

Fire Tube Boiler

Fire in tube or Hot gas through tubes and boiler feed water in shell side

- **Fire Tubes submerged in water Application**

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Boiler Types and Classifications

Fire Tube Boilers

Advantages

- Relatively inexpensive;
- Easy to clean;
- Compact in size;
- Available in sizes from 600,000 btu/hr to 50,000,000 btu/hr;
- Easy to replace tubes;
- Well suited for space heating and industrial process applications.

Disadvantages

- Not suitable for high pressure applications 250 psig and above;
- Limitation for high capacity steam generation.

Boiler Types and Classifications

Water Tube Boiler

- Water flow through tubes
- Water Tubes surrounded by hot gas

Application

- Used for Power Plants
- Steam capacities range from 4.5-120 t/hr

Characteristics

- High Capital Cost
- Used for high pressure high capacity steam boiler
- Demands more controls
- Calls for very stringent water quality

Steam

flue gas

Burners
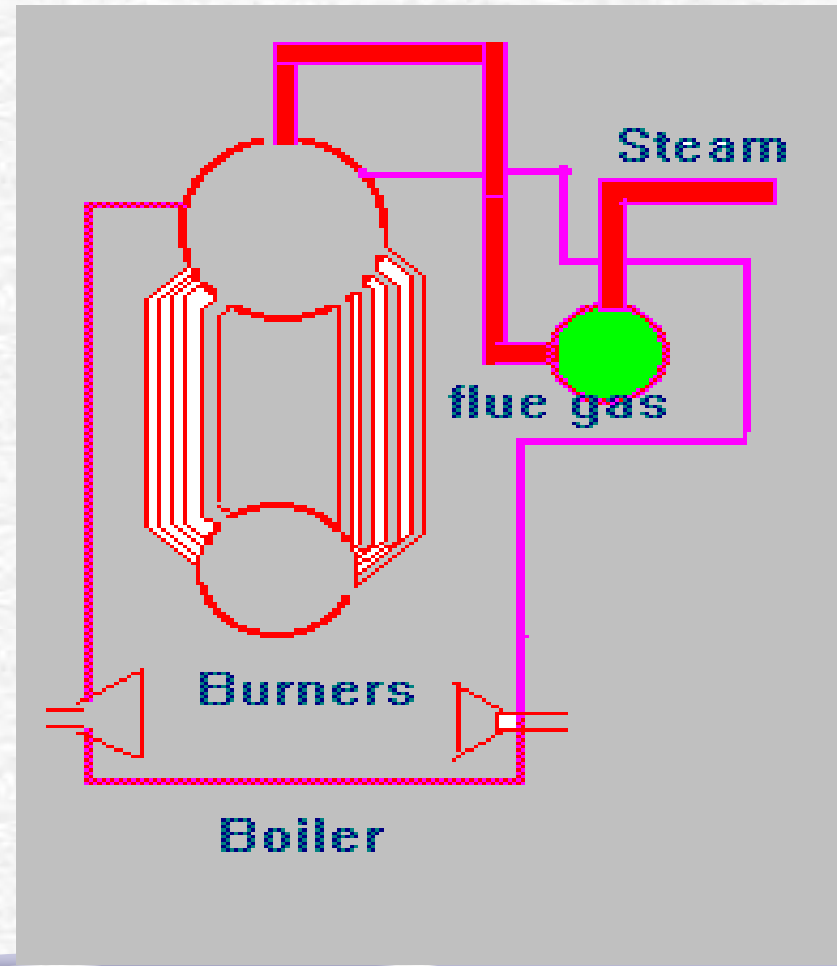
Boiler

Boiler Types and Classifications

Water Tube Boilers

Advantages

- Used for high pressure high capacity steam boiler
- Available in sizes that are far greater than the fire tube design. Up to several million pounds per hour of steam.
- Able to handle higher pressures up to 5,000psig
- Recover faster than their firetube cousin
- Have the ability to reach very high temperatures

Disadvantages

- Calls for very stringent water quality;
- Demand more Control;
- High Capital Cost;
- Cleaning is more difficult due to the design;
- No commonality between tubes;
- Physical size may be an issue

Once Through Boiler
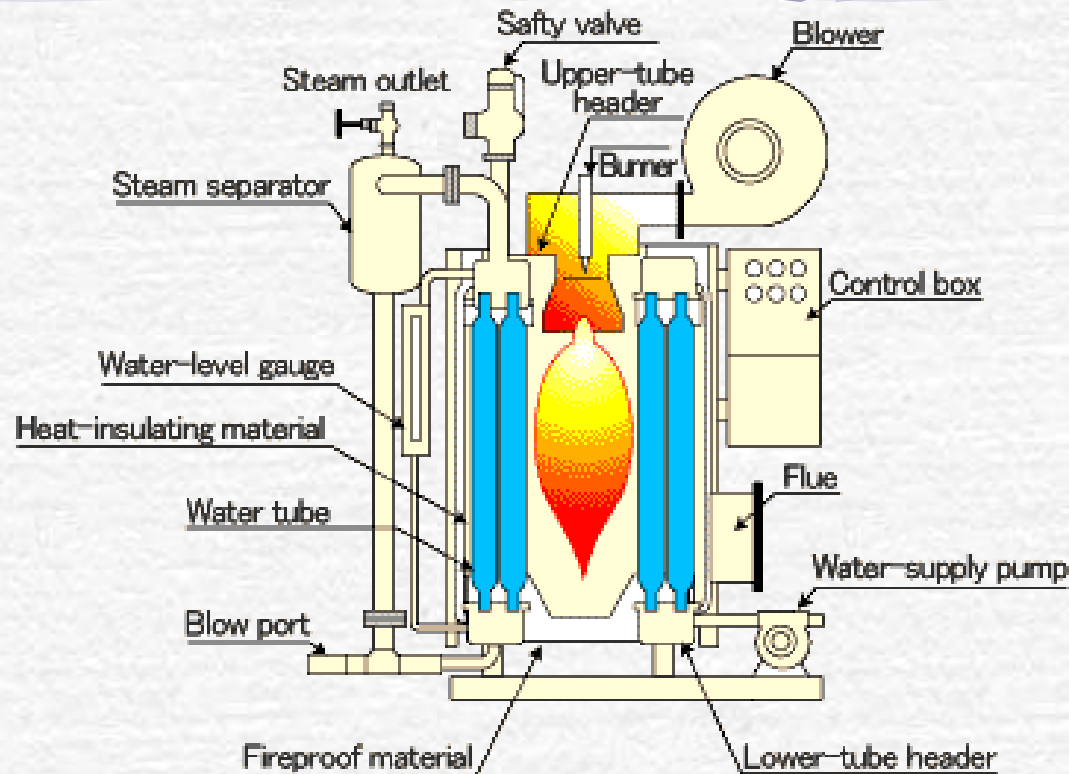
Advantages:
➢ No steam drum, and more safety;
➢ Easy to control.

Disadvantages:
➢ High quality of water needs.

Performance Evaluation of Boilers

Evaporation Rate:

❑ Actual Evaporation Rate;

❑ Equivalent Evaporation Rate;

❑ Boiler Horse power

➢Efficiency of Boiler.

❑ Actual Evaporation Rate is rate of steam produced from boiler under a certain pressure and feed water temperature is equal 30 °C.

❑ Equivalent Evaporation Rate is rate of steam produced from boiler under atmospheric pressure and temperature 100°C.

❑ Boiler Horse Power:

$$1 Bhp = 34.5\,lb\,/\,h = 15.65\,kg\,/\,h$$

Relation between Equivalent Evaporation Rate and Actual Evaporation Rate

Pressure bar g	Saturation temperature °C	Enthalpy kJ/kg			Volume of dry saturated steam m³/kg
		Water h_f	Evaporation h_{fg}	Steam h_g	
0	100	419	2 257	2 676	1.673
1	120	506	2 201	2 707	0.881
2	134	562	2 163	2 725	0.603
3	144	605	2 133	2 738	0.461
4	152	641	2 108	2 749	0.374
5	159	671	2 086	2 757	0.315
6	165	697	2 066	2 763	0.272
7	170	721	2 048	2 769	0.240

Actual Evaporation Rate, (kg/h)

Equivalent Evaporation Rate,(kg/h)

Enthalpy of saturated steam,(kJ/kg)

Enthalpy of feed water,(kJ/kg)

$$M_e = \frac{M_a(h_{ga} - h_{fa})}{2257}$$

$$h_{fa} = 4.19 \times T$$

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Example

A boiler produced equivalent evaporation rate 5,000kg/h. If this boiler operates under pressure and feed water temperature are 5 barg and 25°C respectively. What is the actual evaporation rate?

At P = 5 barg, h_{ga} = 2757kJ/kg

and,

feed water temperature 25°C, h_{fa} = 25°C X 4.19kJ/kg°C = 104.75kJ/kg

$$5,000 \text{kg/h} = \frac{M_a \times (2,757\text{kJ/kg} - 104.75\text{kJ/kg})}{2,257\text{kJ/kg}}$$

$$\Rightarrow M_a = \frac{(5,000\text{kg/h} \times 2,257\text{kJ/kg})}{(2,757\text{kJ/kg} - 104.75\text{kJ/kg})} = 4,254.88 \text{ kg/h}$$
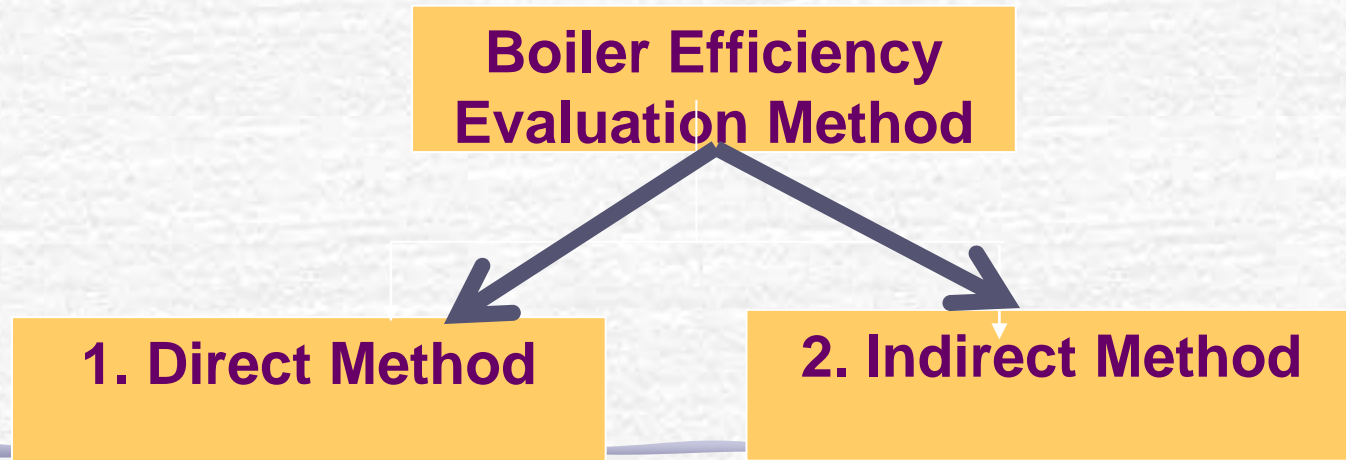
Boiler Efficiency

Thermal efficiency of boiler is defined as the percentage of heat input that is effectively utilized to generate steam.
There are two methods of assessing boiler efficiency.

1)   The Direct Method: Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

2)   The Indirect Method: Where the efficiency is the difference between the losses and the energy input.

Boiler Efficiency Evaluation Method

1. Direct Method

2. Indirect Method

Direct Method

This is also known as 'input-output method'

$$Boiler\,Efficiency = \frac{Heat\,Output}{Heat\,Input} \times 100$$

Boiler efficiency (η):   =   **Q x (H – h)   x 100**

                                                 (q x GCV)

Where: **Q** = Quantity of steam generated per hour, (kg/hr)

H = Enthalpy of saturated steam, (kcal/kg)

h = Enthalpy of feed water, (kcal/kg)

q = Quantity of fuel used per hour, (kg/hr)

GCV = Gross calorific value of the fuel, (kcal/kg)

Advantages of direct method:
➢Plant people can evaluate quickly the efficiency of boilers;
➢Requires few parameters for computation;
➢Needs few instruments for monitoring

Disadvantages of direct method:
➢Does not give clues to the operator as to why efficiency of system is lower;
➢Does not calculate various losses accountable for various efficiency levels

Efficiency Calculation by Direct Method

Example:

Type of boiler: Coal fired Boiler

Heat input data

Qty of oil consumed   : 2.0 TPH

GCV of oil   : 10,200 kCal/kg

Heat output data

- Qty of steam gen   : 24 TPH

- Steam pr/temp:10 kg/cm^2(g)/180^{0}C

- Enthalpy of steam(sat) at 10 kg/cm^2(g) pressure: 665 kCal/kg

- Feed water temperature : 85^0 C

- Enthalpy of feed water   : 85 kCal/kg

Find out the Find efficiency ?

Find out the Evaporation Ratio?

Efficiency Calculation by Direct Method

Boiler efficiency (η)=

$\underline{24 \text{ TPH x1000kg/Tx (665--85) x 100}}$

2.0 TPH x 1000kg/T x 10,200

=   68.2%

Evaporation Ratio = 24Tonne of steam/ 2.0 Ton of oi**l = 12**

Boiler Evaporation Ratio

Evaporation ratio means kilogram of steam generated per kilogram of fuel consumed.

Typical Examples: Coal fired boiler   :   6

Oil fired boiler   : 13

1 kg of coal can generate 6 kg of steam

1 kg of oil can generate 13 kg of steam

However, this figure will depend upon type of boiler, calorific value of the fuel and associated efficiencies.
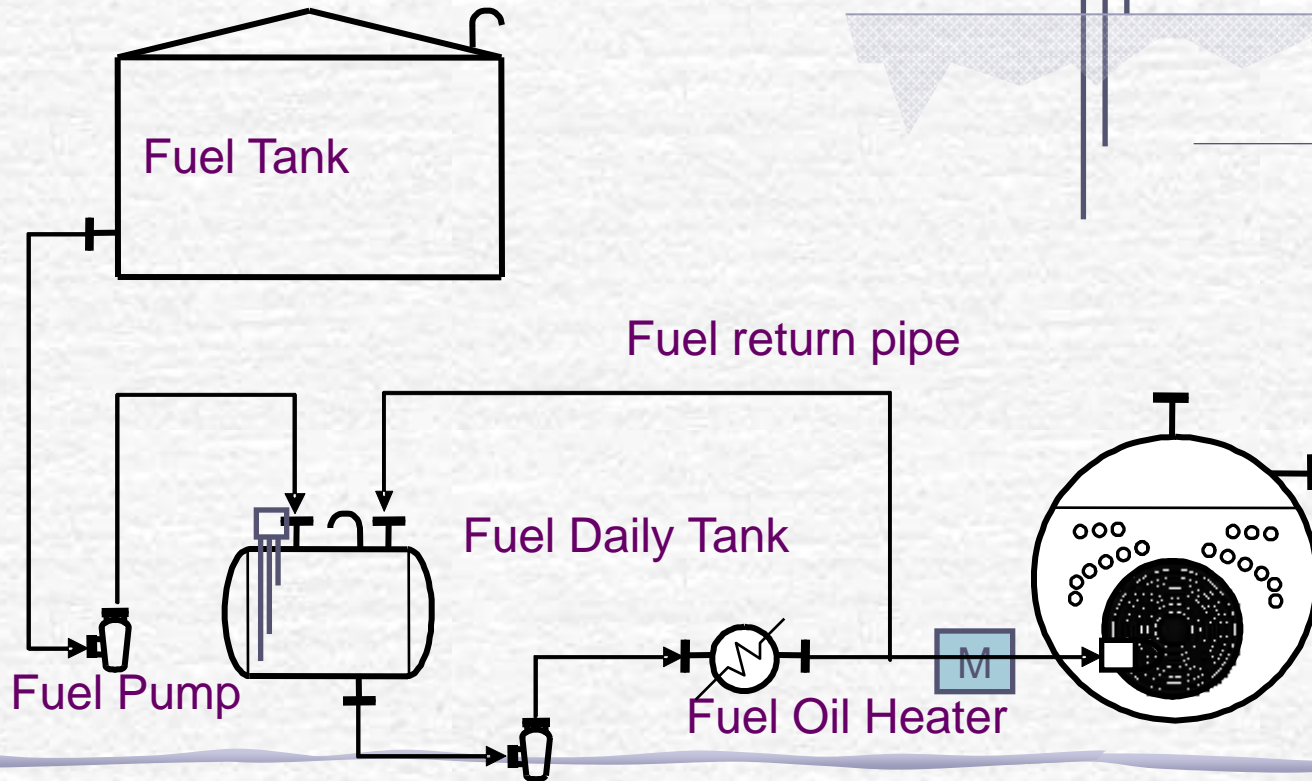
Measurement of fuel consumption rate

$$\eta_B = \frac{\dot{m}_s (h_g - h_f)}{\dot{m}_f (HHV)} \times 100\%$$
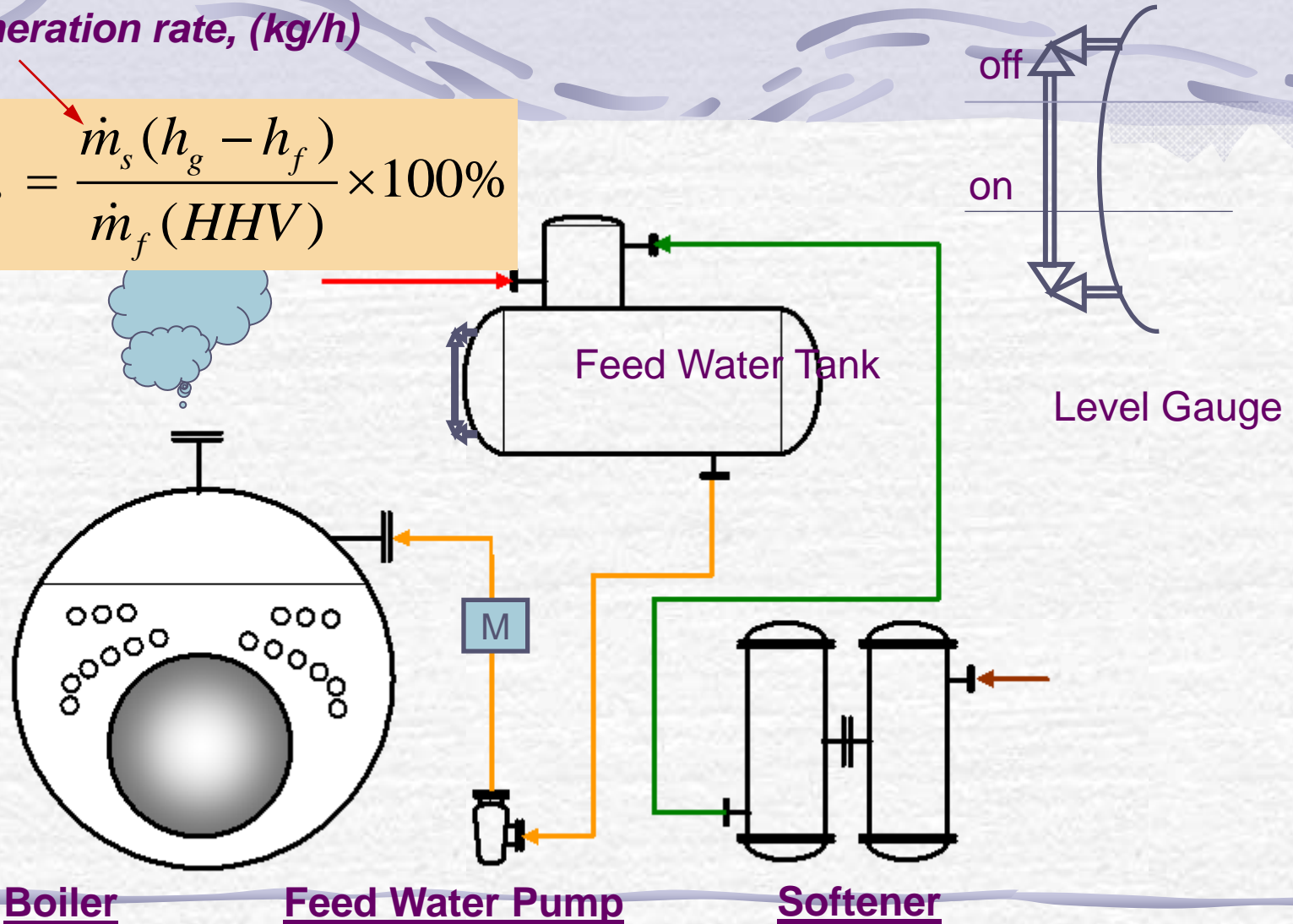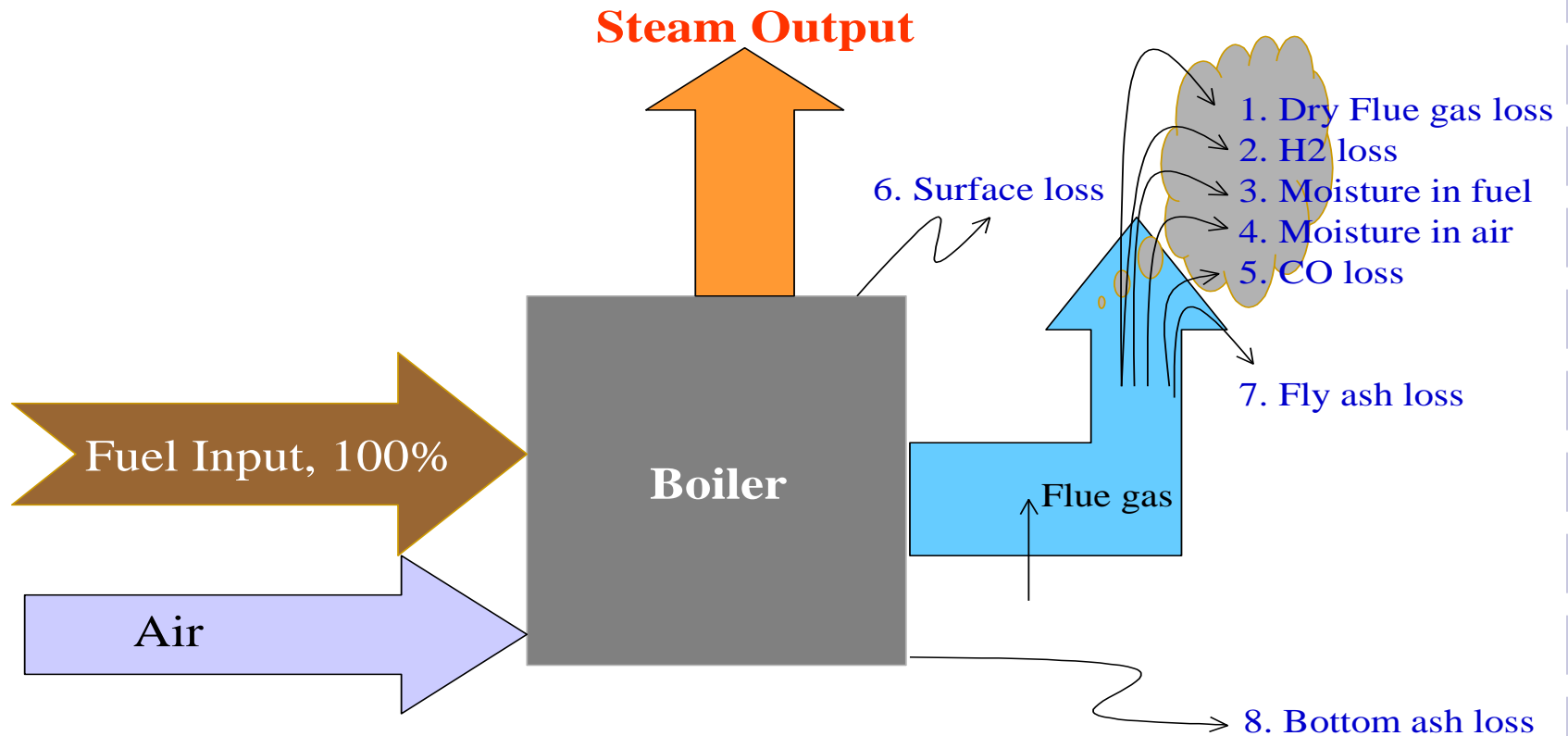
Fuel consumption rate, (kg/h)

Electrode

off

on

Fuel Tank

Fuel return pipe

Fuel Daily Tank

Fuel Pump

Fuel Oil Heater

M
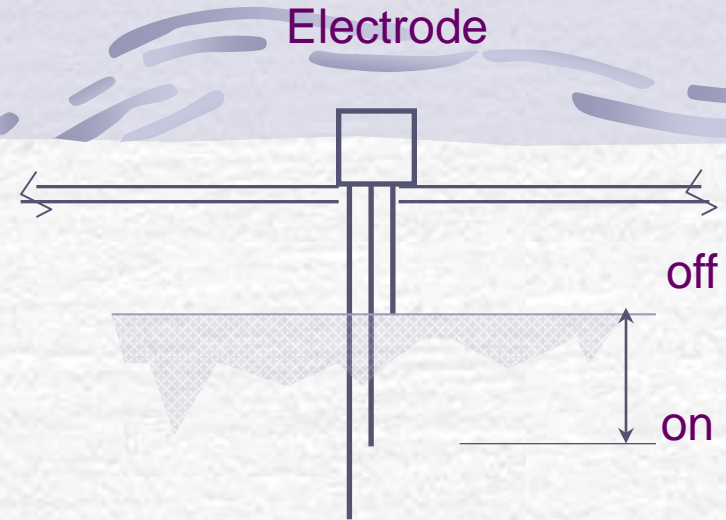
Measurement of steam generation rate

Steam generation rate, (kg/h)

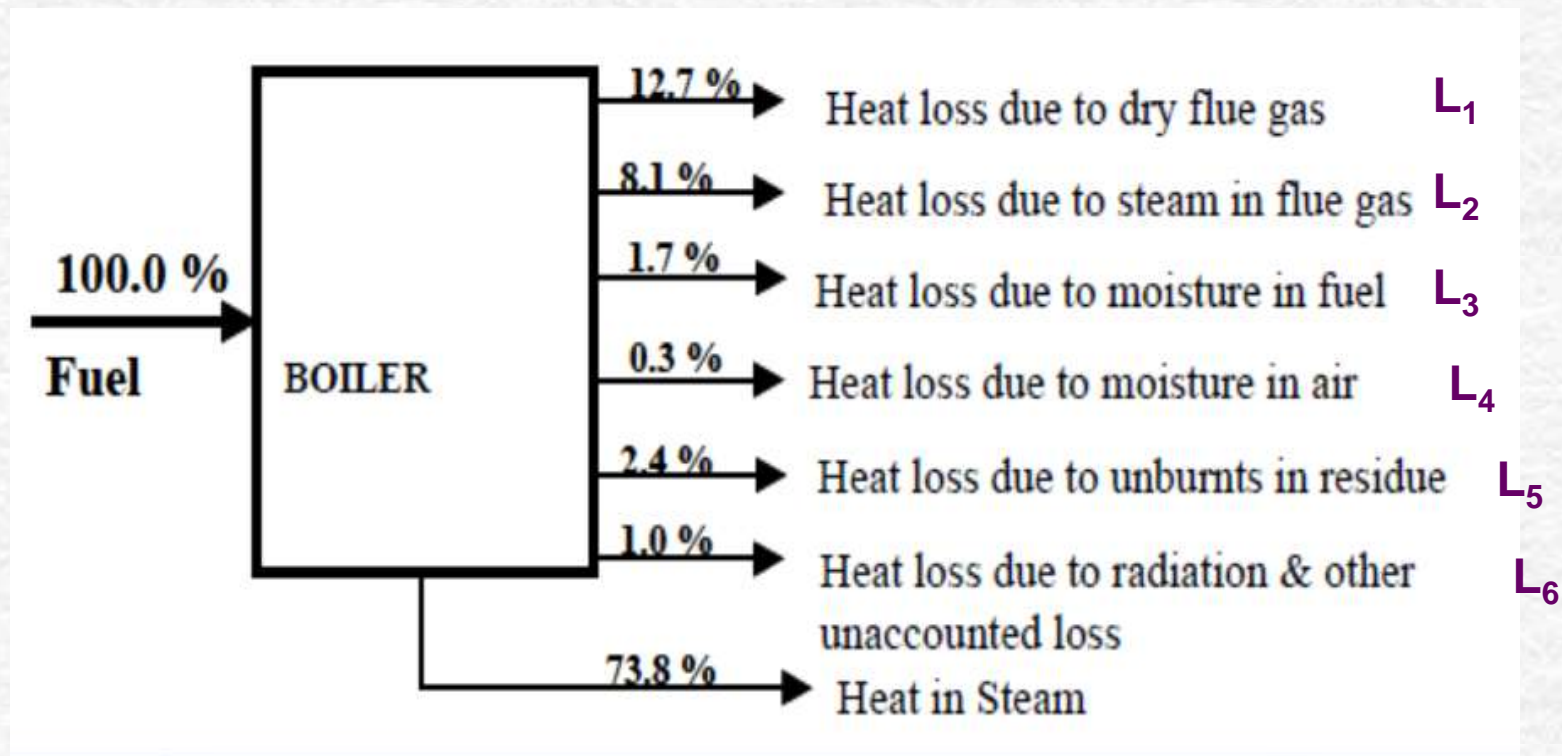$$\eta_B = \frac{\dot{m}_s (h_g - h_f)}{\dot{m}_f (HHV)} \times 100\%$$

off

on

Feed Water Tank

Level Gauge

M

Boiler   **Feed Water Pump**   **Softener**

What are the losses that occur in a boiler?

Steam Output

Fuel Input, 100%

Air

Boiler

6. Surface loss

1. Dry Flue gas loss
2. H2 loss
3. Moisture in fuel
4. Moisture in air
5. CO loss

7. Fly ash loss

Flue gas

8. Bottom ash loss

Efficiency   = 100 – (1+2+3+4+5+6+7+8)

(by In Direct Method)

100.0 %
Fuel

BOILER

12.7 % → Heat loss due to dry flue gas L_1

8.1 % → Heat loss due to steam in flue gas L_2

1.7 % → Heat loss due to moisture in fuel L_3

0.3 % → Heat loss due to moisture in air L_4

2.4 % → Heat loss due to unburnts in residue L_5

1.0 % → Heat loss due to radiation & other unaccounted loss L_6

73.8 % → Heat in Steam

Dry Flue Gas Loss:

$$L1 = \frac{m \times C_p \times (T_f - T_a)}{GCV \text{ of fuel}} \times 100$$

Where,

L_1 = % Heat loss due to dry flue gas
m = Mass of dry flue gas in kg/kg of fuel
= Combustion products from fuel: $CO_2 + SO_2$ + Nitrogen in fuel + Nitrogen in the actual mass of air supplied + O_2 in flue gas. (H_2O/Water vapour in the flue gas should not be considered)
C_p = Specific heat of flue gas in kCal/kg°C
T_f = Flue gas temperature in °C
T_a = Ambient temperature in °C

Heat Loss due to Steam(H_2)

$$L_2 = \frac{9 \times H_2 \times \{584 + C_p\,(T_f - T_a)\}}{GCV \text{ of fuel}} \times 100$$

Where

H_2 = kg of hydrogen present in fuel on 1 kg basis
C_p = Specific heat of superheated steam in kCal/kg°C
T_f = Flue gas temperature in °C
T_a = Ambient temperature in °C
584 = Latent heat corresponding to partial pressure of water vapour

Heat Loss due to present moisture in Fuel

$$L_3 = \frac{M \times \{584 + C_p\,(T_f - T_a)\}}{GCV \text{ of fuel}} \times 100$$

where

M = kg moisture in fuel on 1 kg basis
C_p = Specific heat of superheated steam in kCal/kg°C
T_f = Flue gas temperature in °C
T_a = Ambient temperature in °C
584 = Latent heat corresponding to partial pressure of water vapour

Heat Loss due to present moisture in air

Dry-Bulb Temp °C	Wet Bulb Temp °C	Relative Humidity (%)	Kilogram water per Kilogram dry air (Humidity Factor)
20	20	100	0.016
20	14	50	0.008
30	22	50	0.014
40	30	50	0.024

$$L_4 = \frac{AAS \times \text{humidity factor} \times C_p \times (T_f - T_a) \times 100}{GCV \text{ of fuel}}$$

where

AAS = Actual mass of air supplied per kg of fuel
Humidity factor = kg of water/kg of dry air
C_p = Specific heat of superheated steam in kCal/kg°C
T_f = Flue gas temperature in °C
T_a = Ambient temperature in °C (dry bulb)

Heat Loss due to incomplete combustion

$$L_5 = \frac{\%CO \times C}{\% CO + \% CO_2} \times \frac{5744}{GCV \text{ of fuel}} \times 100$$

L_5 = % Heat loss due to partial conversion of C to CO
CO = Volume of CO in flue gas leaving economizer (%)
CO_2 = Actual Volume of CO_2 in flue gas (%)
C = Carbon content kg / kg of fuel

or

When CO is obtained in ppm during the flue gas analysis
CO formation (M_{co}) = CO (in ppm) $\times 10^{-6} \times M_f \times 28$
M_f = Fuel consumption in kg/hr
L_5 = $M_{co} \times 5744^*$
* Heat loss due to partial combustion of carbon.

Heat loss due to radiation and convection

$$L_6 = 0.548 \times [(T_s / 55.55)^4 - (T_a / 55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times \text{sq.rt of } [(196.85\, V_m + 68.9) / 68.9]$$

where

L_6 = Radiation loss in W/m^2
V_m = Wind velocity in m/s
T_s = Surface temperature (K)
T_a = Ambient temperature (K)

Heat loss due to unburnt in fly ash

$$L_7 = \frac{\text{Total ash collected / kg of fuel burnt} \times \text{G.C.V of fly ash} \times 100}{\text{GCV of fuel}}$$

Heat loss due to unburnt in bottom ash

$$L_8 = \frac{\text{Total ash collected per kg of fuel burnt} \times \text{G.C.V of bottom ash} \times 100}{\text{GCV of fuel}}$$

The following are the data collected for a boiler using furnace oil as the fuel. Find out the boiler efficiency by indirect method.

Ultimate analysis (%)

Carbon	=	84
Hydrogen	=	12
Nitrogen	=	0.5
Oxygen	=	1.5
Sulphur	=	1.5
Moisture	=	0.5
GCV of fuel	=	10000 kCal/kg
Fuel firing rate	=	2648.125 kg/hr
Surface Temperature of boiler	=	80 °C
Surface area of boiler	=	90 m^2
Humidity	=	0.025 kg/kg of dry air
Wind speed	=	3.8 m/s

Flue gas analysis (%)

Flue gas temperature	=	190°C
Ambient temperature	=	30°C
CO_2% in flue gas by volume	=	10.8
O_2% in flue gas by volume	=	7.4

% Heat loss in dry flue gas

$$= \frac{m \times C_p \times (T_f - T_a)}{GCV \text{ of fuel}} \times 100$$

$$= \frac{21.36 \times 0.23 \times (190 - 30)}{10000} \times 100$$

$$L_1 = 7.86 \%$$

Heat loss due to evaporation of water due to H_2 in fuel (%)

$$= \frac{9 \times H_2 \times \{584 + C_p (T_f - T_a)\}}{GCV \text{ of fuel}} \times 100$$

$$= \frac{9 \times 0.12 \times \{584 + 0.45 (190 - 30)\}}{10000} \times 100$$

$$L_2 = 7.08 \%$$

a) Theoretical air required

$= [(11.6 \times C) + [\{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)] /100$ kg/kg of fuel. [from fuel analysis]

$= [(11.6 \times 84) + [\{34.8 \times (12 - 1.5/8)\} + (4.35 \times 1.5)] / 100$

$= \textbf{13.92 kg/kg of oil}$

b) Excess Air supplied (EA)

$= (O_2 \times 100) / (21 - O_2)$

$= (7.4 \times 100) / (21 - 7.4)$

$= \textbf{54.4 \%}$

c) Actual mass of air supplied/ kg of fuel (AAS)

$= \{1 + EA/100\} \times$ theoretical air

$= \{1 + 54.4/100\} \times 13.92$

$= \textbf{21.49 kg / kg of fuel}$

Mass of dry flue gas

$=$ Mass of $(CO_2 + SO_2 + N_2 + O_2)$ in flue gas + N_2 in air we are supplying

$$= \frac{0.84 \times 44}{12} + \frac{0.015 \times 64}{32} + 0.005 + \frac{7.4 \times 23}{100} + \frac{21.49 \times 77}{100}$$

$= \textbf{21.36 kg / kg of oil}$

% Heat loss due to moisture in fuel $= \dfrac{M \times \{584 + C_p (T_f - T_a)\}}{GCV \text{ of fuel}} \times 100$

$= \dfrac{0.005 \times \{584 + 0.45 (190 - 30)\}}{10000} \times 100$

$L_3 = 0.033\%$

% Heat loss due to moisture in air $= \dfrac{AAS \times \text{humidity} \times C_p \times (T_f - T_a) \times 100}{}$

Radiation and convection loss $= 0.548 \times [(T_s / 55.55)^4 - (T_a / 55.55)^4] + 1.957$
(L_6) $\times (T_s - T_a)^{1.25} \times \text{sq.rt of } [(196.85 \, V_m + 68.9) / 68.9]$

$= 0.548 \times [(353 / 55.55)^4 - (303 / 55.55)^4] + 1.957$
$\times (353 - 303)^{1.25} \times \text{sq.rt of } [(196.85 \times 3.8 + 68.9)/ 68.9]$

$= 1303 \, W/m^2$

$= 1303 \times 0.86$

$= 1120.58 \, kCal / m^2$

Total radiation and convection loss per hour
$= 1120.58 \times 90 \, m^2$
$= 100852.2 \, kCal$

% Radiation and convection loss $= \dfrac{100852.2 \times 100}{10000 \times 2648.125}$

$L_6 = 0.38 \%$
Normally it is assumed as 0.5 to 1 % for simplicity

Boiler efficiency by indirect method
$= 100 - (L_1 + L_2 + L_3 + L_4 + L_6)$
$= 100 - (7.86 + 7.08 + 0.033 + 0.38 + 0.38)$
$= 100 - 15.73$
$= 84.27 \%$

Input/Output Parameter		kCal / kg of furnace oil	% Loss
Heat Input	=	10000	100
Losses in boiler :			
1. Dry flue gas, L_1	=	786	7.86
2. Loss due to hydrogen in fuel, L_2	=	708	7.08
3. Loss due to Moisture in fuel, L_3	=	3.3	0.033
4. Loss due to Moisture in air, L_4	=	38	0.38
5. Partial combustion of C to CO, L_5	=	0	0
6. Surface heat losses, L_6	=	38	0.38
Boiler Efficiency = $100 - (L_1 + L_2 + L_3 + L_4 + L_6) = 84.27\%$			

Boiler Blowdown

When water is boiled and steam is generated, any dissolved solids contained in the water remain in the boiler. If more

solids are put in with the feed water, they will concentrate and may eventually reach a level where their solubility in the water is exceeded and they deposit from the solution. Above a certain level of concentration, these solids encourage foaming and cause carryover of water into the steam. The deposits also lead to scale formation inside the boiler, resulting in localized overheating and finally causing boiler tube failure.

Energy Conservation Opportunities in Boilers

1. Reduce Stack Temperature

- Stack temperatures greater than 200°C indicates potential for recovery of waste heat.

- It also indicate the scaling of heat transfer/recovery equipment and hence the urgency of taking an early shut down for water / flue side cleaning.

22° C reduction in flue gas temperature increases boiler efficiency by 1%

- **For an older shell boiler, with a flue gas exit temperature of 260°C, an economizer could be used to reduce it to 200°C, Increase in overall thermal efficiency would be in the order of 3%.**

- **Condensing economizer(N.Gas) Flue gas reduction up to 65°C**

Vertical Installation

To Chimney

Cooled Exhaust

Water in

Hot water out

Wasted Heat

BOILER

Exhaust Heat Recovery
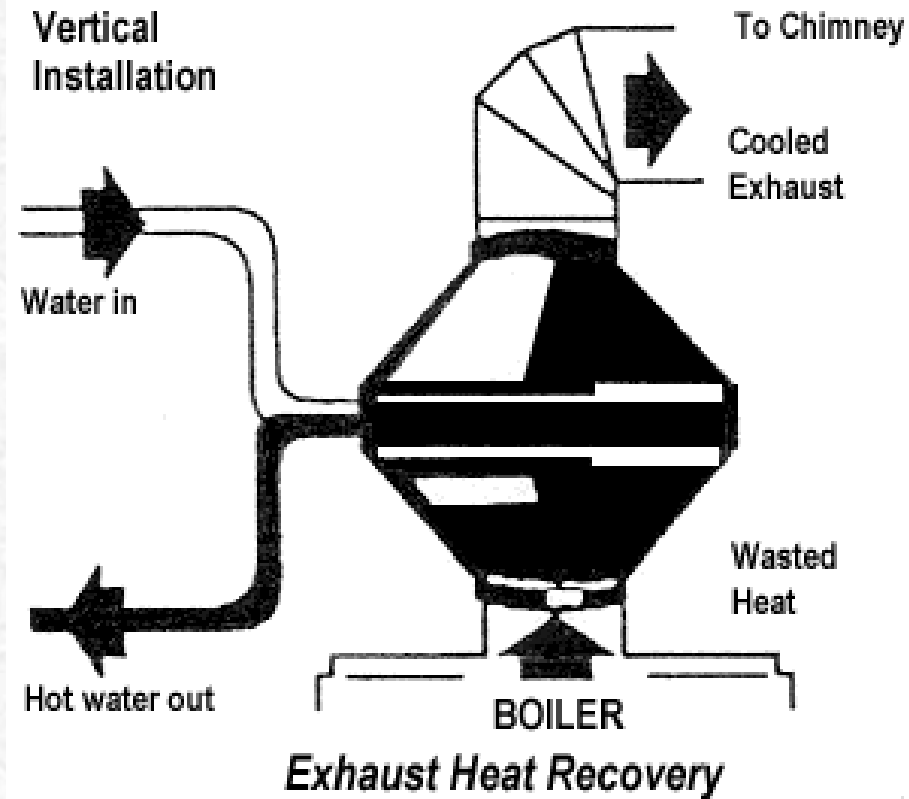
6°C raise in feed water temperature, by economiser/condensate recovery, corresponds to a 1% saving in fuel consumption

Combustion air preheating is an alternative to feed water heating.

- In order to improve thermal efficiency by 1%, the combustion air temperature must be raised by 20 ^{o}C.

4. Incomplete Combustion
(C C C C C   +   CO CO CO CO)

- Incomplete combustion can arise from a shortage of air or surplus of fuel or poor distribution of fuel.

- In the case of oil and gas fired systems, CO or smoke with normal or high excess air indicates burner system problems.

  Example: Poor mixing of fuel and air at the burner. Poor oil fires can result from improper viscosity, worn tips, carbonization on tips and deterioration of diffusers.

- With coal firing: Loss occurs as grit carry-over or carbon-in-ash (2% loss).

  Example :In chain grate stokers, large lumps will not burn out completely, while small pieces and fines may block the air passage, thus causing poor air distribution.

  Increase in the fines in pulverized coal also increases carbon loss.

5. Control excess air
for every 1% reduction in excess air ,0.6% rise in efficiency.

The optimum excess air level varies with furnace design, type of burner, fuel and process variables.. **Install oxygen trim system**

EXCESS AIR LEVELS FOR DIFFERENT FUELS

Fuel	Type of Furnace or Burners	Excess Air (% by wt)
Pulverized coal	Completely water-cooled furnace for slag tap or dry ash removal	15-20
	Partially water-cooled furnace for dry ash removal	15-40
Coal	Spreader stoker	30-60
	Water-cooler vibrating grate stokers	30-60
	Chain-grate and traveling grate stokers	15-50
	Underfeed stoker	20-50
Fuel oil	Oil burners, register type	15-20
	Multi-fuel burners and flat flame	20-30
Natural gas	High pressure burner	5-7
Wood	Dutch over (10-23% through grates) and Hofft type	20-25
Bagasse	All furnaces	25-35
Black liquor	Recovery furnaces for draft and soda pulping processes	30-40

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6. Blow down Heat Recovery

- Efficiency Improvement - Up to 2 percentage points.

- Blowdown of boilers to reduce the sludge and solid content allows heat to go down the drain.

- The amount of blowdown should be minimized by following a good water treatment program, but installing a heat exchanger in the blowdown line allows this waste heat to be used in preheating makeup and feedwater.

- Heat recovery is most suitable for continuous blowdown operations which in turn provides the best water treatment program.
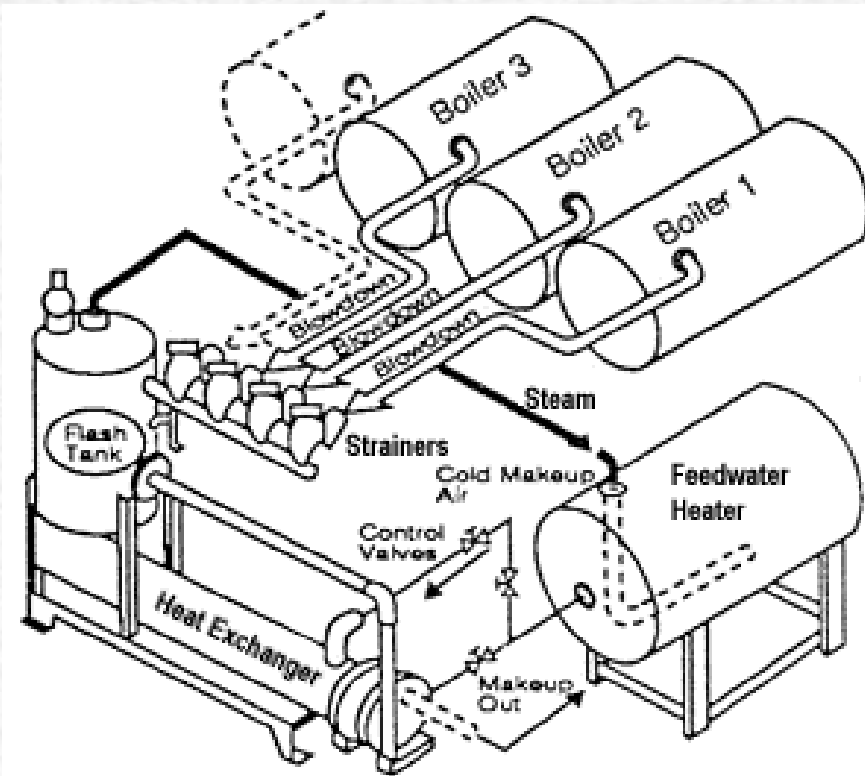
Blowdown Heat Recovery System

8. Reduction of Scaling and Soot Losses

- In oil and coal-fired boilers, soot buildup on tubes acts as an insulator against heat transfer. Any such deposits should be removed on a regular basis. Elevated stack temperatures may indicate excessive soot buildup. Also same result will occur due to scaling on the water side.

- High exit gas temperatures at normal excess air indicate poor heat transfer performance. This condition can result from a gradual build-up of gas-side or waterside deposits. Waterside deposits require a review of water treatment procedures and tube cleaning to remove deposits.

- Stack temperature should be checked and recorded regularly as an indicator of soot deposits. When the flue gas temperature rises about $20^{o}C$ above the temperature for a newly cleaned boiler, it is time to remove the soot deposits

9. Reduction of Boiler Steam Pressure

- Lower steam pressure gives a lower saturated steam temperature and without stack heat recovery, a similar reduction in the temperature of the flue gas temperature results. Potential 1 to 2% improvement.

- Steam is generated at pressures normally dictated by the highest pressure / temperature requirements for a particular process. In some cases, the process does not operate all the time, and there are periods when the boiler pressure could be reduced.

- Adverse effects, such as an increase in water carryover from the boiler owing to pressure reduction, may negate any potential saving.

- Pressure should be reduced in stages, and no more than a 20 percent reduction should be considered.

10. Variable Speed Control for Fans, Blowers and Pumps

Generally, combustion air control is effected by throttling dampers fitted at forced and induced draft fans. Though dampers are simple means of control, they lack accuracy, giving poor control characteristics at the top and bottom of the operating range.

If the load characteristic of the boiler is variable, the possibility of replacing the dampers by a VSD should be evaluated.

11. Effect of Boiler Loading on Efficiency

- As the load falls, so does the value of the mass flow rate of the flue gases through the tubes. This reduction in flow rate for the same heat transfer area, reduced the exit flue gas temperatures by a small extent, reducing the sensible heat loss.

- Below half load, most combustion appliances need more excess air to burn the fuel completely and increases the sensible heat loss.

- Operation of boiler below 25% should be avoided

- Optimum efficiency occurs at 65-85% of full loads

12. Boiler Replacement

if the existing boiler is :

Old and inefficient, not capable of firing cheaper substitution fuel, over or under-sized for present requirements, not designed for ideal loading conditions replacement option should be explored.

- Since boiler plants traditionally have a useful life of well over 25 years, replacement must be carefully studied.

Steam Equipments

- **Indirect steam equipments**
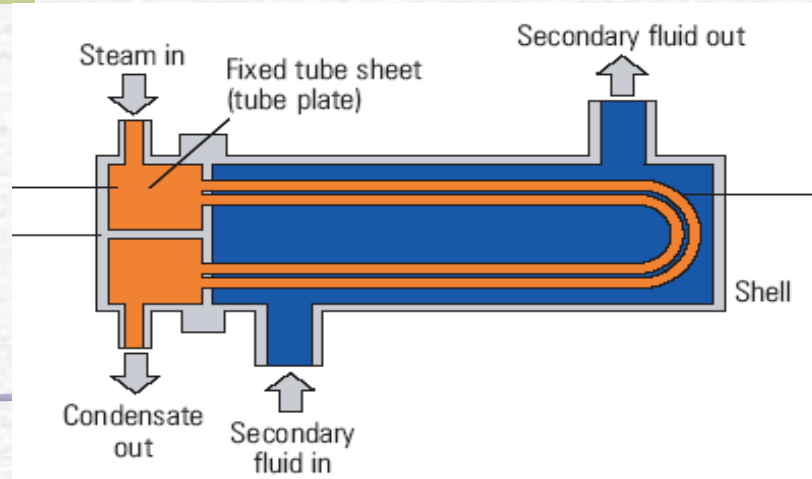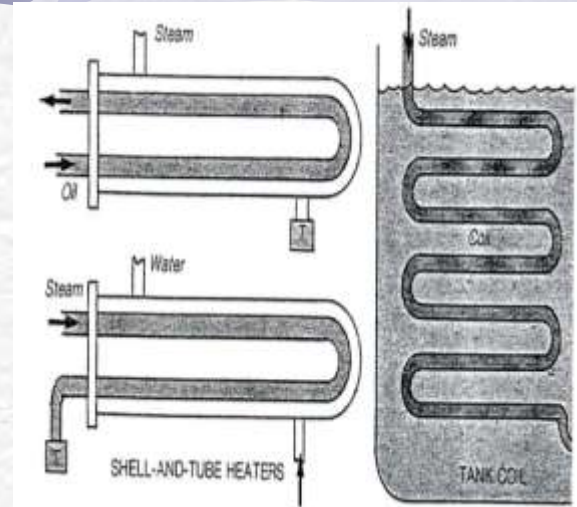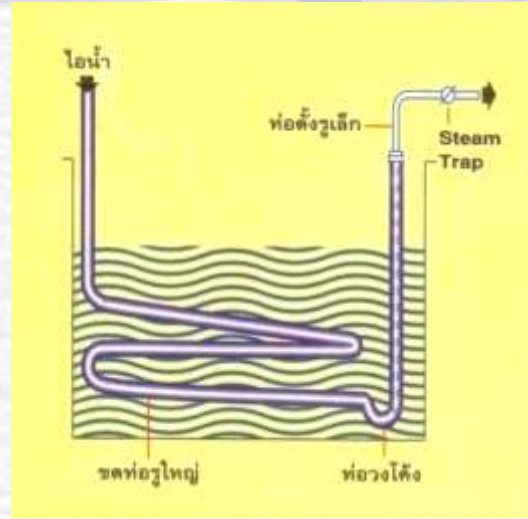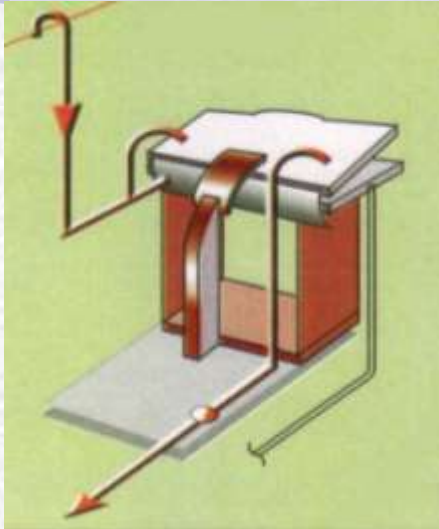
Introduction

Why do we use steam?

- Transport and provision of energy:
  - Highest specific heat and latent heat;
  - Highest heat transfer coefficient.
- Benefits:
  - Efficient and economic to generate;
  - Easy to distribute and control;
  - Cheap and Inert;
  - Easily transferred to the process;
  - Steam plant easy to manage;
  - Flexible;
- Alternatives are hot water and oils

Steam Equipments

- **Direct steam equipments**
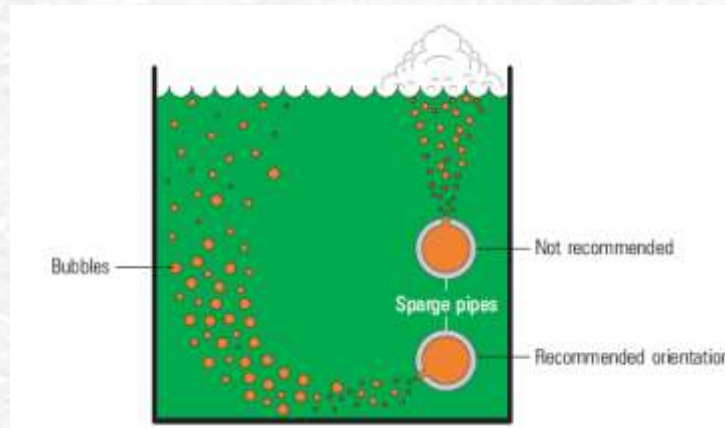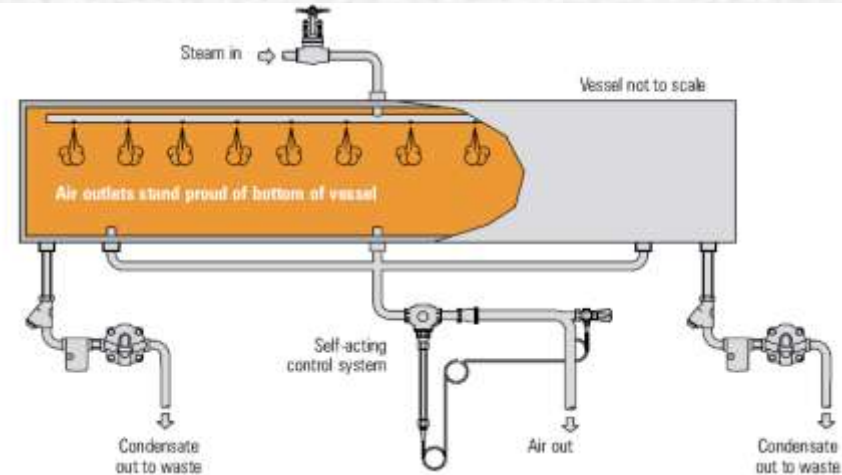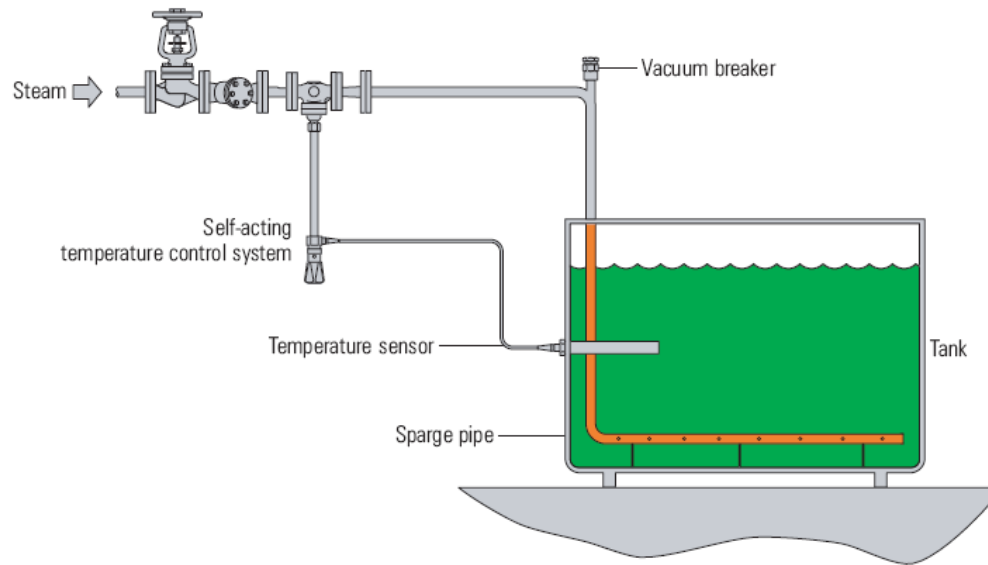
Introduction

What is steam - Enthalpy

- Enthalpy of water (h_f)
  - Heat required to raise temperature from $0\,^oC$ to current temperature
- Enthalpy of evaporation (h_{fg})
  - Heat required to change water into steam at boiling point
- Enthalpy of saturated steam (h_g)
  - Total energy in saturated steam

$$h_g = h_f + h_{fg}$$

Introduction(Cont...)

What is steam?

𝒸 Steam saturation curve

Superheated steam

Steam saturation curve

Sub-saturated water
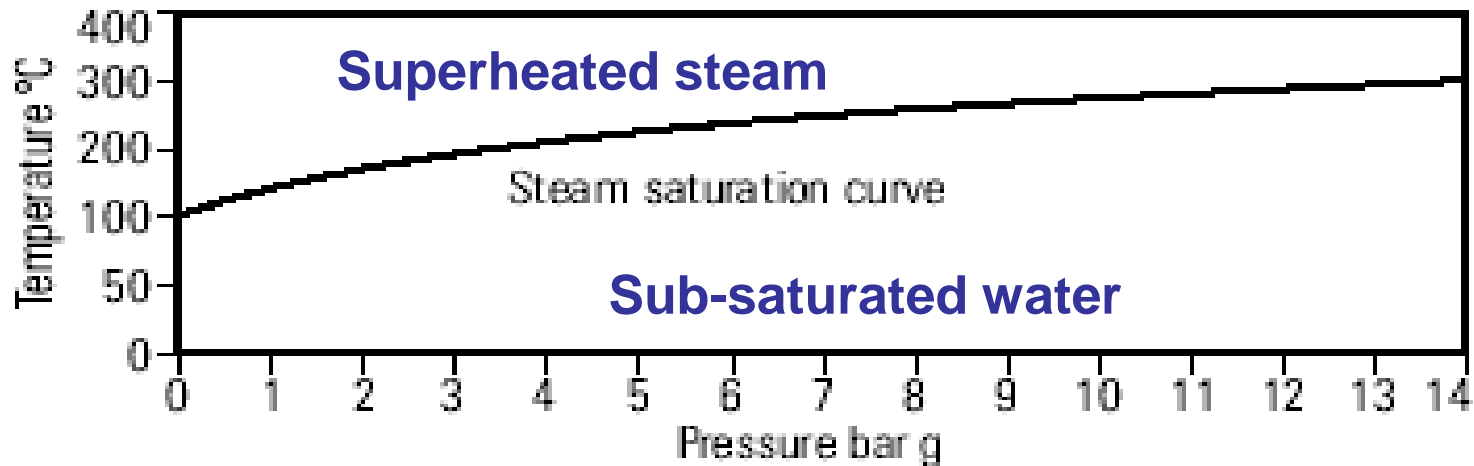
Steam Saturation Curve (Spirax Sarco)
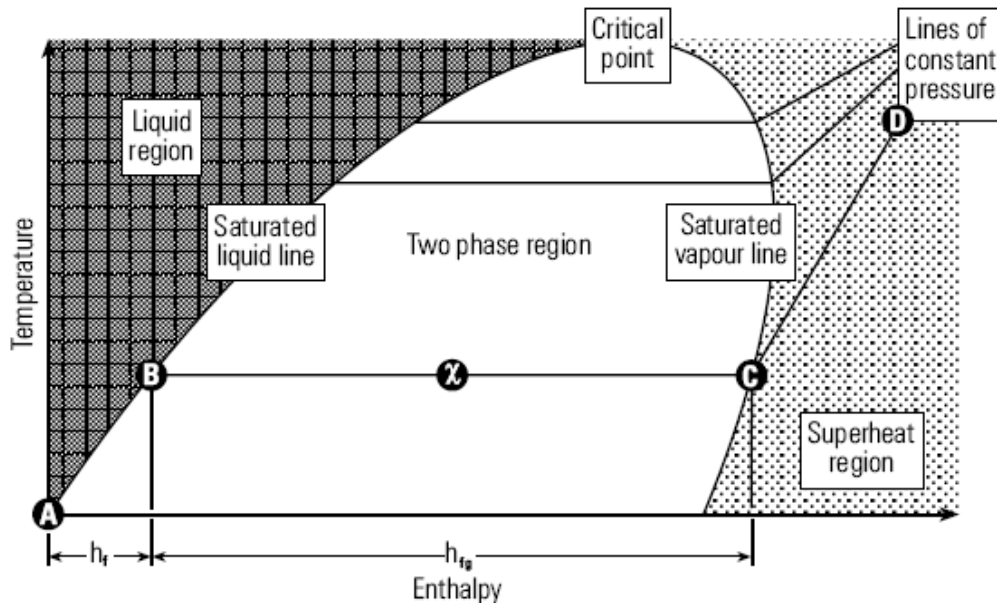
Boiling Point vs Pressure
ຈຸດຟົດ ກັບ ຄວາມດັນ
ຄວາມຮ້ອນແຝງ(Latent heat)
ອາຍນ້ຳອີ່ມຕົວ(Saturated steam)
ອາຍຮ້ອນ(Superheated steam)

Pressure bar g	Saturation temperature °C	Enthalpy kJ/kg			Volume of dry saturated steam m³/kg
		Water h_f	Evaporation h_{fg}	Steam h_g	
0	100	419	2 257	2 676	1.673
1	120	506	2 201	2 707	0.881
2	134	562	2 163	2 725	0.603
3	144	605	2 133	2 738	0.461
4	152	641	2 108	2 749	0.374
5	159	671	2 086	2 757	0.315
6	165	697	2 066	2 763	0.272
7	170	721	2 048	2 769	0.240

The Working Pressure

The distribution pressure of steam is influenced by a number of factors, but is limited by:

- The maximum safe working pressure of the boiler;
- The minimum pressure required at the plant.

As steam passes through the distribution pipework, it will inevitably lose pressure due to:

- Frictional resistance within the pipework;
- Condensation within the pipework as heat is transferred to the environment.

Therefore allowance should be made for this pressure loss when deciding upon the initial distribution pressure.

Steam Quality

Steam should be available at the point of use:

- In the correct quantity;
- At the correct temperature and pressure;
- Free from air and incondensable gases;
- Dry and Clean.

Carry over

Carryover can be caused by two factors:

Operating the boiler below its design pressure

Operating the boiler with too high a water level.

Priming
This is the ejection of boiler water into the steam take-off

Excessive steam demand

Carry over

Water quality →

Foaming

This is the formation of foam in

the space between

the water surface and the steam off-take

↓

difficult to accurately determine the water level

47
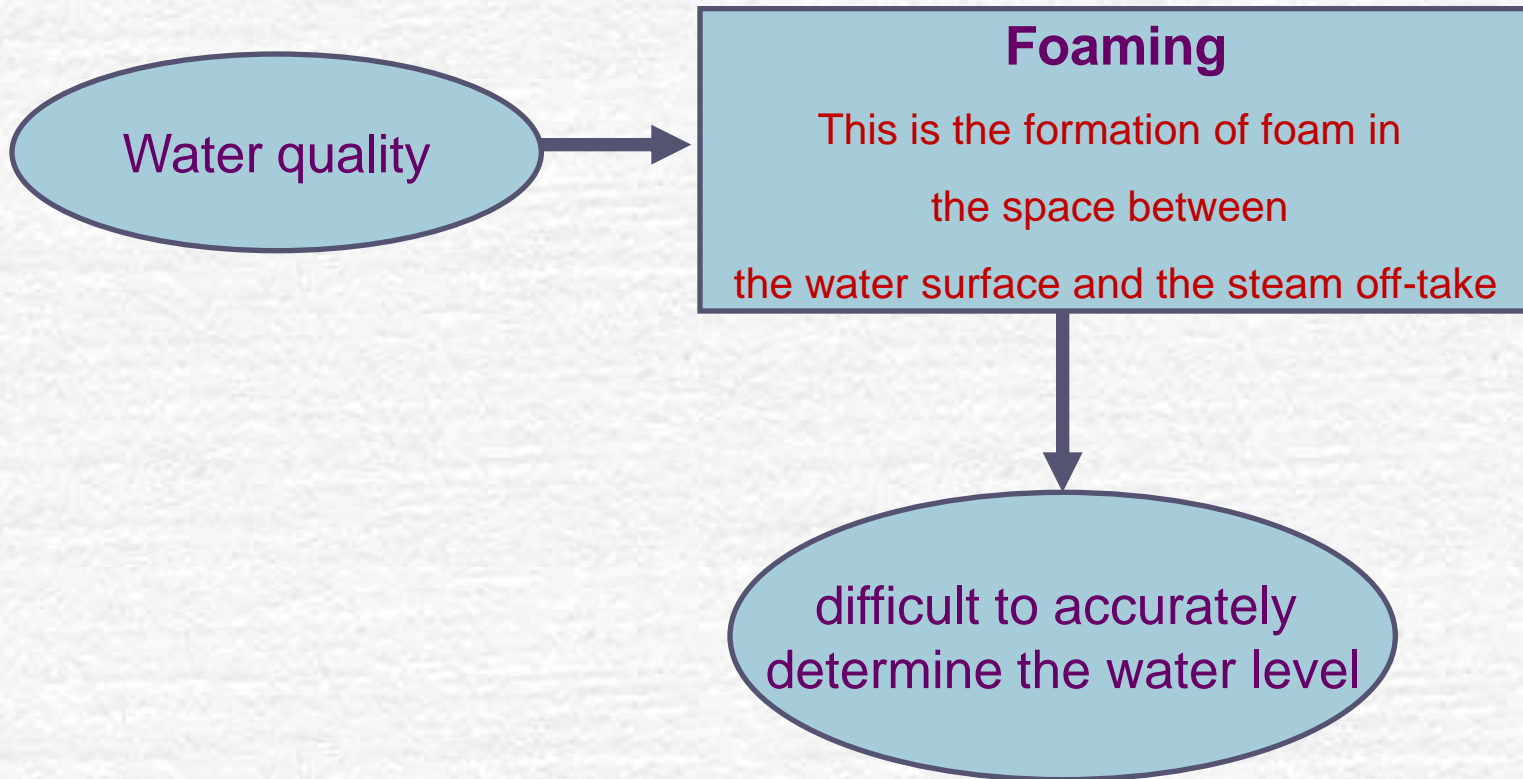
Effect of air

- Reduce in product temperature

Steam side — Water side — Metal wall — T_1 — T_2 — Thin air layer
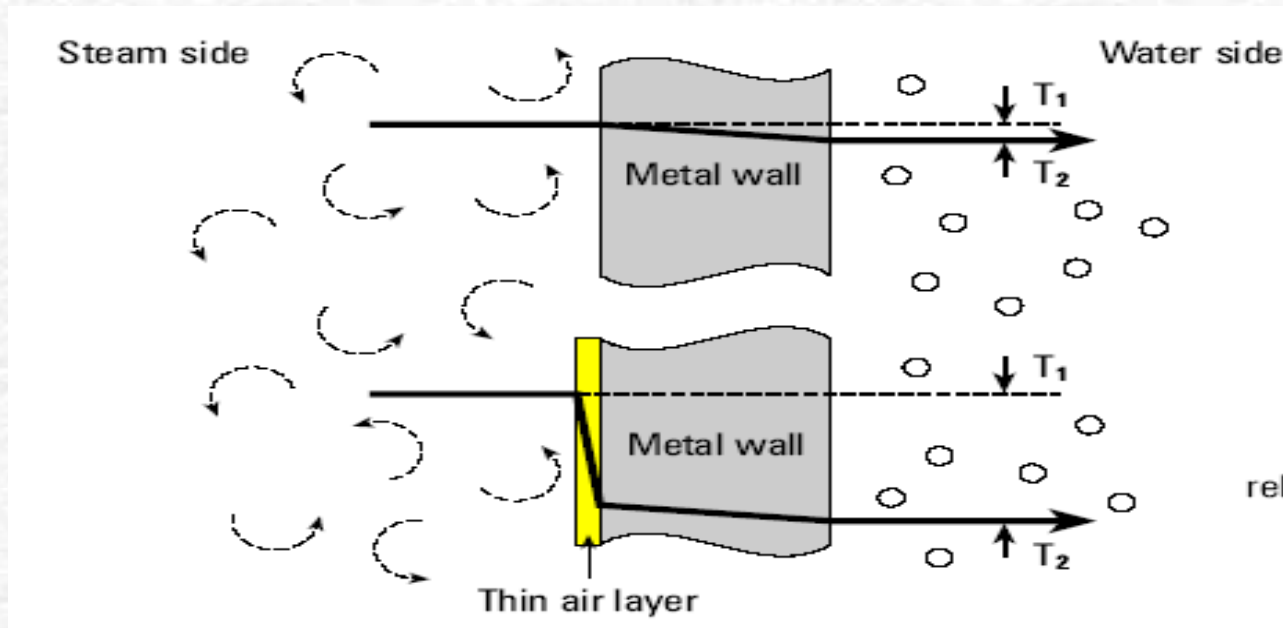
Effect of air

- Reduce in steam temperature

Pressure bar g	Saturation temperature °C
0	100
1	120
2	134
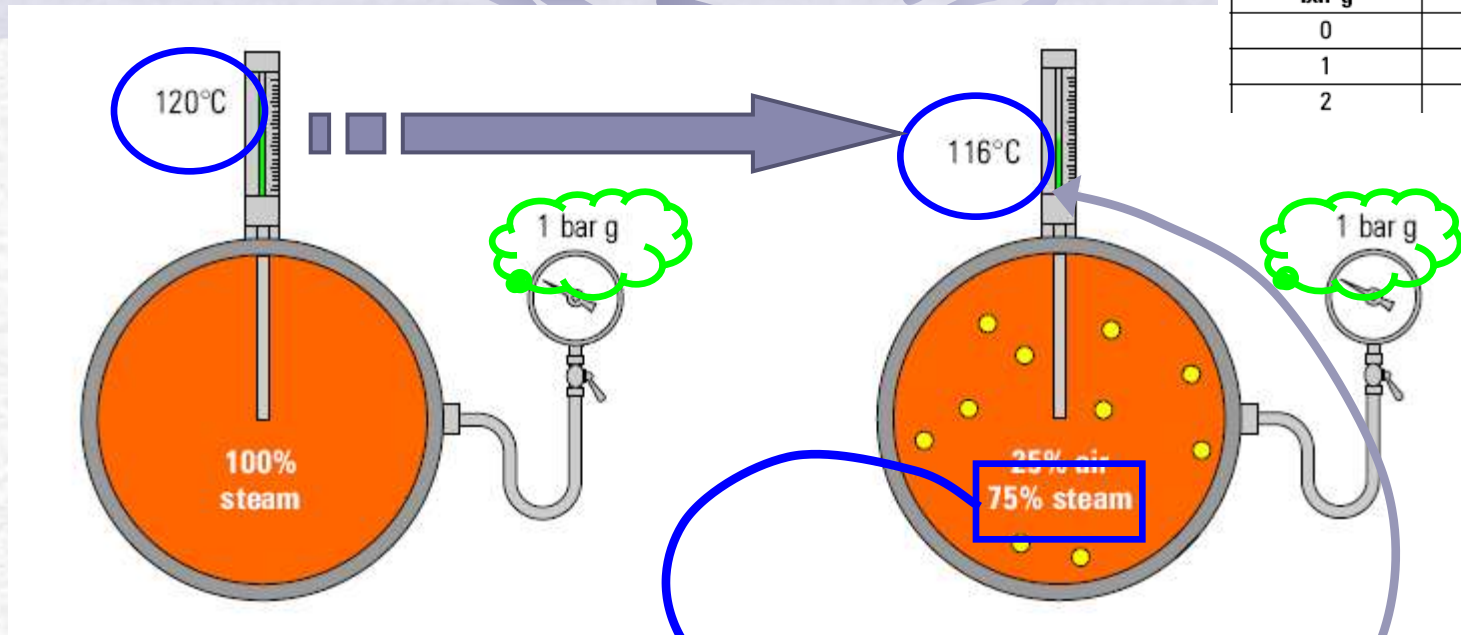
Partial pressure of steam is

$$\frac{3}{4} \times 2\, bar\, a = 1.5\, bar\, a$$

Partial pressure of air is

$$\frac{1}{4} \times 2\, bar\, a = 0.5\, bar\, a$$

Total pressure is

$$2\, bar\, a = 1\, bar\, g$$

Flow behavior of air in steam equipments

Air in system will be purged by steam
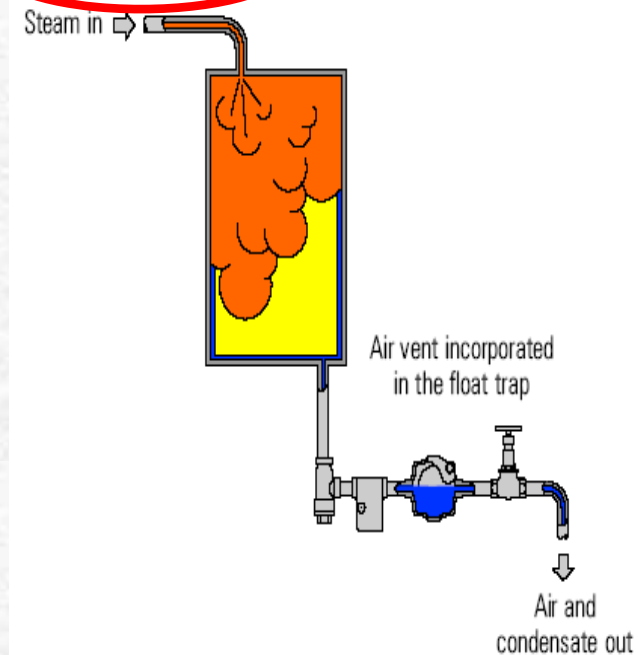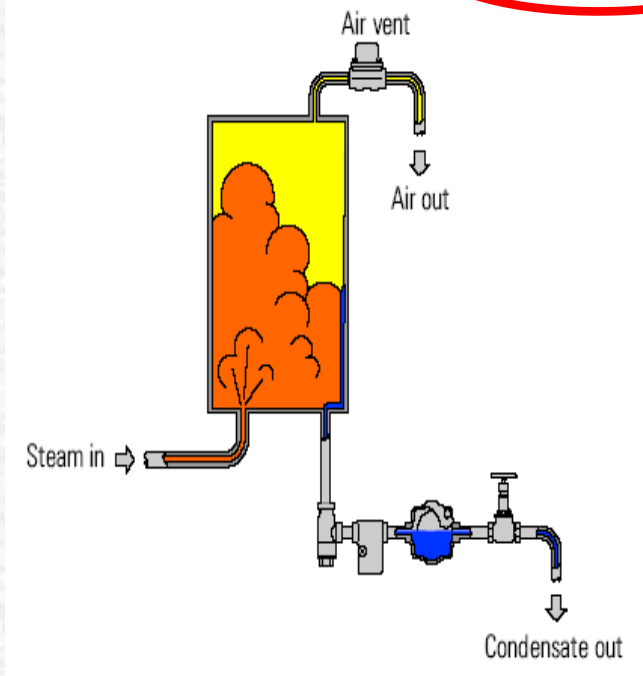
Automatic air vent valve
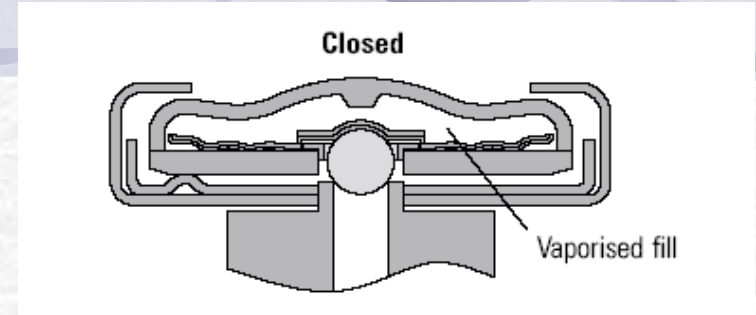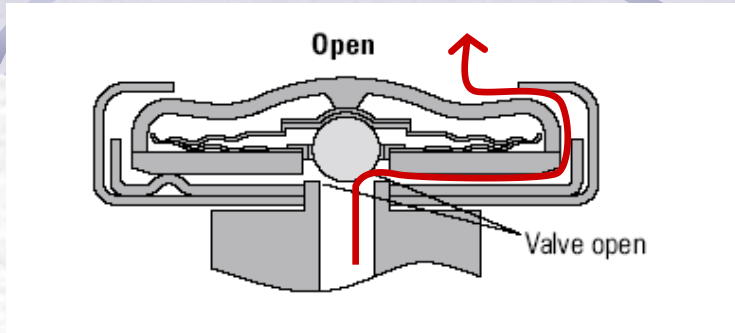
Automatic air vent valves are necessary for batch process, however for continuous process manual valves may be used.

Installation of air vent valves
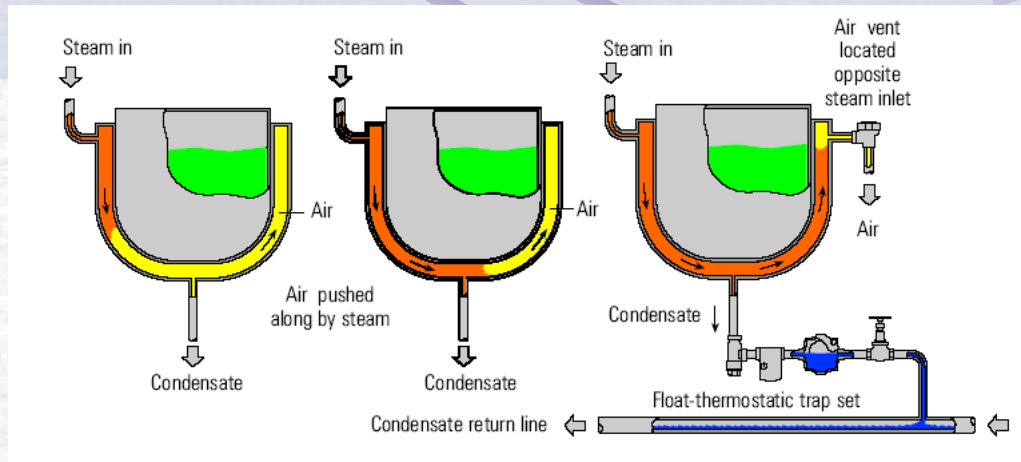
Steam equipment
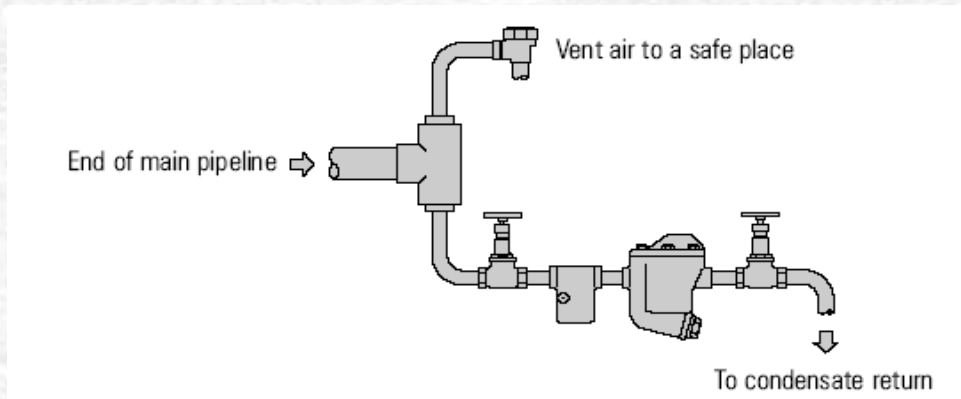
Piping system

Effect of wet steam

Advantages of dry steam:

- Higher latent heat;
- Higher heat transfer coefficient;
- Higher efficient in sterilization.

Example:

An equipment requires heat rate of 700000kJ/h at 6 bar g. Determine the difference in the steam consumption between dry steam and steam having 90% dryness.

At 6 bar g, h_{fg} = 2066 kJ/kg

Dry steam consumption:

$$\frac{700000\, kJ/h}{2066 kJ/kg} = 338.82\, kg/h$$

90% dryness steam consumption:

$$\frac{700000\, kJ/h}{2066 kJ/kg \times 0.9} = 376.47\, kg/h$$

Difference in steam consumption:

$$\frac{376.47 - 338.82}{338.82} \times 100 = 11.11\%$$

Example

An equipment requires heat rate of 700000kJ/h at 6 bar g. Determine the difference in the steam consumption between dry steam and steam having 90% dryness.

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Dry steam consumption

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90% dryness steam consumption

$$\frac{700000\,kJ/h}{2066kJ/kg \times 0.9} = 376.47\,kg/h$$

Difference in steam consumption

$$\frac{376.47 - 338.82}{338.82} \times 100 = 11.11\%$$

How to improve steam dryness

- Steam Separator
- Pressure Reducing Valve
- Steam Header
- Operate boilers at recommend operating conditions
- Feed water treatment
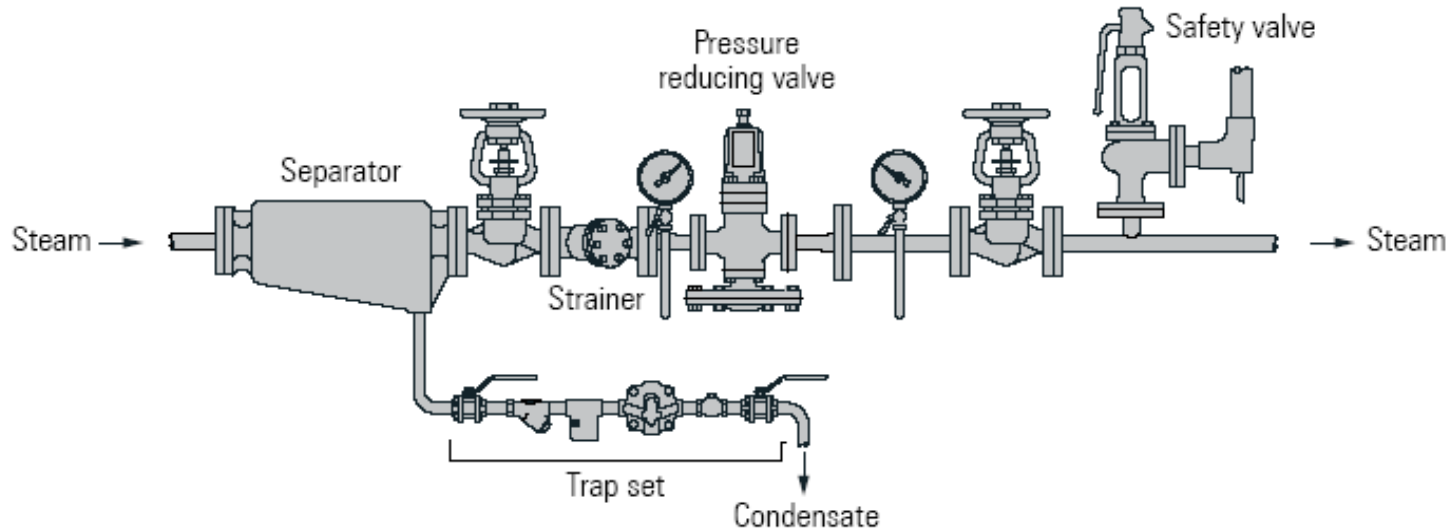
• **Steam Separator**

Air and incondensable gases vented

Wet steam in

Dry steam out

Moisture to trap set

Main stop valve

Control valve

Controller

Boiler

- **Steam Header**

Steam supply → Steam branch lines Steam to next manifold →

Isolating valve

Steam header

Condensate to return ⬇
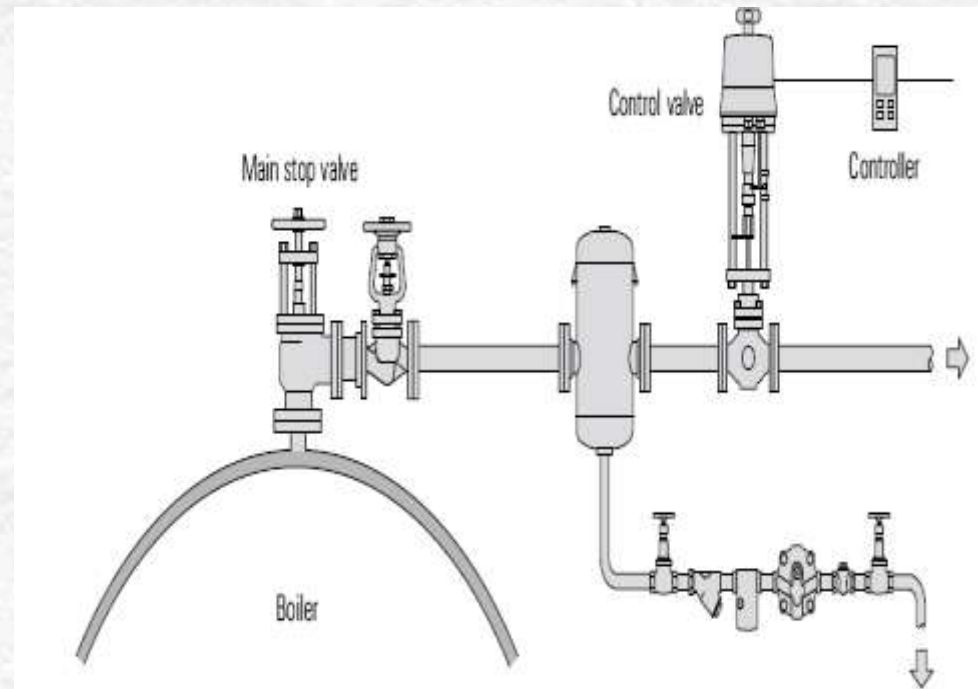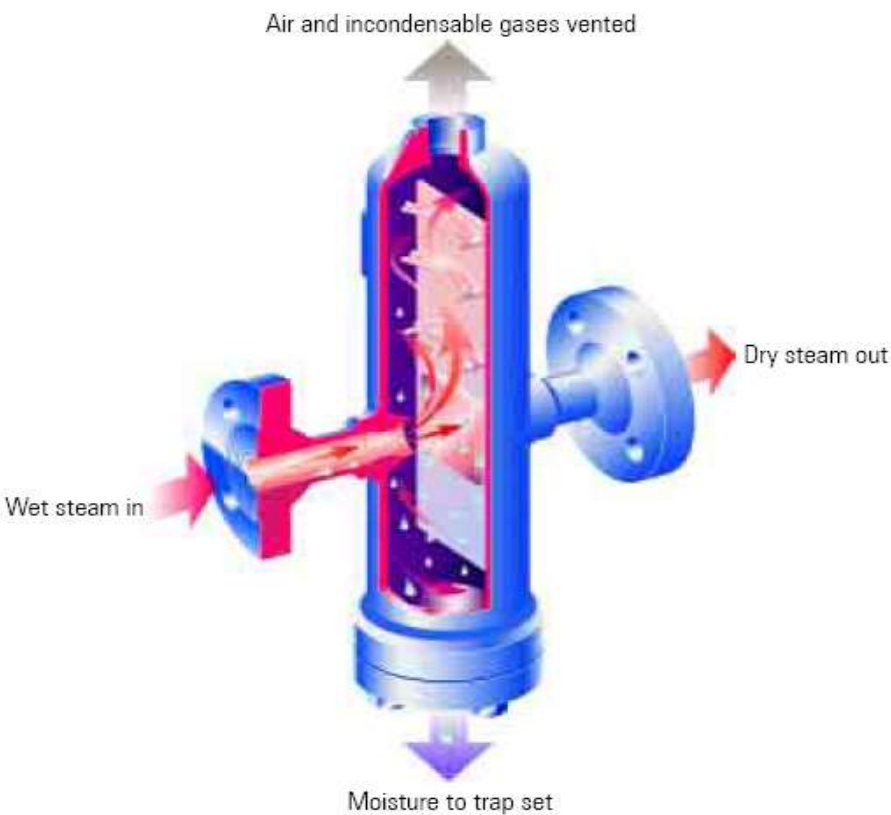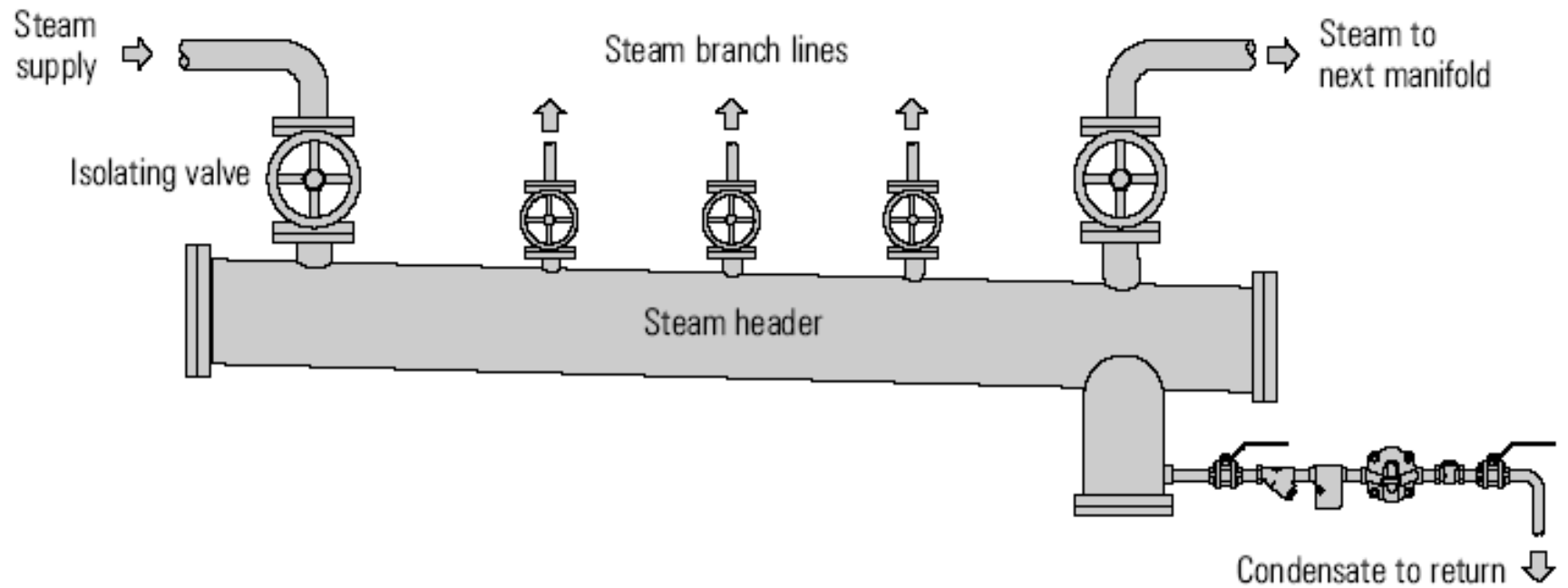
• **Pressure Reducing Valve**

| Pressure bar g | Saturation temperature °C | Enthalpy kJ/kg | | | Volume of dry saturated steam m³/kg |
		Water h_f	Evaporation h_{fg}	Steam h_g	
0	100	419	2 257	2 676	1.673
1	120	506	2 201	2 707	0.881
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3	144	605	2 133	2 738	0.461
4	152	641	2 108	2 749	0.374
5	159	671	2 086	2 757	0.315
6	165	697	2 066	2 763	0.272
7	170	721	2 048	2 769	0.240

Condensation
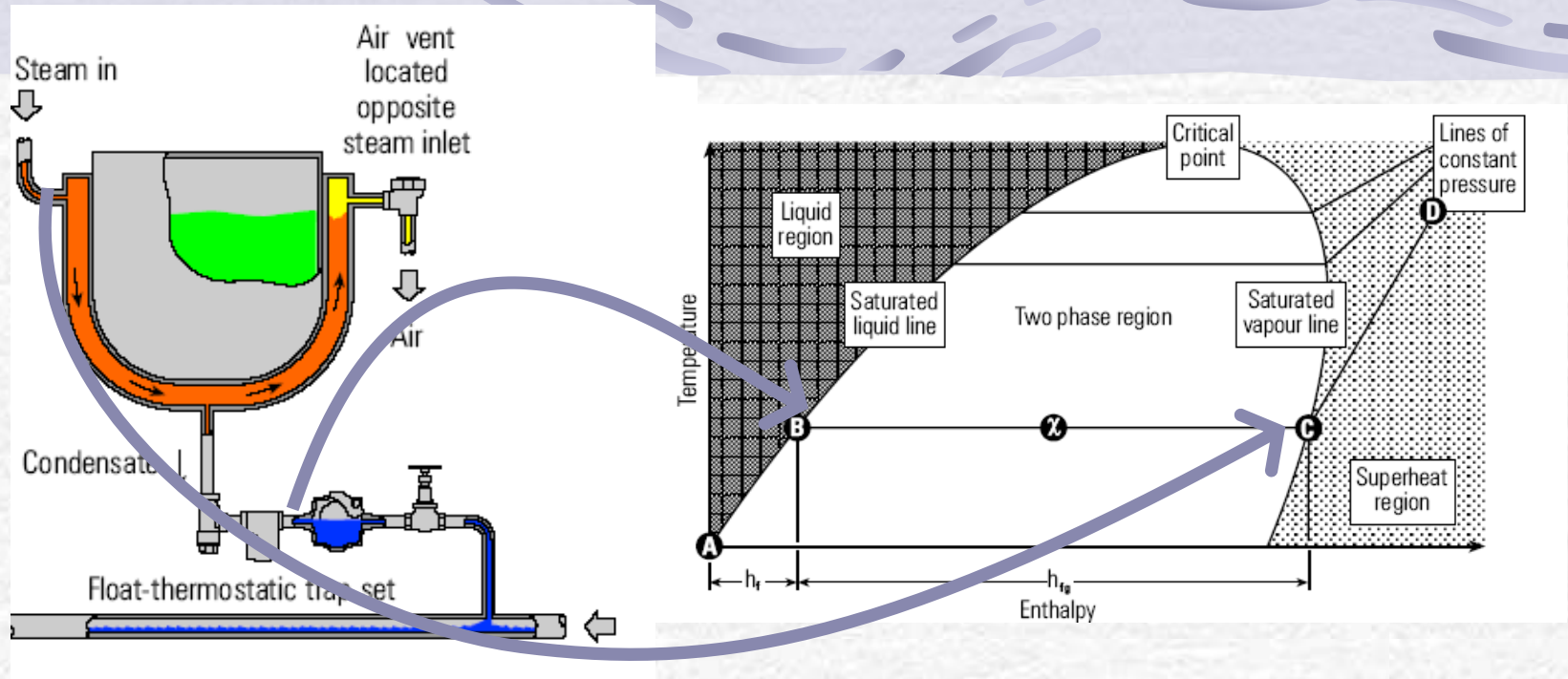
Steam distribution system
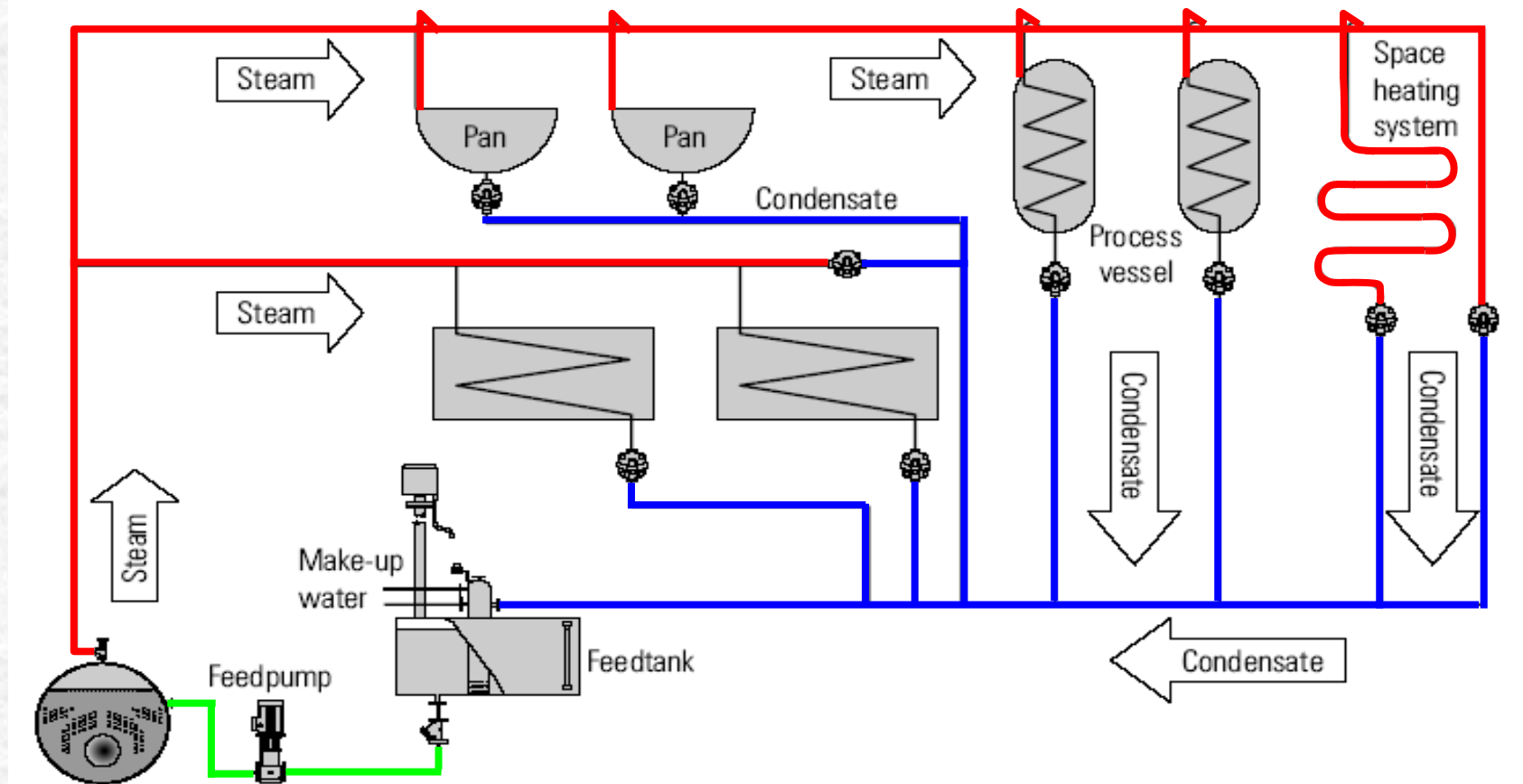
Steam piping

- Pipe should be sized base on steam velocity of 25-35 m/s;
- Proper condensate drainage;
- Insulation;
- No leakage.

Pipeline layout: 1 m fall for every 100 m
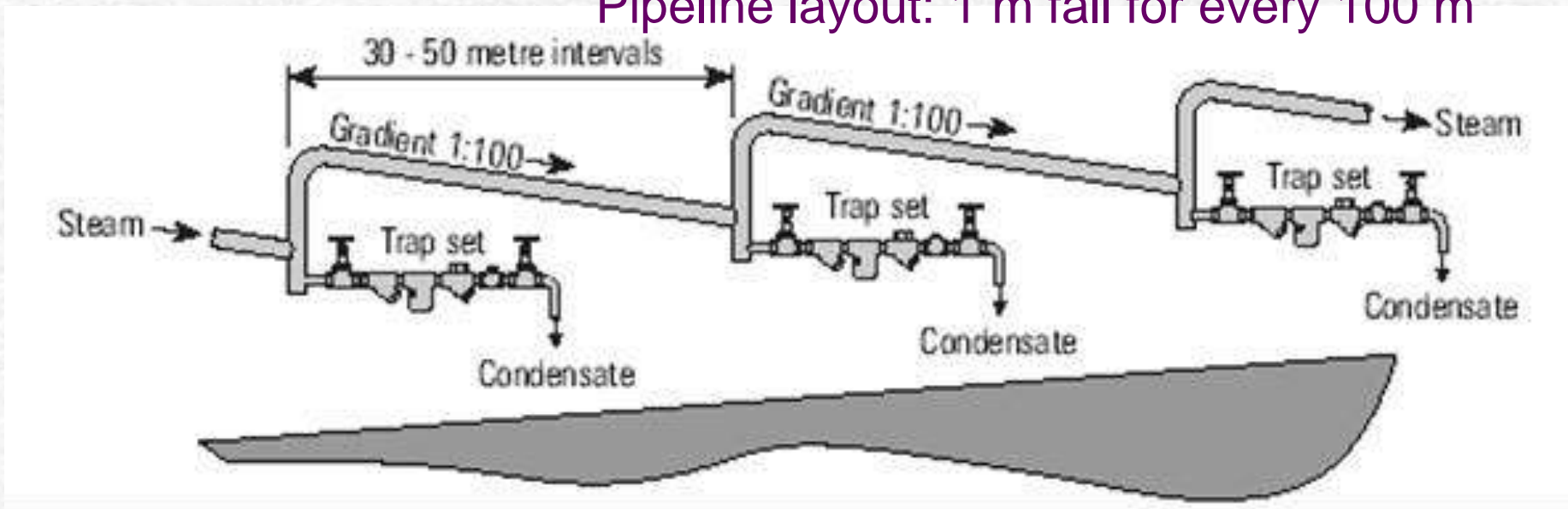

(Spirax Sarco)

Pipe Sizing

The objective of the steam distribution system is to supply steam at the correct pressure to the point of use. It follows, therefore, that pressure drop through the distribution system is an important feature.

Proper sizing of steam pipelines help in minimizing pressure drop. The velocities for various types of steam are:

Types of Steam	Steam Velocity,(m/s)
Superheated	50-70
Saturated	30-40
Wet or Exhaust	20-30

Pressure Drop in Steam Pipeline
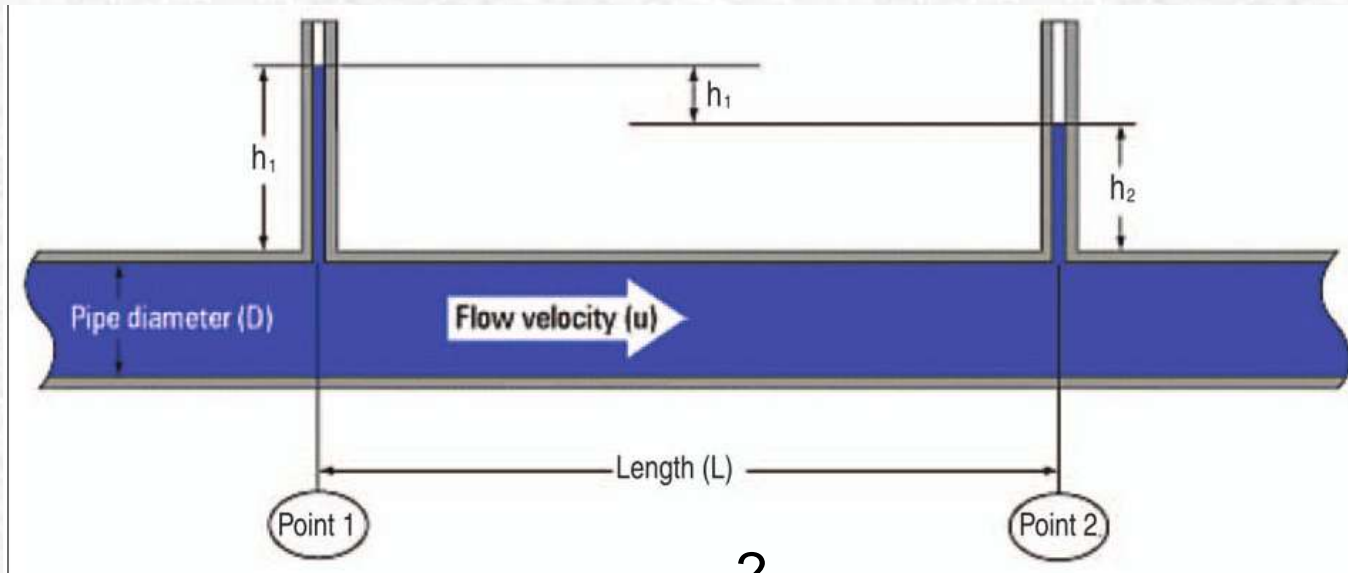
$$h_f = \frac{4 \, f \, L \, U^2}{2 \, g \, D}$$

Where: h_f - Head loss due to friction, (m of water).

f - Friction Factor(Dimensionless).

L - Pipe length, (m)

U - Steam Velocity,(m/s).

g - Gravitational Constant,(9.81m/s^2).

D - Pipe Diameter, (m).

Example:

Water pipe

Determine the difference in pressure between two points 1 km apart in a 150 mm bore horizontal pipework system. The water flow rate is 45 m³/h at 15°C and the friction factor for this pipe is taken as 0.005.

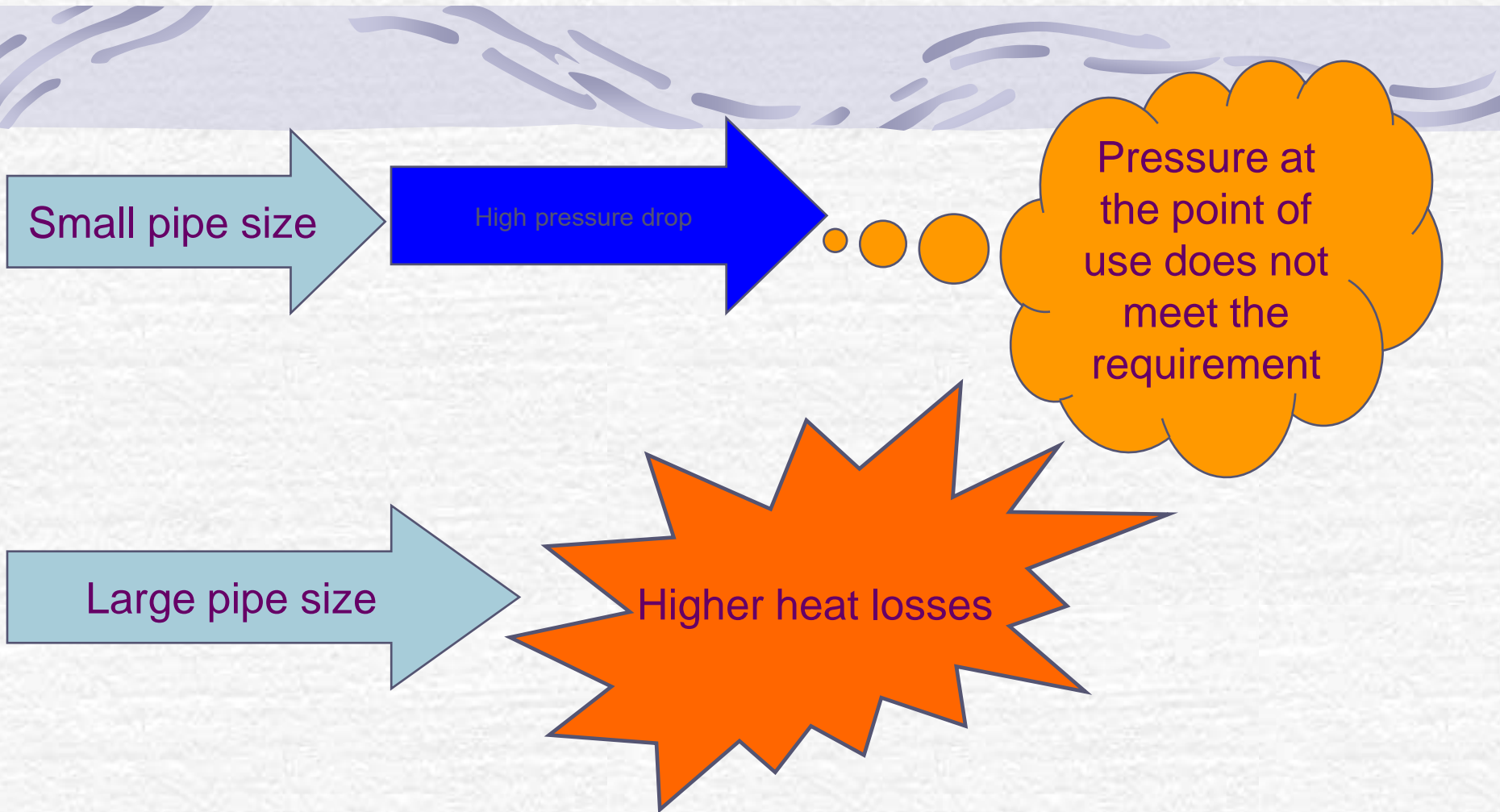$$\text{Water Velocity (m/s)} = \frac{\text{Volume Flow Rate}(m^3/h)}{\text{Pipe Crossectional Area}(m^2)}$$

$$\text{Water Velocity (m/s)} = \frac{45(m^3/h)x4}{3600s/hx3.14(0.15m)^2} = 0.71m/s$$

$$h_f = \frac{4\,f\,L\,U^2}{2\,g\,D}$$

$$h_f = \frac{4\,x0.005x1,000mx(0.71m/s)^2}{2\,x9.81m/s^2x0.150m} = 3.43\,m\,of\,Water\,or\,0.343\,bar$$

Effect of pipe size

Small pipe size → High pressure drop → Pressure at the point of use does not meet the requirement

Large pipe size → Higher heat losses
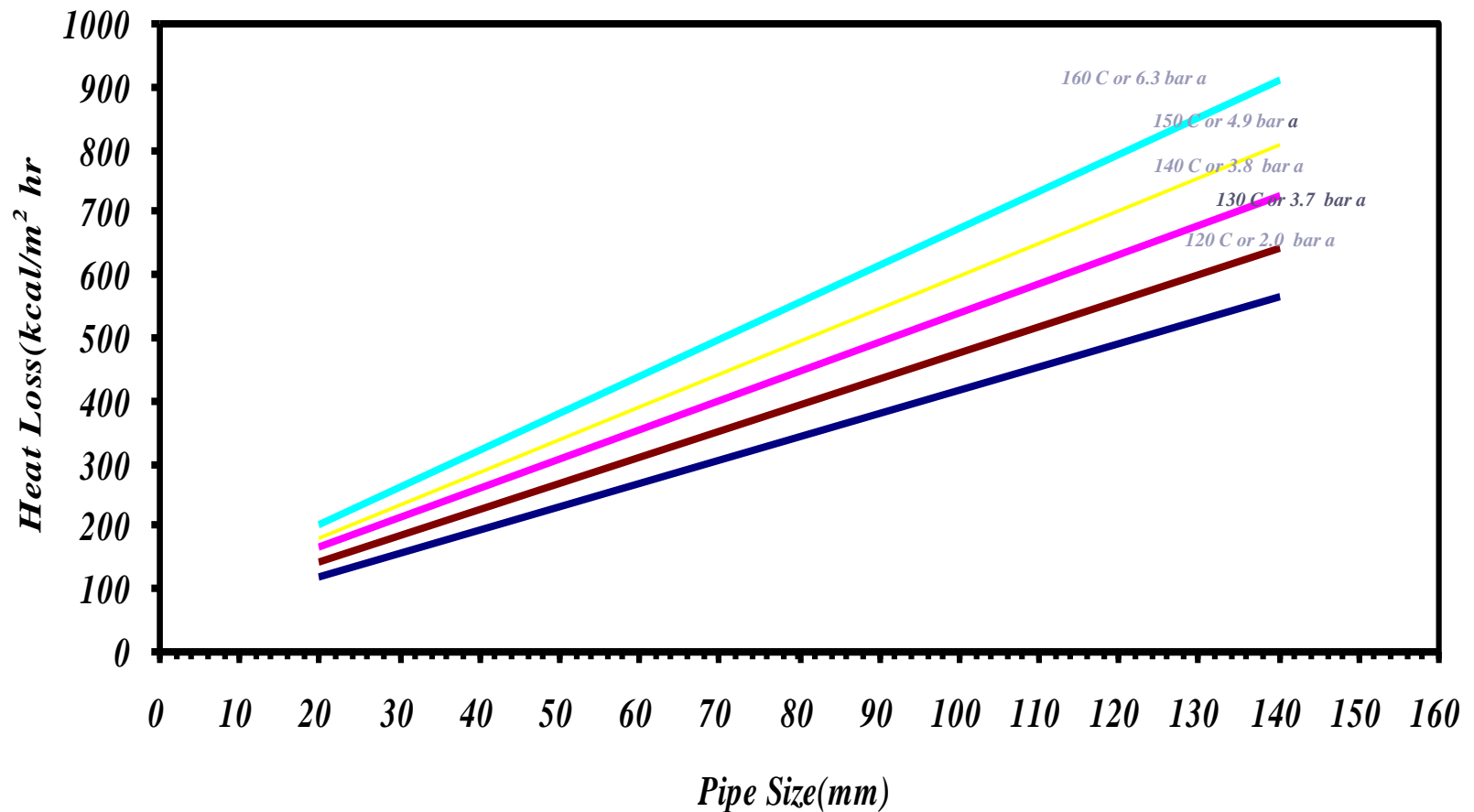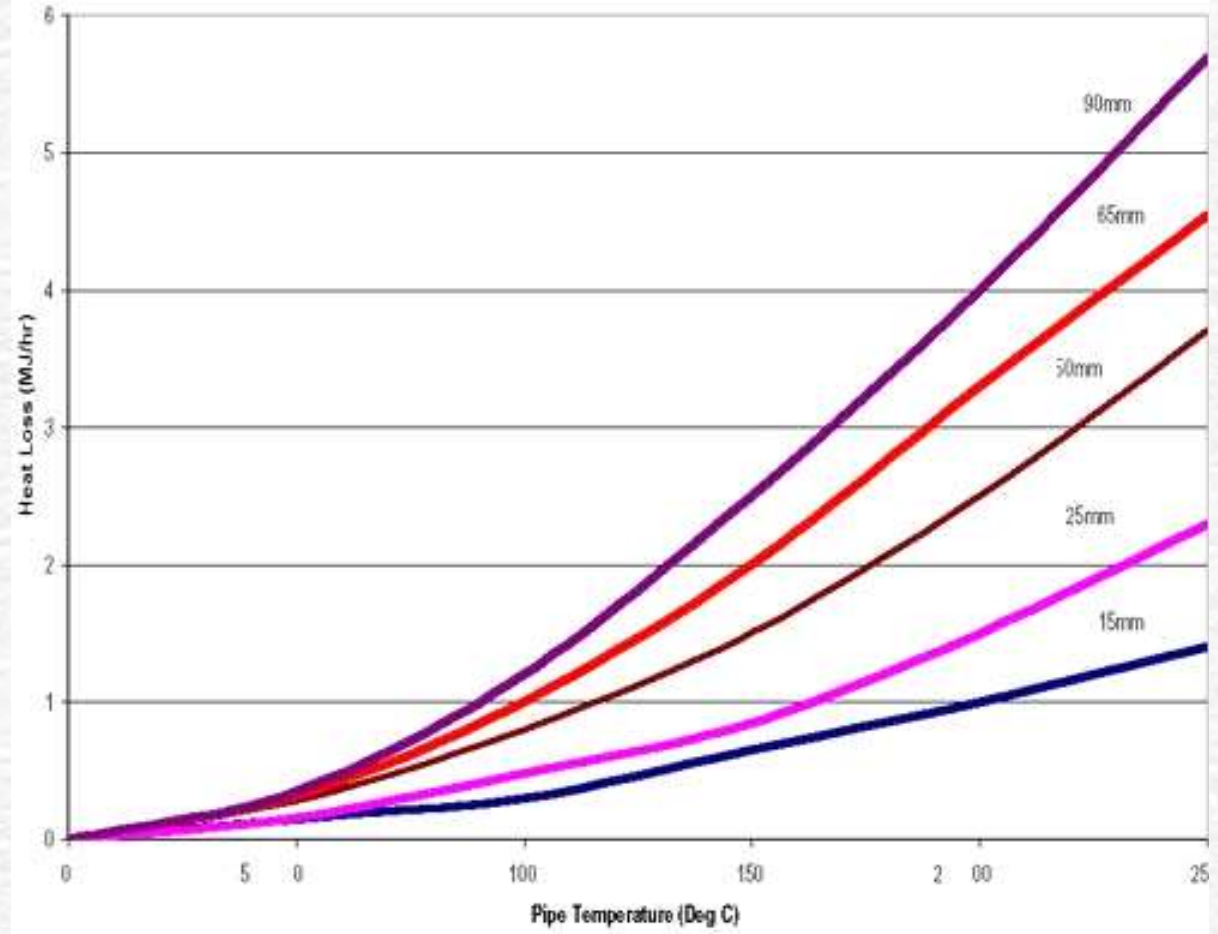
Insulation
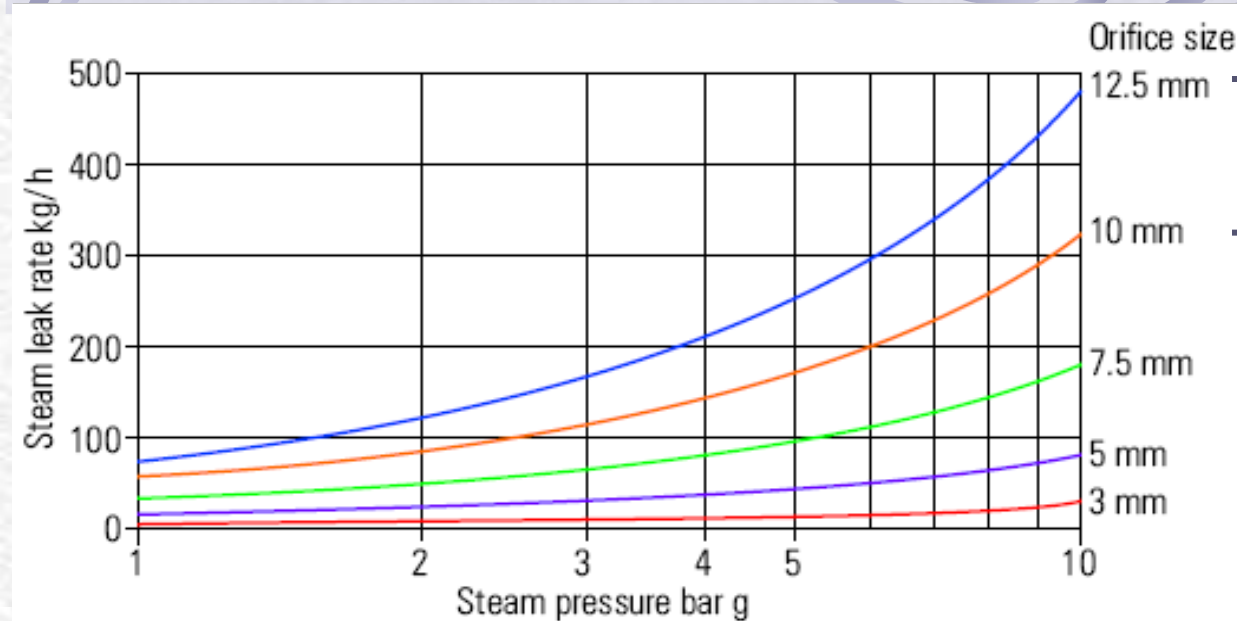
Heat losses from bare pipes

Insulation

Insulation of steam and condensate lines

- Major source of heat loss
- Suitable materials: cork, glass wool, rock wool, asbestos
- Also insulate flanges!

Leakage

Cost of fuel oil (B/litre)	Cost of fuel oil for producing steam 1000 kg
8.00	650
9.00	730
10.00	805
11.00	885
12.00	970
20.0	1610

Example

A steam distribution system operate at 8 bar g. If there is a hole of diameter 10 mm and the cost of heavy oil is 20 Baht/liter, what is the loss in Baht per hour.

At 8 bar g and orifice size of 10 mm, steam leakage is 250 kg/h

Loss $$= 250 \, kg/h \times 1h \times \frac{1610B}{1000kg} = 402.5 \, B/h$$

Condensate drainage

- Steam Trap

- Drainage
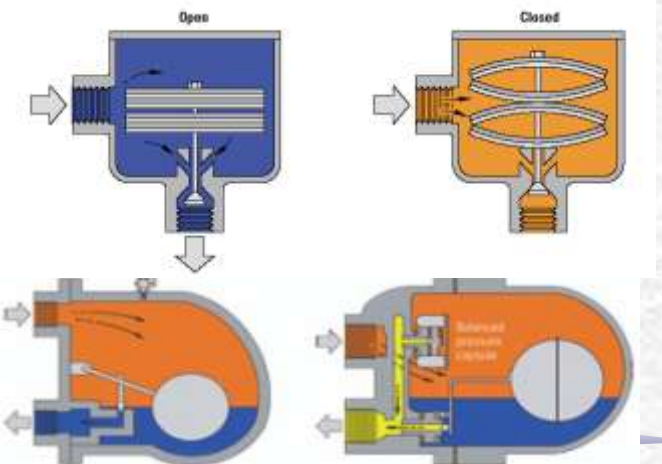 - Drain from piping system
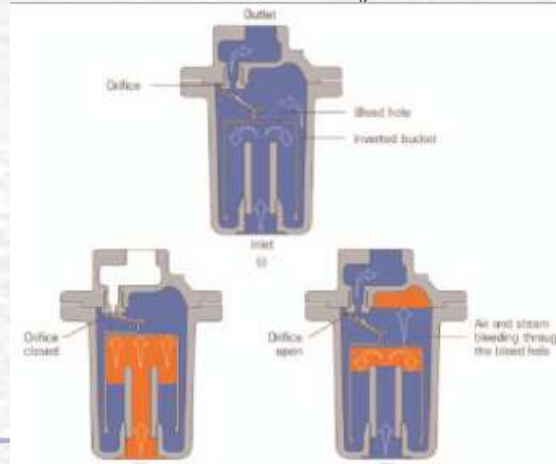 - Drain from equipments

Steam traps

Three groups of steam traps

Thermostatic: Operated by changes in fluid temperature

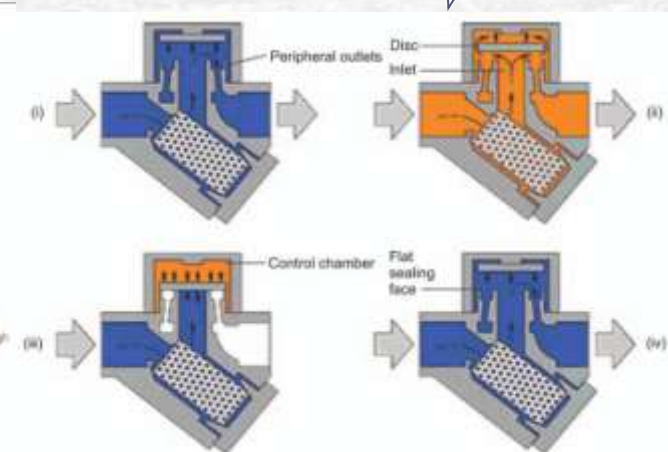**Mechanical: Operated by changes in fluid density**

Thermodynamic: Operated by changes in fluid dynamics

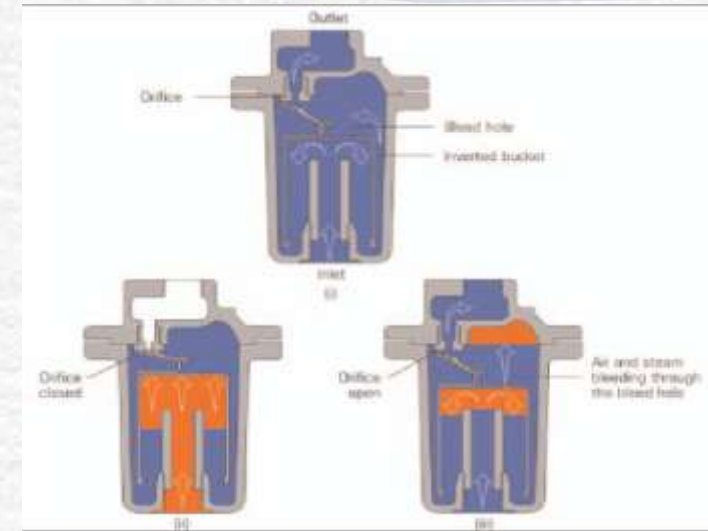Float Trap with Thermostatic Air Vent

Inverted Bucket Traps

Thermostatic Traps

Inverted Bucket Trap

Advantages of the inverted bucket steam trap

➢ The inverted bucket steam trap can be made to withstand high pressures.

➢Like a float-thermostatic steam trap, it has a good tolerance to water hammer conditions.

➢Can be used on superheated steam lines with the addition of a check valve on the inlet.

➢ Failure mode is usually open, so it's safer on those applications that require this feature, for example turbine drains.

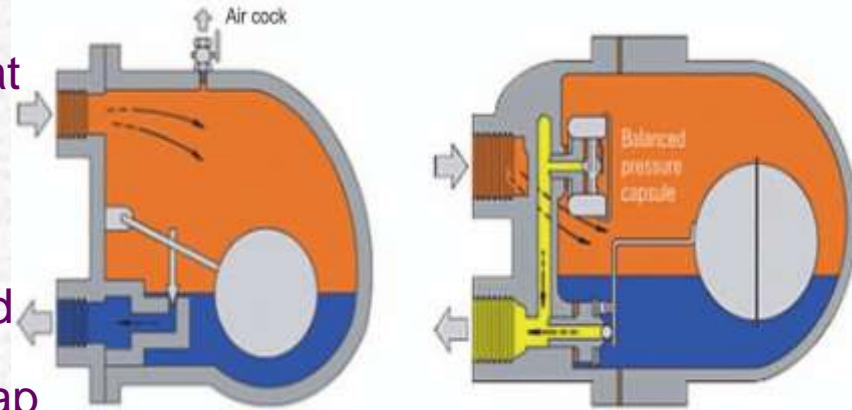**Disadvantages of the inverted bucket steam trap**

➢The small size of the hole in the top of the bucket means that this type of trap can only discharge air very slowly. The hole cannot be enlarged, as steam would pass through too quickly during normal operation.

➢There should always be enough water in the trap body to act as a seal around the lip of the bucket. If the trap loses this water seal, steam can be wasted through the out- let valve. The bucket loses its buoyancy and sinks, allowing live steam to pass through the trap orifice. Only if sufficient condensate reaches the trap will the water seal form again, and prevent steam wastage.

Float and Thermostatic Traps

Advantages of the thermostatic steam trap

➤The trap continuously discharges condensate at steam temperature. This makes it the first choice for applications where the rate of heat transfer is high for the area of heating surface available.
➤ It is able to handle heavy or light condensate loads equally well and is not affected by wide and sudden fluctuations of pressure or flowrate.
➤As long as an automatic air vent is fitted, the trap is able to discharge air freely.
➤It has a large capacity for its size.
➤The versions which have a steam lock release valve are the only type of trap entirely suitable for use where steam locking can occur.
➤It is resistant to waterhammer.

Disadvantages of the thermostatic steam trap

➤Although less susceptible than the inverted bucket trap, the float type trap can be damaged by severe freezing and the body should be well lagged, and / or complemented with a small supplementary thermostatic drain trap, if it is to be fitted in an exposed position.
➤As with all mechanical type traps, different internals are required to allow operation varying pressure ranges. Traps operating on higher differential pressures have smaller orifices to balance the buoyancy of the float.

Thermodynamic Steam Traps

Advantages of the thermodynamic steam trap

➤ Relatively small size for the condensate loads they handle.

➤ Resistance to damage from water hammer.

A disadvantage is that they must be set, generally at the plant, for a particular steam operating pressure. If the trap is used for a lower pressure, it may discharge live steam. If used at a higher steam pressure, it can back up condensate into the system.
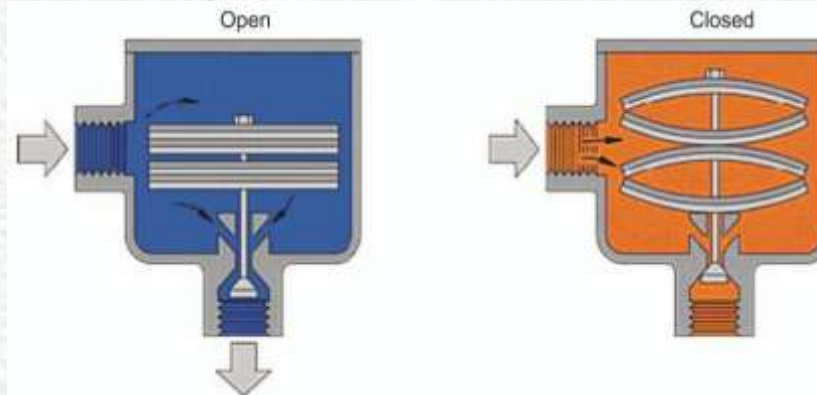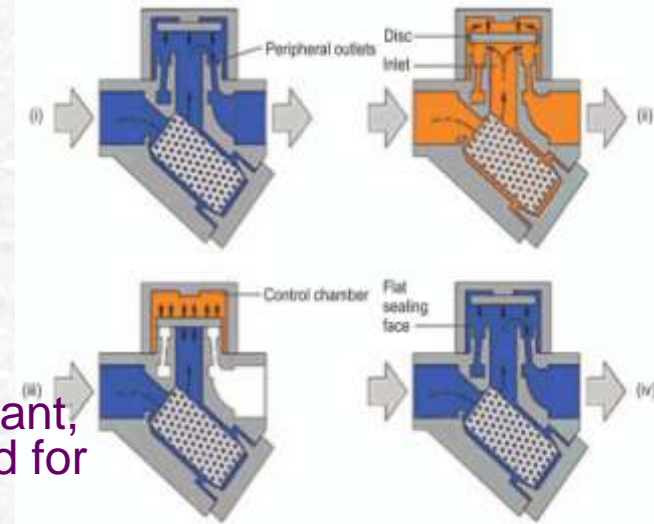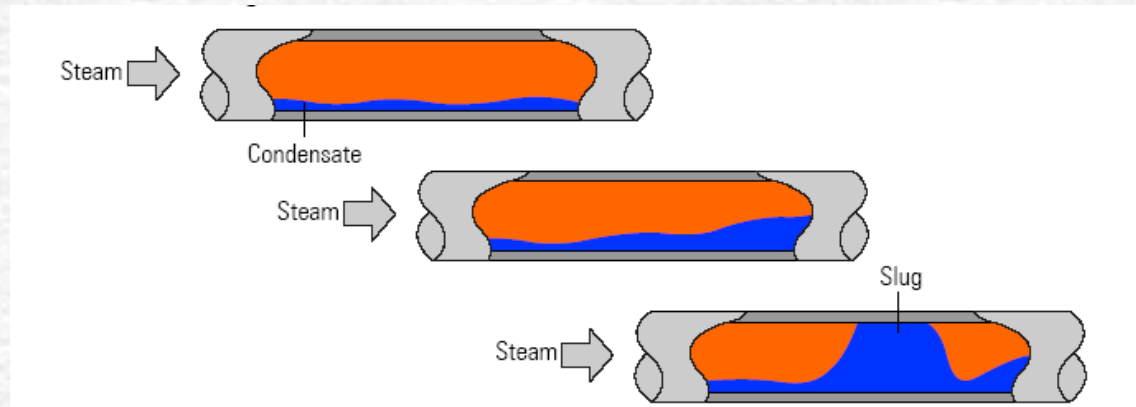
Bimetallic Steam Trap

Condensate drainage from piping system

Condensate occurs in the piping system by poor Insulation or Steam loss heat

- To eliminate condensate before supply steam to equipments.
- To prevent "Water Hammer"

Piping arrangement for condensate drainage
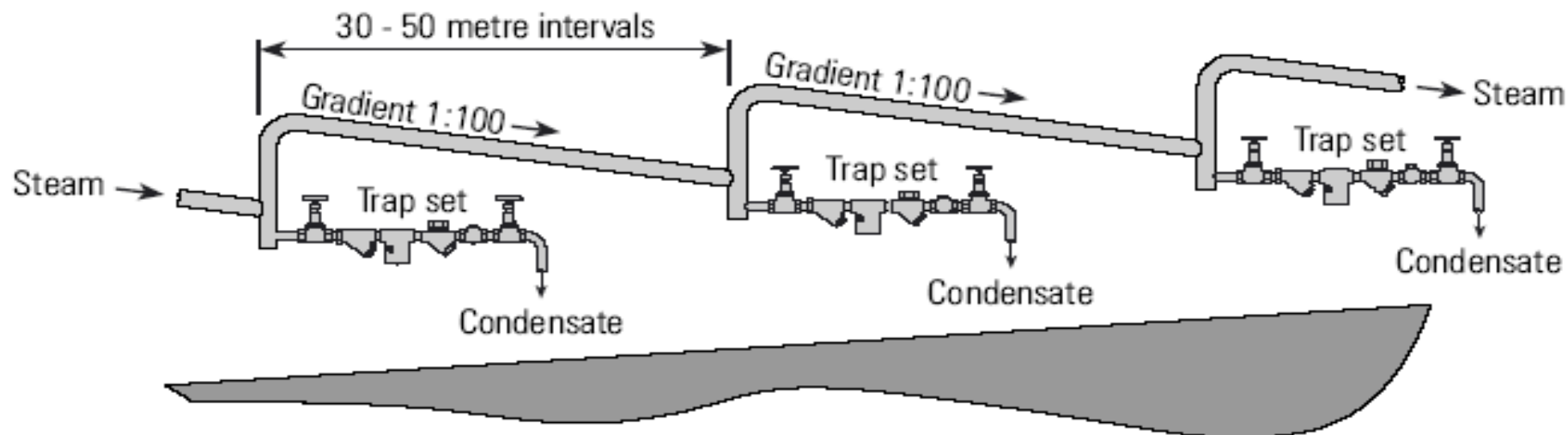
Mains diameter - D	Pocket diameter - d_1	Pocket depth - d_2
Up to 100 mm nb	$d_1 = D$	Minimum $d_2 = 100$ mm
125 - 200 mm nb	$d_1 = 100$ mm	Minimum $d_2 = 150$ mm
250 mm and above	$d_1 \geq D/2$	Minimum $d_2 = D$
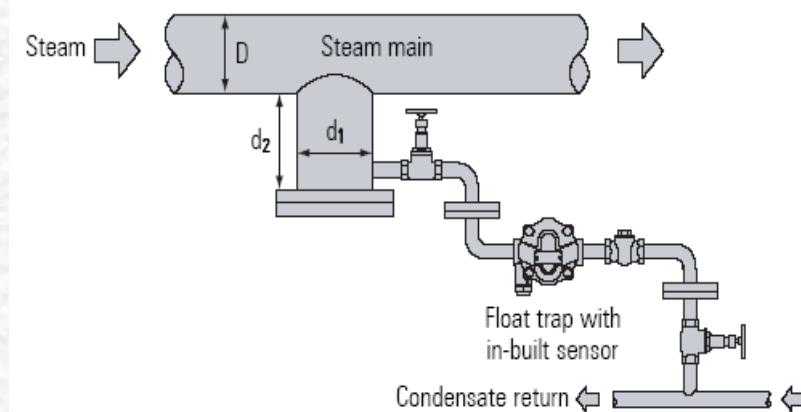
Condensate drainage from equipments

Steam in

Air vent located opposite steam inlet

Air

Condensate ↓

Float-thermostatic trap set
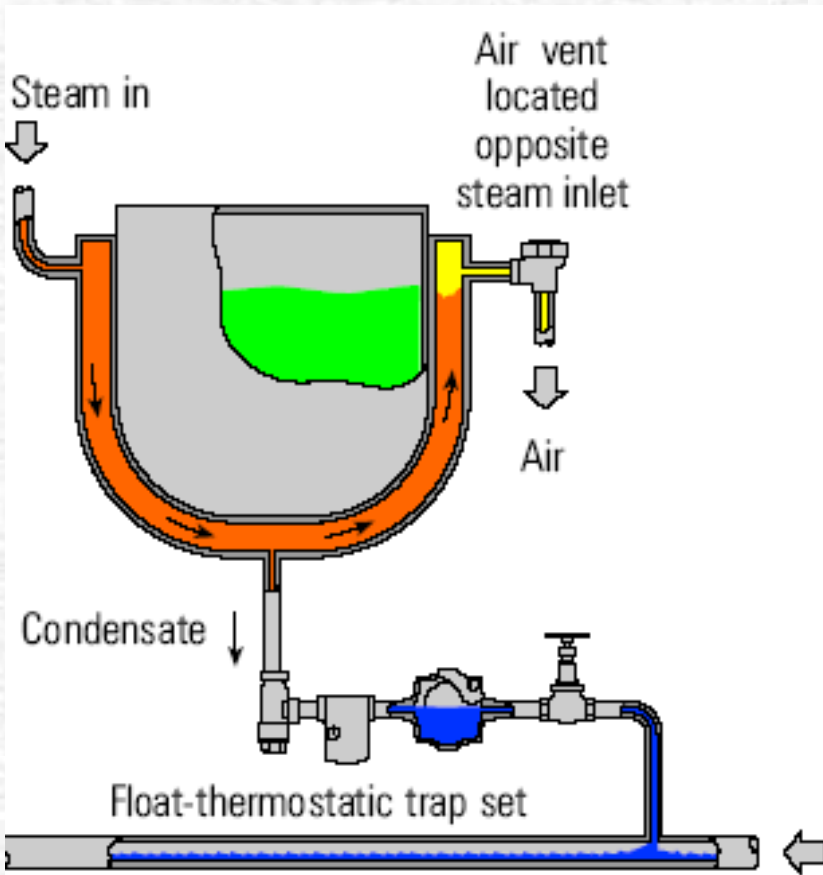
- To prevent "Water Hammer"
- Higher heat transfer coefficient

Steam temperature 121°C

Steam at 1 bar g

Air film

Condensate film

Scale

Metal heating surface

Scale

Product film

Product

99°C Product temperature
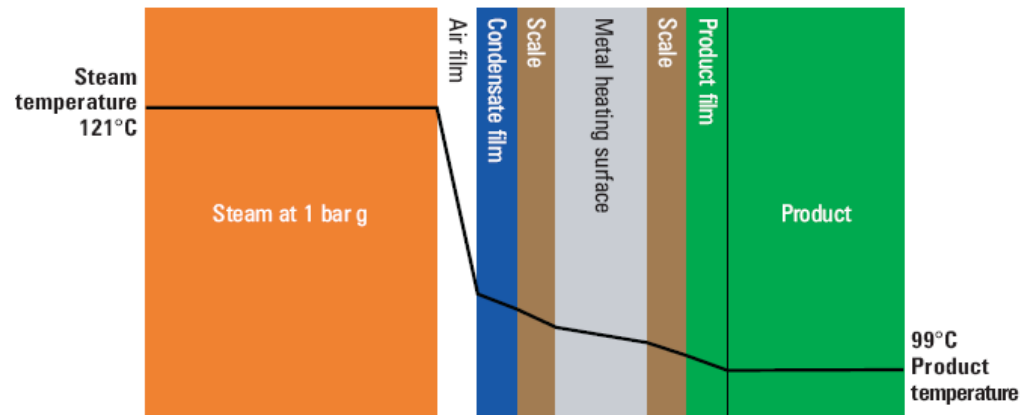
Guide for proper drainage and layout of steam lines:

1. The steam mains should be run with a falling slope of not less that 125mm for every 30metres length in the direction of the steam flow.
2. Drain points should be provided at intervals of 30–45 metres along the main.
3. Drain points should also be provided at low points in the mains and where the main rises. Ideal locations are the bottom of expansion joints and before reduction and stop valves.
4. Drain points in the main lines should be through an equal tee connection only.
5. It is preferable to choose open bucket or TD traps on account of their resilience.
6. The branch lines from the mains should always be connected at the top Otherwise, the branch line itself will act as a drain for the condensate.
7. Insecure supports as well as an alteration in level can lead to formation of water pockets in steam, leading to wet steam delivery. Providing proper vertical and support hangers helps overcome such eventualities.
8. To ensure dry steam in the process equipment and in branch lines, steam separators can be installed as required.
9. Expansion loops are required to accommodate the expansion of steam lines while starting from cold.

Condensate recovery

Advantages of condensate:

- High temperature
- Treated water

Condensate utilization:

- Feed to feed water tank;
- Flash steam.

Feed to feed water tank

% Fuel Reduction vs *Feed Water Temp.(C)*
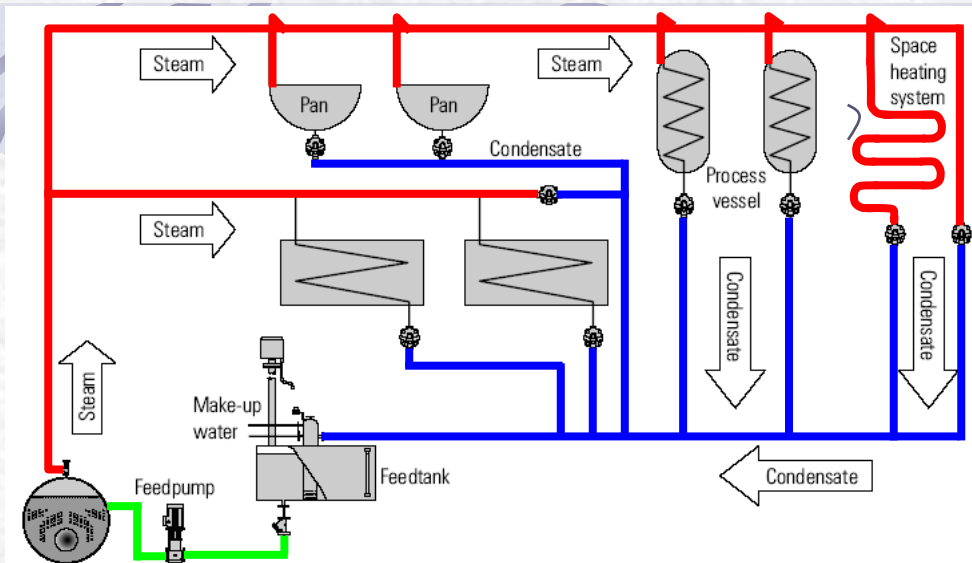
- Fuel can be reduced about 1.6% if water temperature is increased 10C.

- Reduce water and water treatment cost

- Reduce amount of "Blow Down"

- As it has high temp., it has less dissolved gas.
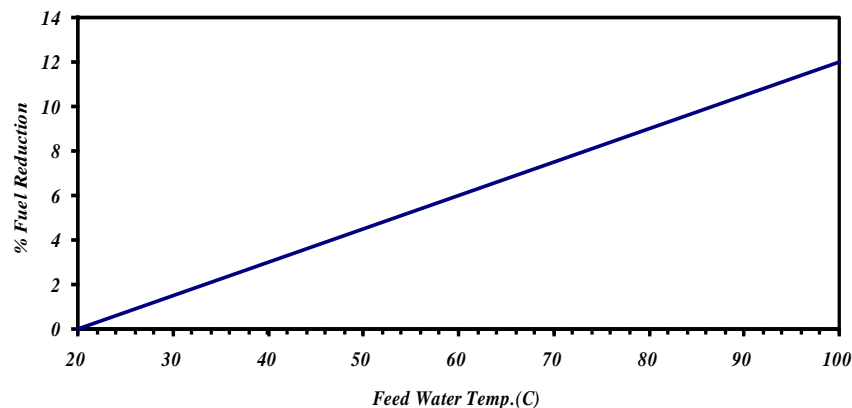
Percent reduction of fuel for steam generation at 9 bar g and feed water temperature of 20°C.

Flash steam

Steam in

**Steam at
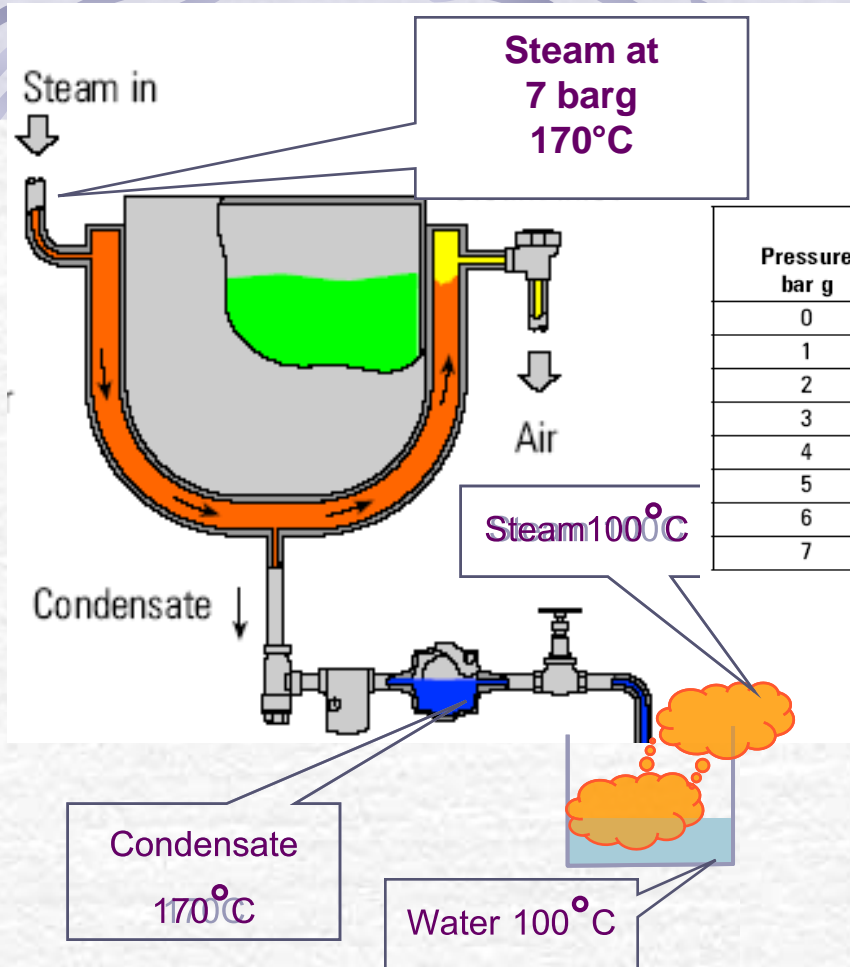7 barg
170°C**

Air

Condensate

Steam 100°C

**Condensate
170°C**

Water 100°C

Pressure bar g	Saturation temperature °C	Enthalpy kJ/kg			Volume of dry saturated steam m³/kg
		Water h_f	Evaporation h_{fg}	Steam h_g	
0	100	419	2 257	2 676	1.673
1	120	506	2 201	2 707	0.881
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5	159	671	2 086	2 757	0.315
6	165	697	2 066	2 763	0.272
7	170	721	2 048	2 769	0.240

Flash steam

0.134 (See Example 14.6.1)
kg Flash per kg condensate
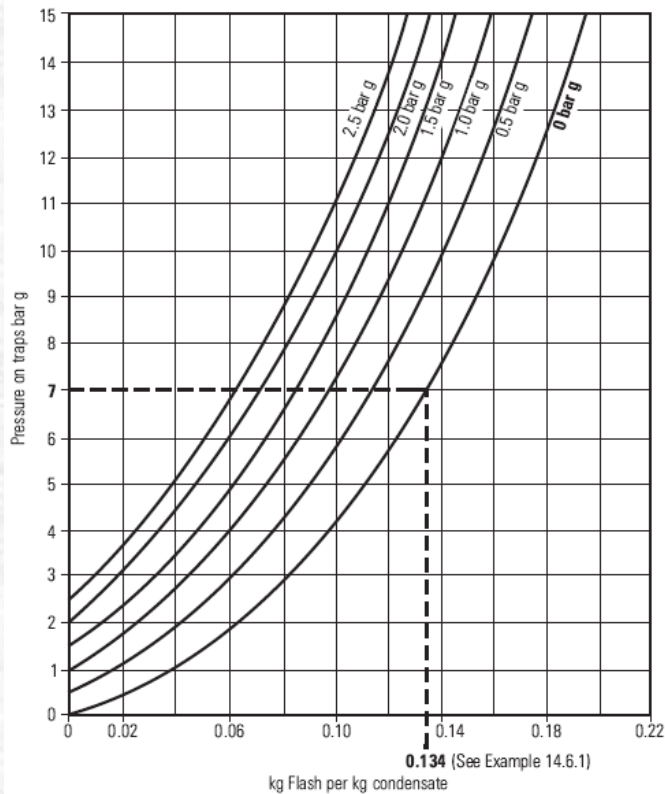
Percent of flash steam

|		Flash Steam Pressure (bar g)								
		0	*0.3*	*0.5*	*1.0*	*1.5*	*2.0*	*3.0*	*4.0*	*5.0*
	1	3.7	2.5	1.7						
	2	6.2	5.0	4.2	2.6	1.2				
	3	8.1	6.9	6.1	4.5	3.2	2.0			
	4	9.7	8.5	7.7	6.1	4.8	3.6	1.6		
Pressure before flash (bar g)	5	11.0	9.8	9.1	7.5	6.2	5.0	3.1	1.4	
	6	12.2	11.0	10.3	8.7	7.4	6.2	4.3	3.0	1.3
	8	14.2	13.1	12.3	10.8	9.5	8.3	6.4	4.8	3.4
	10	15.9	14.8	14.2	12.5	11.2	10.1	8.2	6.6	5.3
	12	17.4	16.3	15.5	14.0	12.7	11.6	9.8	8.2	6.9
	14	18.7	17.6	16.9	15.4	14.1	13.0	11.2	9.6	8.3
	16	19.0	18.8	18.1	16.6	15.3	14.3	12.4	10.9	9.6

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Percent condensate recovery of open feed water tanks

Percent condensate recovery of open feed water tanks

Pressure (kg / cm^2)	Steam Temp. (°C)	Useful latent heat (%)	Loss as flash steam (%)	Useful heat in condensate (%)	Max condensate recovery (%)
0.5	110	83	2	15	98
1	119	81	4	15	96
2	133	79	6	15	94
4	151	76.5	10	13.5	90
6	164	75	12	13	88
8	175	73	14	13	86
10	184	72	16	12	84

Maximum percentage of condensate recovery decreases as operating pressure increases.

Flash steam utilization
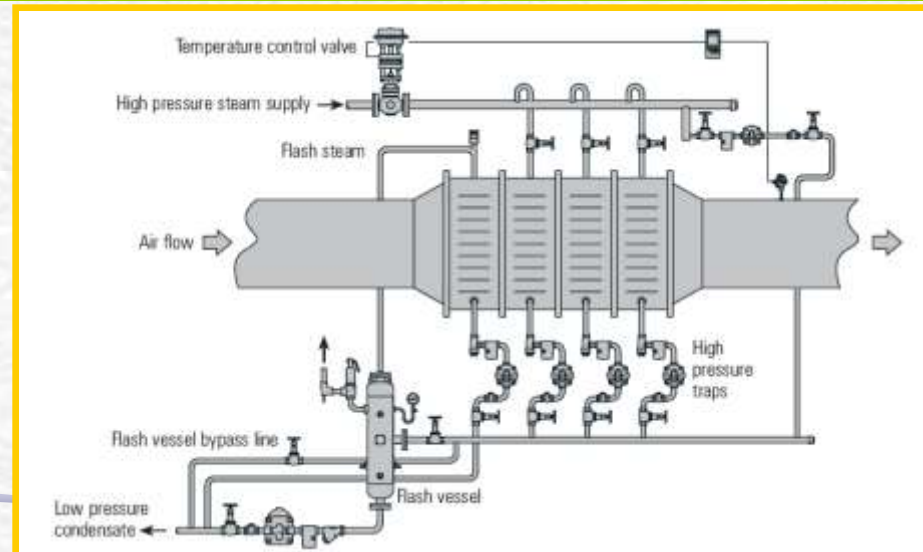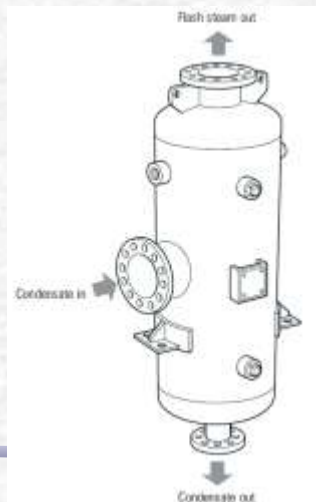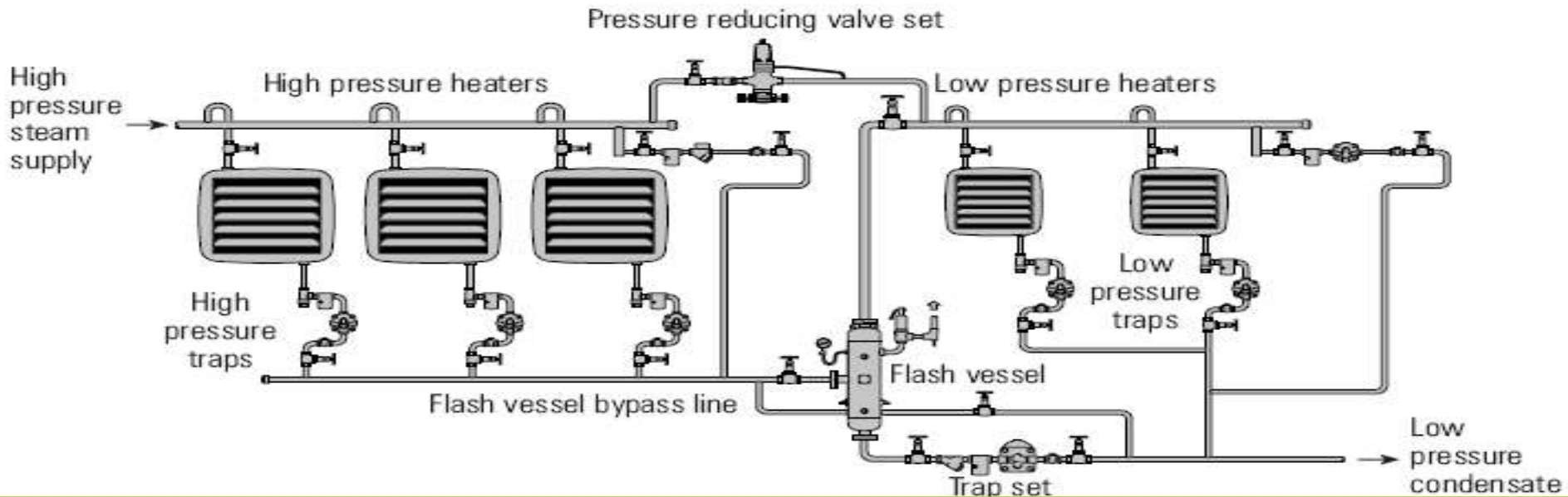
Boiler blown down

- Surface Blow Down or Continuous Blow Down

TDS sensor

Isolating valve
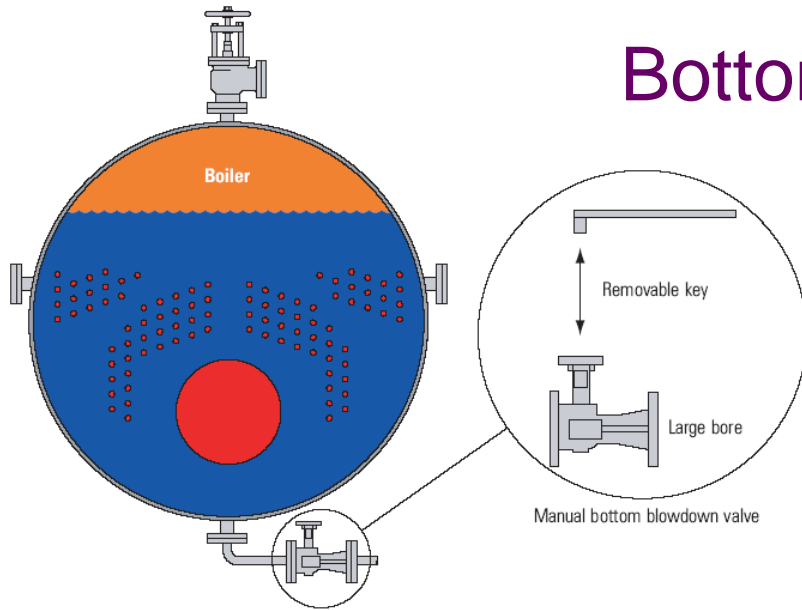
Blowdown valve

Sample cooler
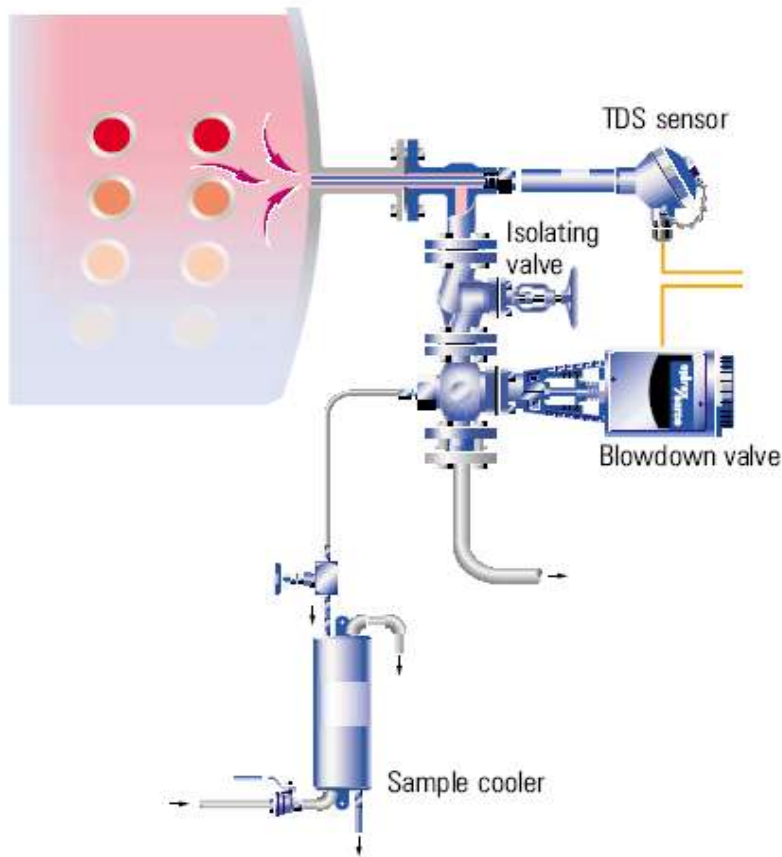
- To maintain water concentration.
- Water is drained from area near water surface;
- Water is drained continuously, it may be called as Continuous Blowdown;
- Heat recovery from blowdown is possible.

Boiler blown down

Bottom blowdown

• It should be performed when boilers operate under low fired (LF) condition;
• To drain sludge;
• Water is drained from the bottom of steam drum;
• Water is blown in a very short period, 3-5 seconds.

Heat recovery from surface blowdown

Make up Water

Blown Down

TDS sensor

Isolating valve

Blowdown valve

Sample cooler

Drain

To Feed Tank
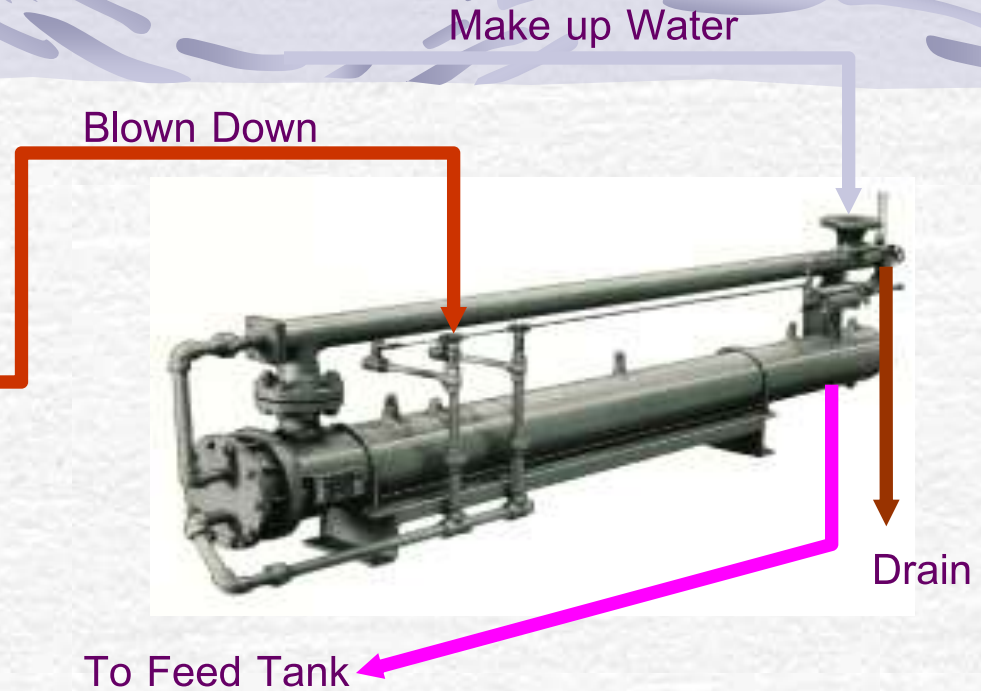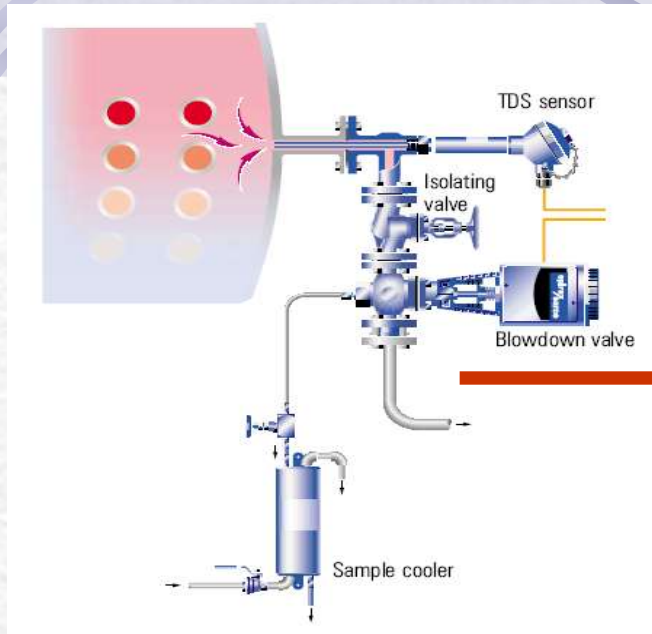
- 80% of blowdown heat can be recovered.

Blowdown tank
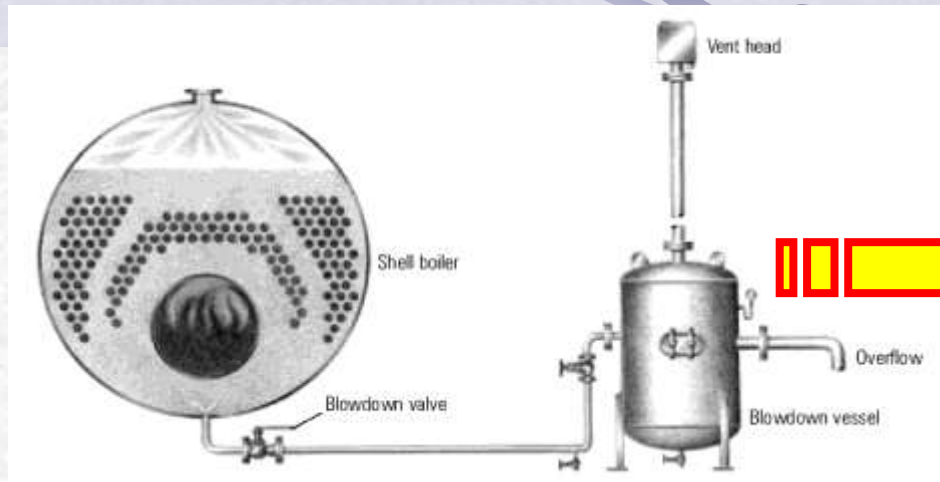
- Because of very short period in drainage, it is difficult to recover the heat from bottom blowndown.
- Sludge in blowdown water is separate by using blowdown tank.

Feed water

- Feed water system

- Feed water quality

- Blowdown rate

- Condensate utilization

Feed water system

Condensate

Feed Tank

Eliminate
Mg^{+2}, Ca^{+2}

Raw Water

Boiler   Feed Water Pump   Softener
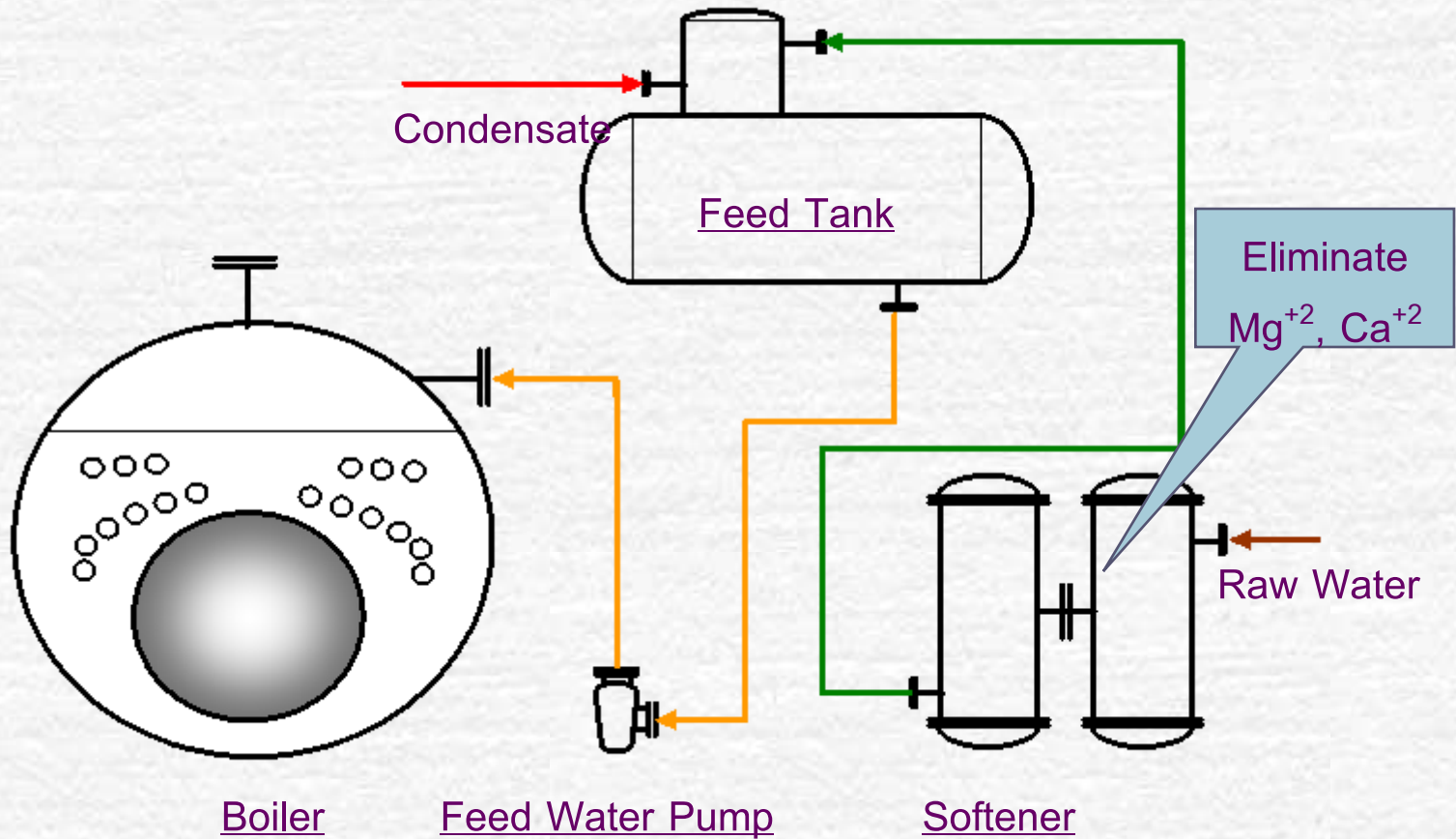
Water quality measurement

$(\mu s \, / \, cm)$

Conductivity meter

TDS Meter

$$TDS \approx 0.7 \times MicroCement \, / \, cm(\mu s \, / \, cm)$$

Boiler water quality

The quality of feed water should be conform to recommendation of the boiler manufacture.

Some broad guidelines on the maximum permissible levels of boiler water TDS

Boiler type	Maximum TDS (ppm)
Lancashire	10 000
Two-pass economic	4 500
Packaged and three-pass economic	3 000 to 3 500
Low pressure water-tube	2 000 to 3 000
Medium pressure water-tube	1 500
High pressure water-tube	1 000

Boiler water quality

American Boiler Manufacturers Association (ABMA) Standard Boiler Water Concentrations for Minimizing Carryover

Drum Pressure (psig)	Boiler Water		
	Total Silica* (ppm SiO2)	Specific** Alkalinity (ppm CaCO3)	Conductance (microoomhs/cm)
0-300	150	700	7000
301-450	90	600	6000
451-600	40	500	5000
601-750	30	400	4000
751-900	20	300	3000
901-1000	8	200	2000
1001-1500	2	0	150
1501-2000	1	0	100

*This value will limit the silica content of the steam to 0.25 ppm as a function of selective vaporization of silica.*

** Specific conductance is unneutralized*

Boiler water quality

ASME Guidelines for Water Quality in Modern Industrial Water Tube Boilers for Reliable Continuous Operation

Boiler Feed Water				Boiler Water		
Drum Pressure (psi)	Iron (ppm Fe)	Copper (ppm Cu)	Total Hardness (ppm CaCO3)	Silica (ppm SiO2)	Total Alkalinity** (ppm CaCO3)	Specific Conductance (micromhos/cm) (unneutralized)
0-300	0.100	0.050	0.300	150	700*	7000
301-450	0.050	0.025	0.300	90	600*	6000
451-600	0.030	0.020	0.200	40	500*	5000
601-750	0.025	0.020	0.200	30	400*	4000
751-900	0.020	0.015	0.100	20	300*	3000
901-1000	0.020	0.015	0.050	8	200*	2000
1001-1500	0.010	0.010	0.0	2	0***	150
1501-2000	0.010	0.010	0.0	1	0***	100

Blowdown rate

Condensate
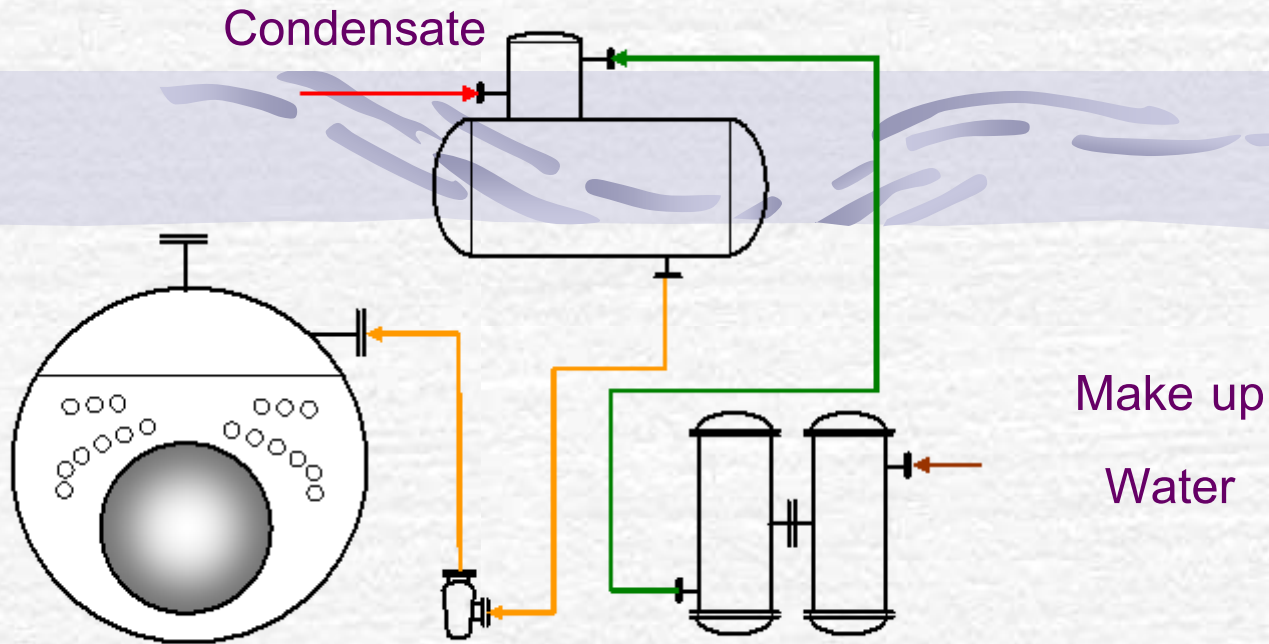
Make up

Water

$$\text{Min \%Blowdown (A)} = \frac{\%\text{make up} \times [\text{TDS}]_{\text{make up}}}{[\text{TDS}]_{\text{max allowable in boiler}}}$$
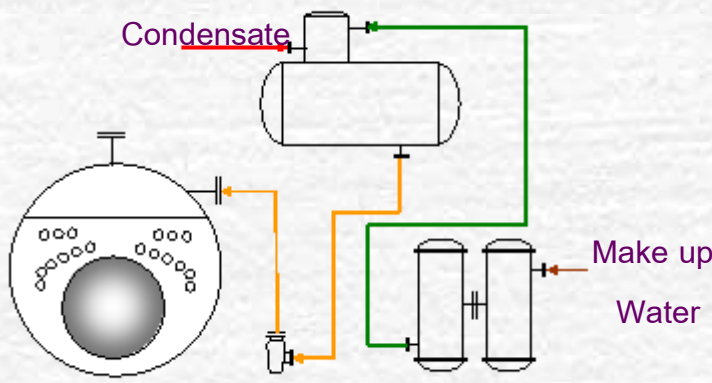
$$\text{Steam generation rate} = \text{B ton/hr}$$

$$\text{Blowdown rate} = \frac{A \times B}{100\text{-}A} \times 1000 \text{ litre/hr}$$

Example:

Compare blowdown rate of a boiler under conditions:
a) 100% make up water
b) 60% condensate recovery
The boiler has max allowable TDS of 3500ppm, TDS of make up water is 150 ppm and steam generation rate in 1 ton/hr.

Condensate

Make up
Water

Steam generation rate (B) = 1 ton/hr

$$\text{Min \%Blowdown (A)} = \frac{\%\text{make up} \times [\text{TDS}]_{\text{make up}}}{[\text{TDS}]_{\text{max allowable in boiler}}}$$

Case a)
$$= \frac{100 \times 150}{3500} = 4.3$$

$$\text{Min \%Blowdown (A)} = \frac{\%\text{make up} \times [\text{TDS}]_{\text{make up}}}{[\text{TDS}]_{\text{max allowable in boiler}}}$$

Case b)
$$= \frac{60 \times 150}{3500} = 1.7$$

Case a) $\quad \text{Blowdown rate} = \frac{A \times B}{100\text{-}A} \times 1000 \text{ litre/hr} = \frac{4.3 \times 1}{100\text{-}4.3} \times 1000 = 45 \text{ l/hr}$

Case b) $\quad \text{Blowdown rate} = \frac{A \times B}{100\text{-}A} \times 1000 \text{ litre/hr} = \frac{1.7 \times 1}{100\text{-}1.7} \times 1000 = 18 \text{ l/hr}$
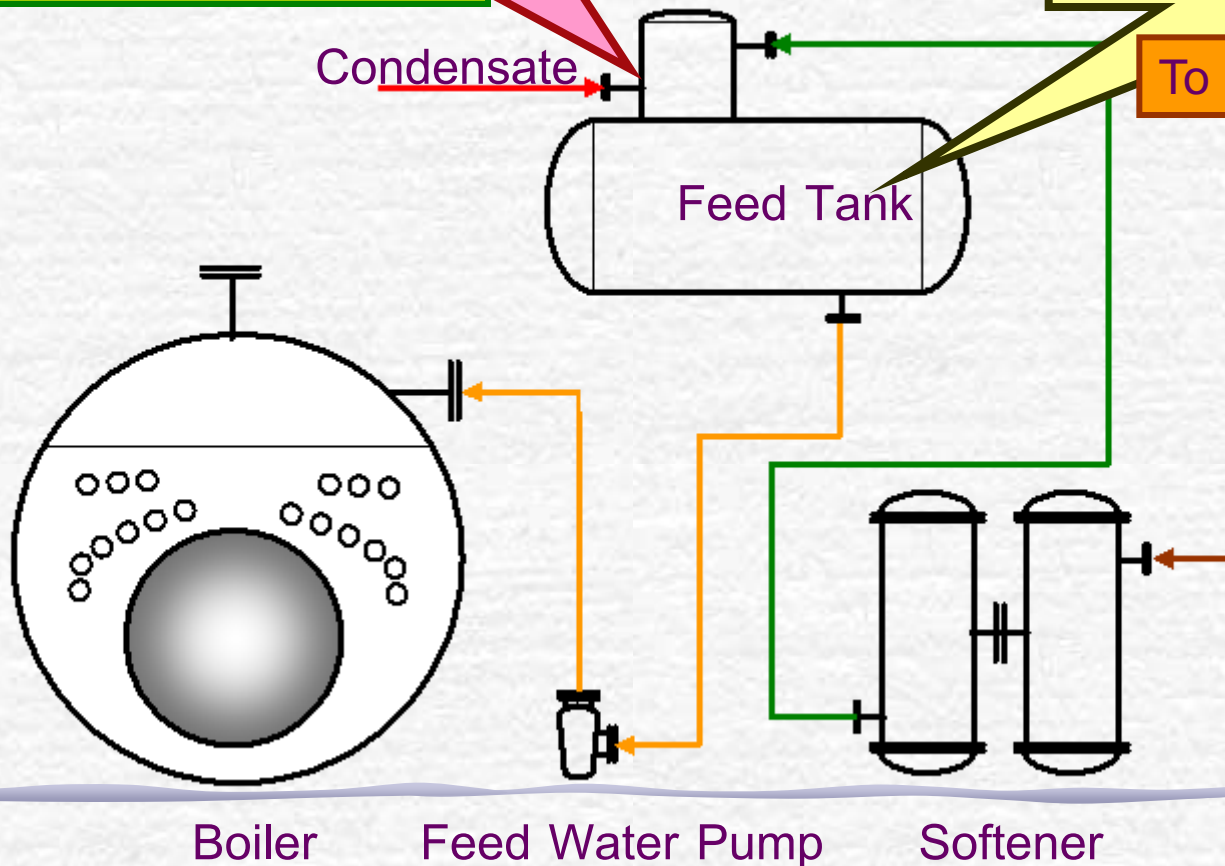
Advantages of condensate

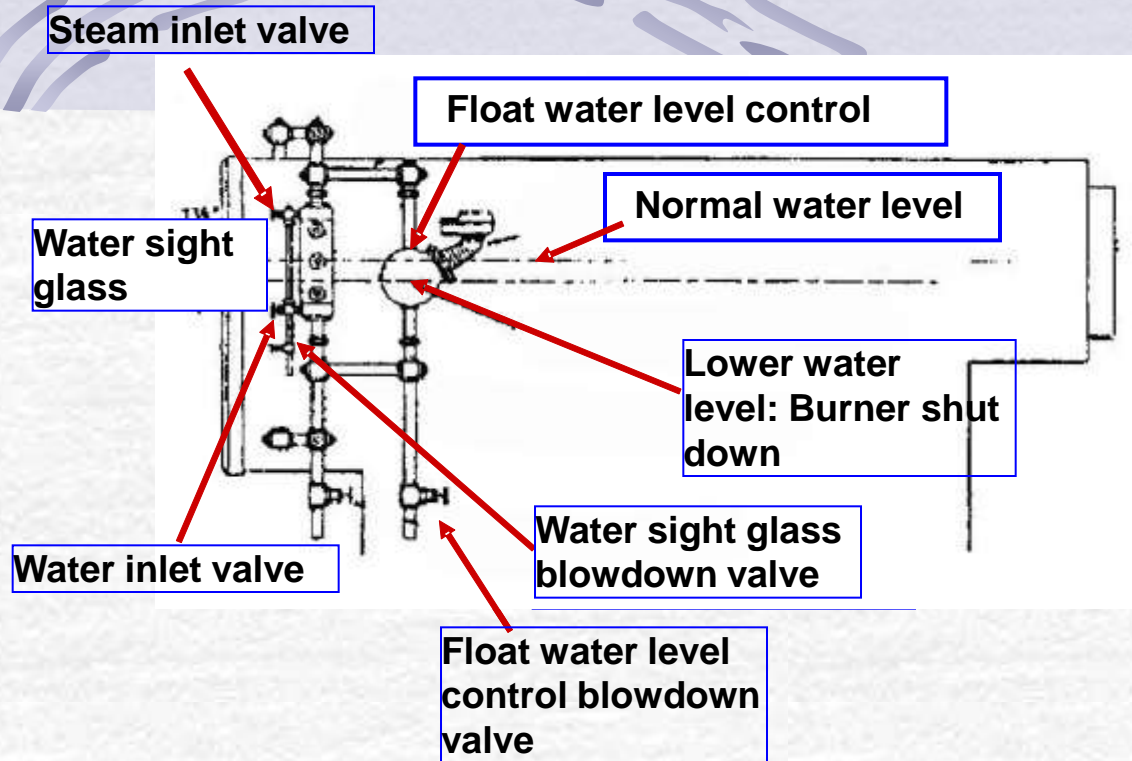Return condensate to feed water tank as much as possible

To reduce blowdown rate

Feed water temperature should be as high as possible

Condensate

To reduce dissolve air

Feed Tank

Boiler   Feed Water Pump   Softener

Controlling of boiler water

Steam inlet valve

Float water level control

Normal water level

Water sight glass

Lower water level: Burner shut down

Water inlet valve

Water sight glass blowdown valve

Float water level control blowdown valve

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