Module-3A: Heat Transfer Equipment

Applied Thermo Fluids-II (Autumn 2017)

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Introduction

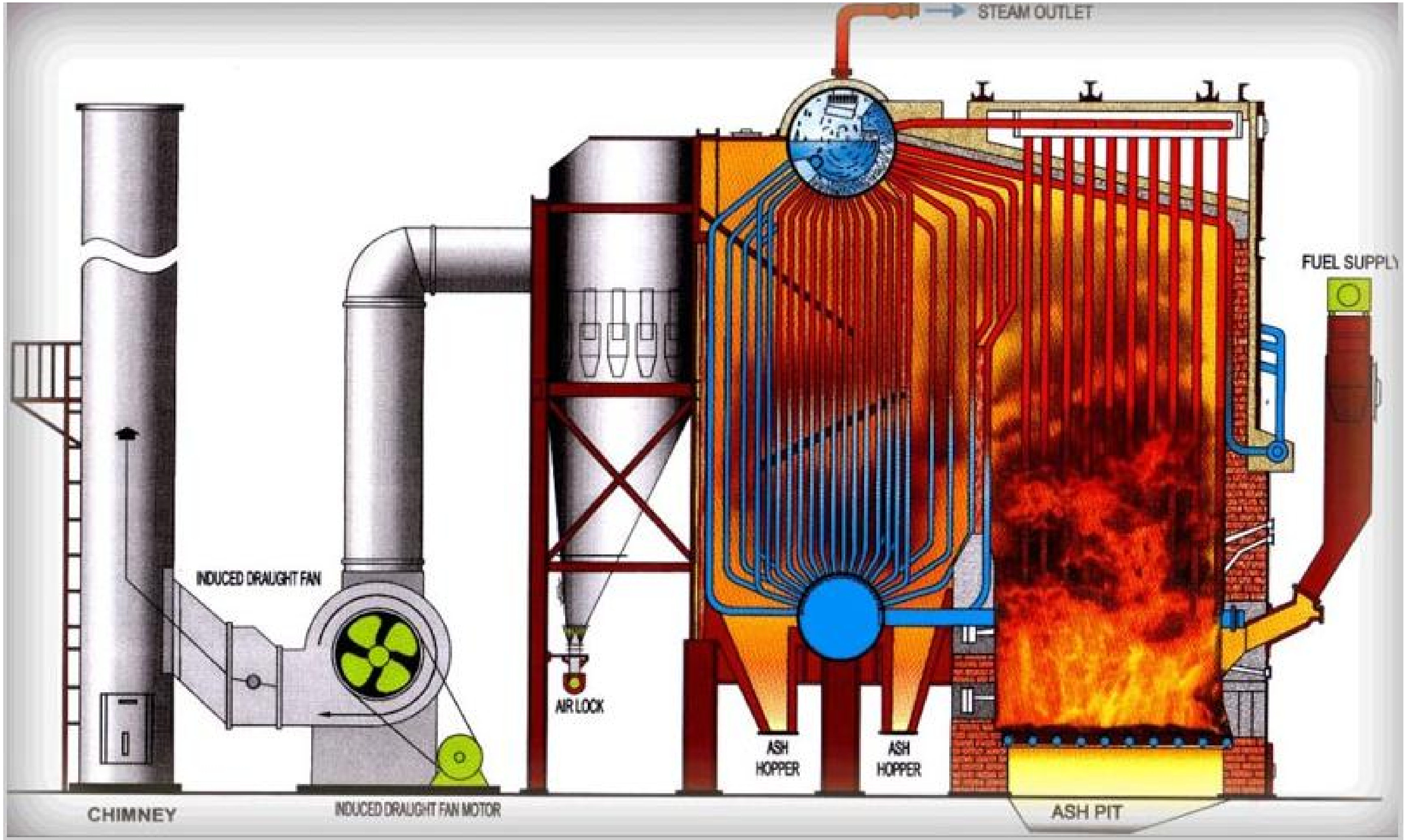
- From **1st law of thermodynamics** applied to the combustion reaction;

$$\sum_R H_R = \boxed{\sum_P H_P + \Delta Q}$$

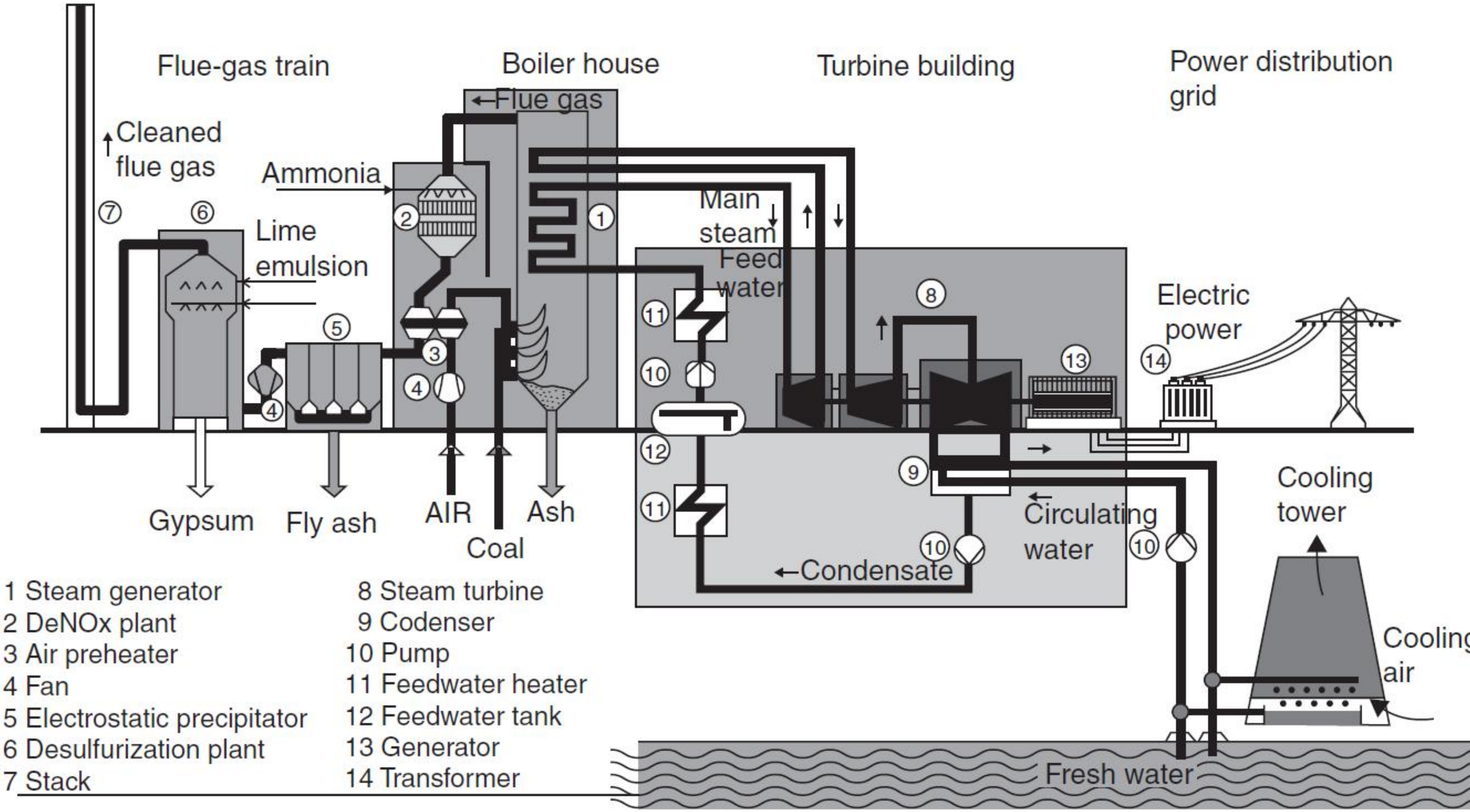
To be **utilized** efficiently
in **power generation**

- Various **heat transfer equipment** are used in a power plant to **utilize** the heat released during combustion and energy contained in the products of combustion efficiently for power generation

- Finally the products of combustion are to be discharged safely into the environment using a **draft system**



http://mechanicalfieldexperience.blogspot.in/2016/02/types-of-boilers.html



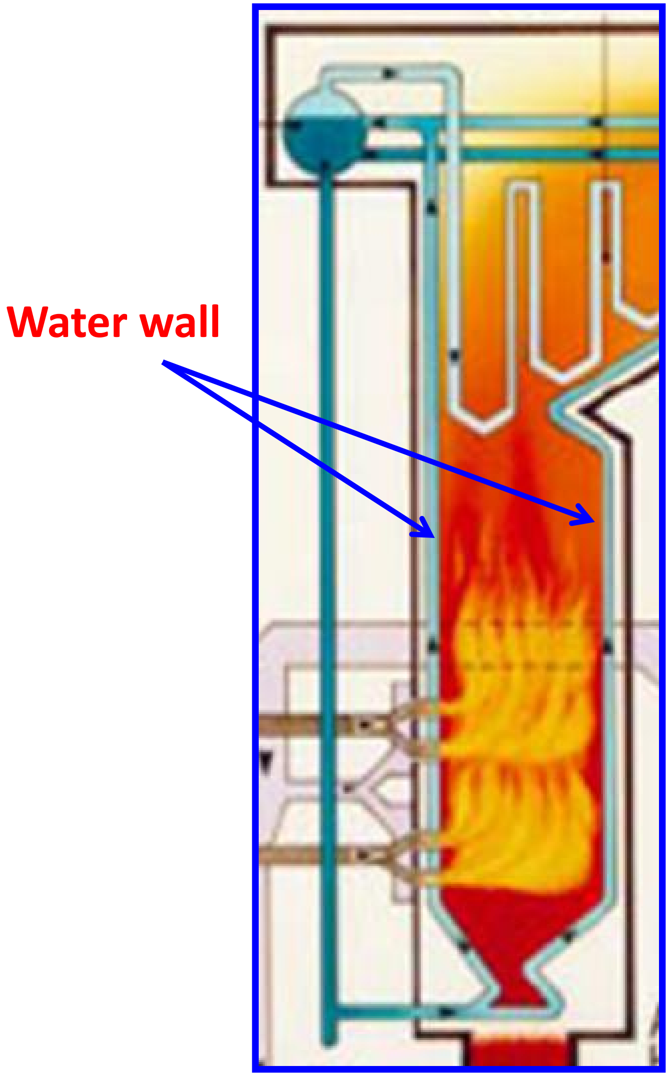
Advanced pulverized coal-fired power plant (*Source*: Termuehlen & Empsberger 2003, Janos Beer 2009; reproduced with the permission of Professor Janos Beer © Elsevier).

Water walls in steam generators

- **In modern boilers**, the **water tubes** are **attached** to the **furnace walls** and are called as **water walls**
- **Using** the **water walls** it is **possible to integrate** the furnace, economizer, boiler, superheater, and re-heater into a single unit
- **Heat transfer** takes place both by convection and radiation
- Provides **efficient and compact unit**
- **Due to large no. of feedwater heaters** and **high pressure,** in modern steam generators **most of the heat transfer** takes place in the **superheated region**

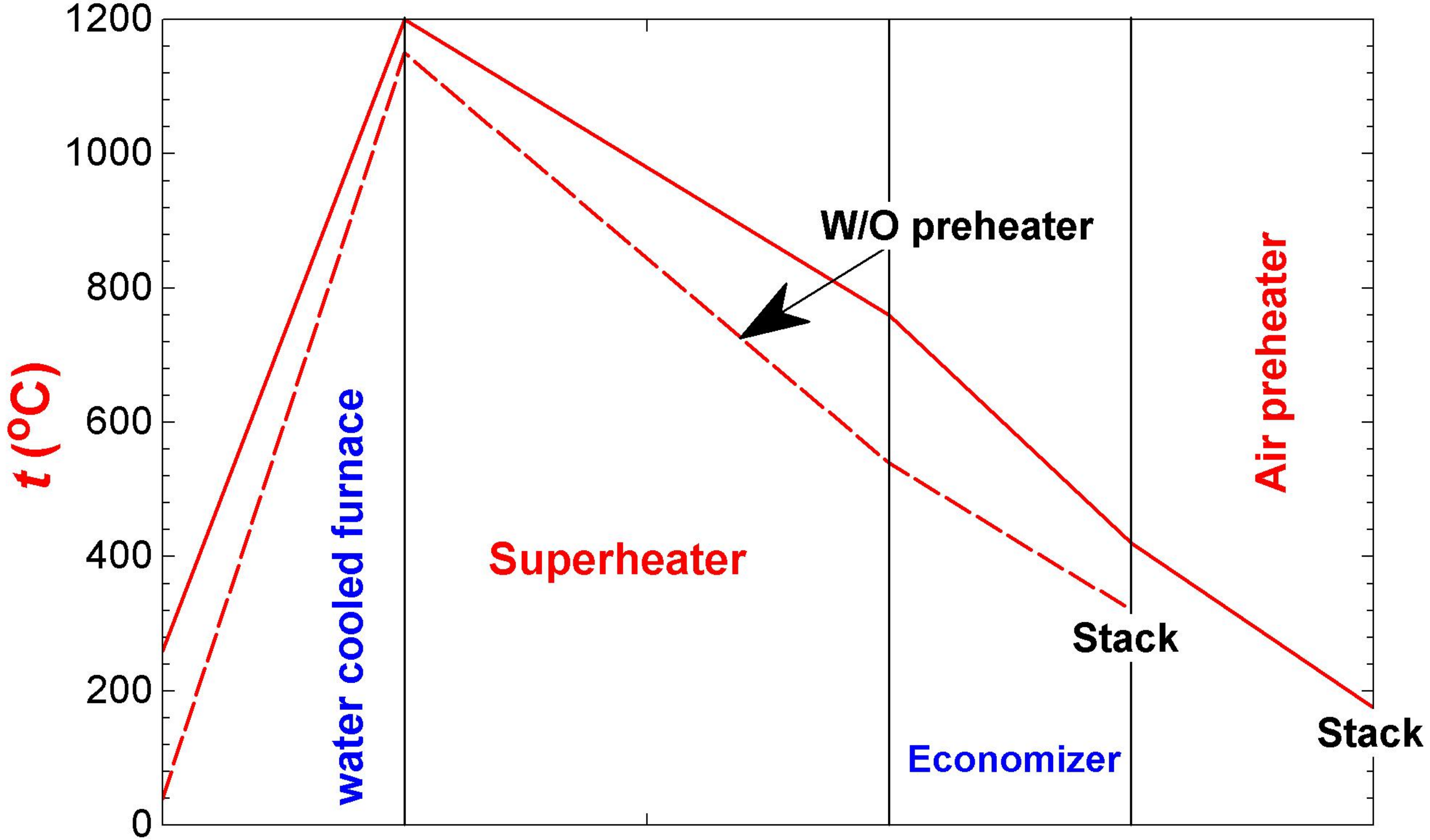
Introduction (contd.)

- **Modern power plants** commonly use **water wall steam generators**
- In these systems the combustion chamber is **integrated** with the **steam generator tubes** through which water flows
- **Boiling** of water takes place **in the water walls** inside the combustion chamber itself
- Depending upon the **chamber design**, **30 to 40 %** of the **heat released** is absorbed by water in the furnace itself
- Most of the **remaining energy** is transferred to steam in **superheater**, reheater, **feedwater heater** and finally **air pre-heater**
- **Finally** the combustion products are **discharged** through **chimney** (or stack)



Water wall steam generator

Typical temperature distribution of combustion products



Introduction to Steam Generators

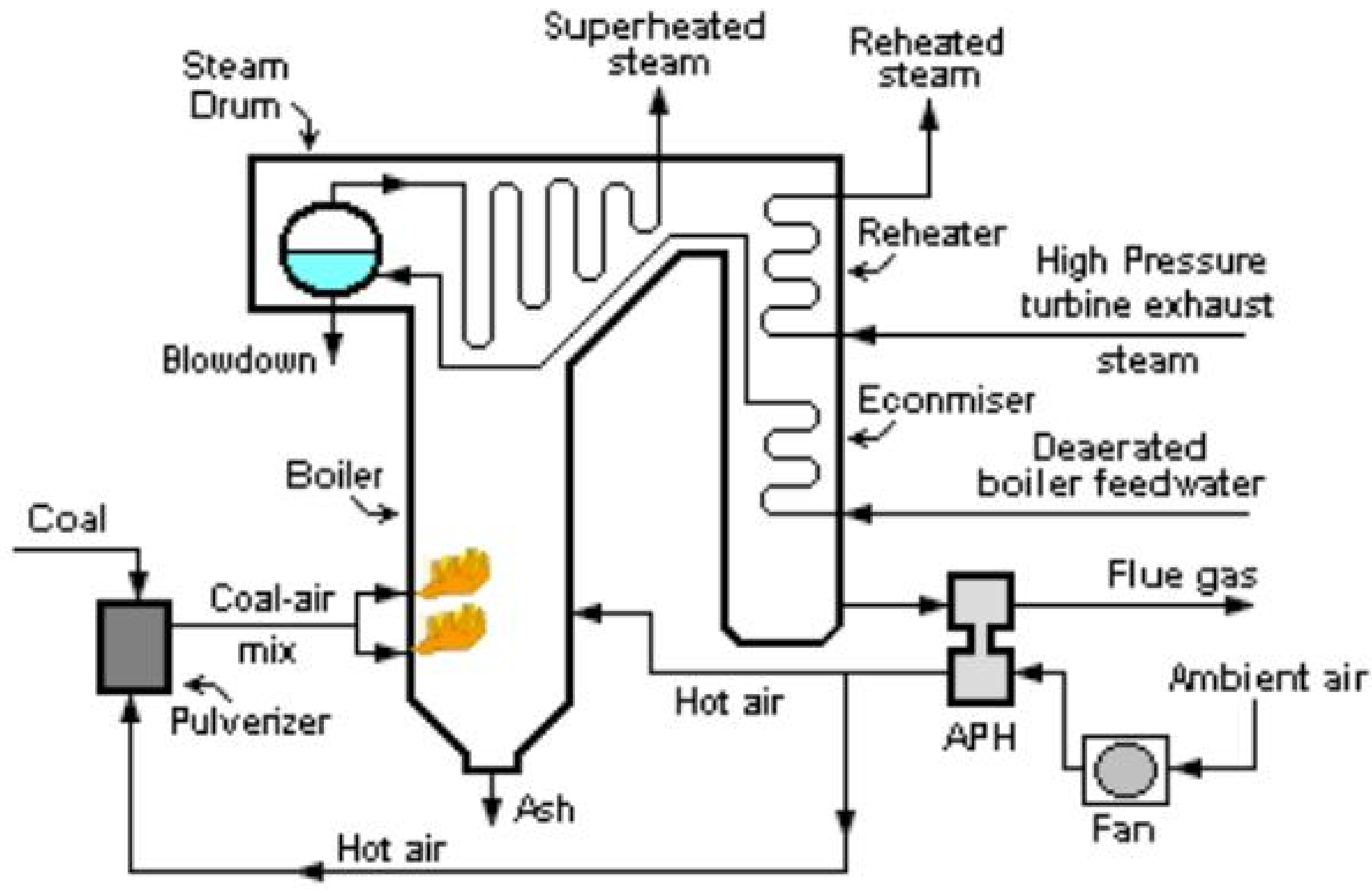
- A **steam generator** is essentially a **device** that **transfers** heat released during the combustion of the fuel **to** the **feedwater**, **steam** and **air**
- The **transfer of heat** should be done **safely**, **reliably** and **efficiently**
- The term "**boiler**" is often used as **synonym** to "steam generator"
- However, strictly speaking **boiler** is that **part of the steam generator** where the saturated liquid water is converted into saturated steam
- Steam generators can be:

1. **Utility steam generators** used for generation of **electrical power**, and
2. **Industrial steam generators** used for production of **saturated steam** or even hot water!

Introduction (Contd.)

- **Utility steam generators** are **used** in **both fossil fuel** based and **nuclear** fuel based **power plants**
- The **most modern steam generators** used **in fossil fuel** power plants can **produce superheated steam** at **375** bar and **720°C**
- The **steam produced** is **invariably used** in a **Rankine cycle** to produce electricity
- Starting with very **early form** of **water-filled vessels heated by fire**, steam generators have **evolved** over the last **2 centuries** into **very efficient, safe and reliable** equipment
- **Currently**, steam generators represent the **largest source** from which **electricity** is generated

Major components of a steam generator



Note: APH is the air preheater

Major components of a steam generator

- **The major components of a steam generator are**:

1. **Economizer :** First part of the boiler through which feedwater flows and is heated by the flue gases.
2. **Boiler tubes**: It is that part of the steam generator where steam is generated from saturated water
3. **Steam drum:** It is the unit in which steam is separated from the steam-water mixture. **Not used in once through type boilers**
4. **Superheaters:** Bundles of boiler tubes located in the path of the hot flue gases in which the saturated steam is superheated.
5. **Re-heaters:** Bundles of boiler tubes through which steam expanded in the high stage turbine is reheated by extracting heat from the hot combustion gases

Major components of a steam generator (contd.)

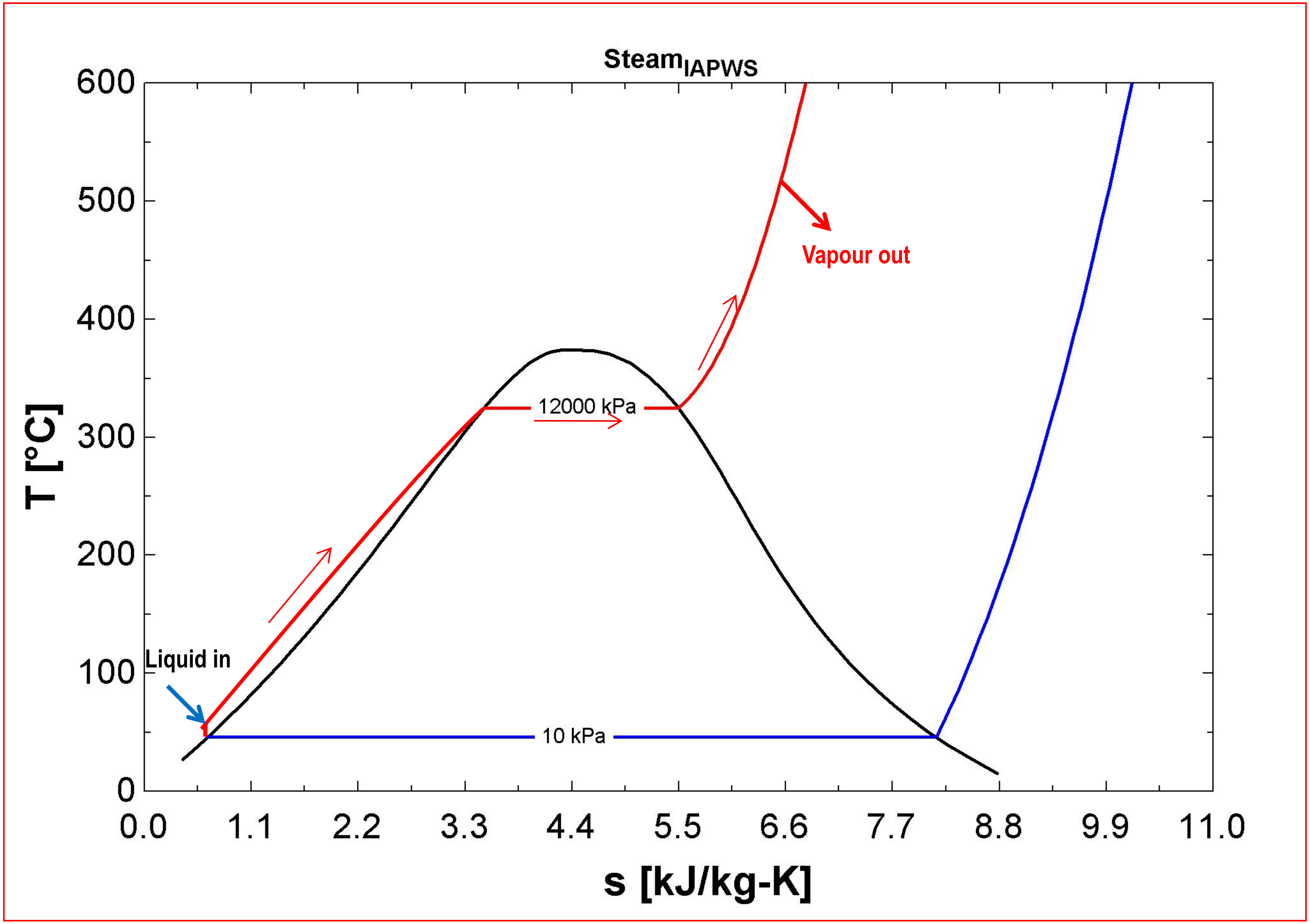
6. **Spray attemptators or desuperheaters:** They are the **spray nozzles** in the boiler tubes, located between two superhaters to prevent damage of tubes due to overheating.

7. **Air pre-heaters:** Units in which the incoming air is heated by using the energy of the outgoing flue gases. Atmospheric air is pre-heated to a temperature of about 350^{o}C.

8. **Fans:** Both induced and forced draft fans are used to circulate air through the pre-heaters, boiler tubes, superheaters, reheaters and chimney stack

9. **Stack:** The purpose of installing the stack is to ensure dispersion of the flue gases into the atmosphere, at a height that ensures a large spread.

Steam generation

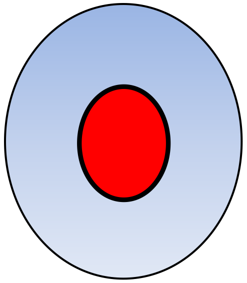


Boiler classification

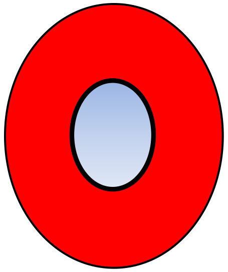
- Depending upon the arrangement and/or operating conditions, boilers can be classified into:

1. **Fire-tube boilers**
2. **Water-tube boilers**
3. **Natural circulation boilers**
4. **Controlled-circulation boilers**
5. **Once-through flow type boilers**
6. **Subcritical boilers**
7. **Supercritical boilers etc.**

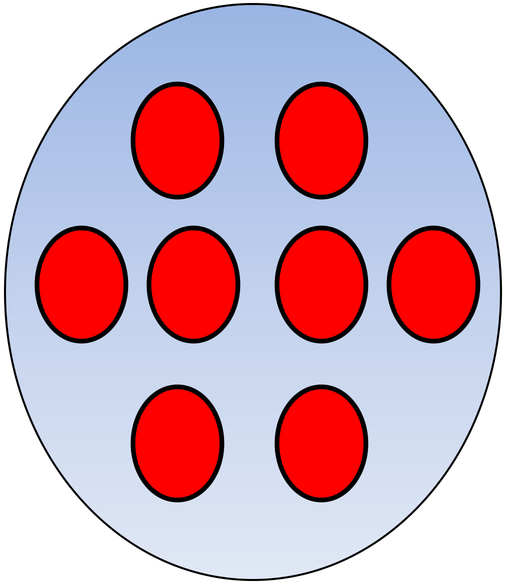
Generation of high pressure and high temperature steam from high pressure liquid water



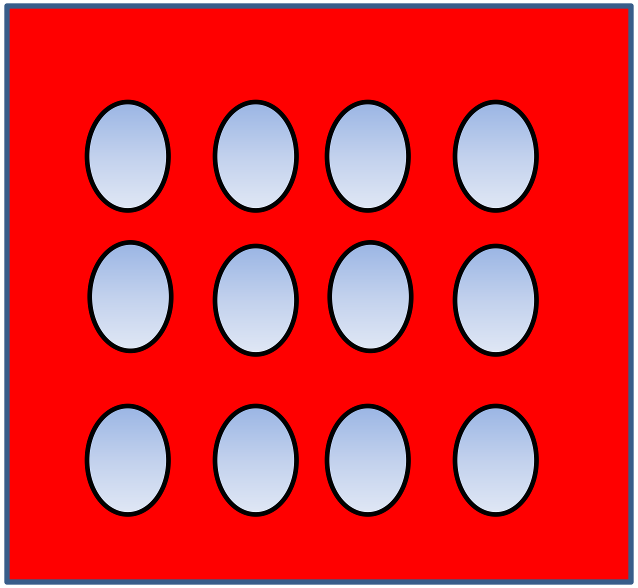
Fire tube



Water tube

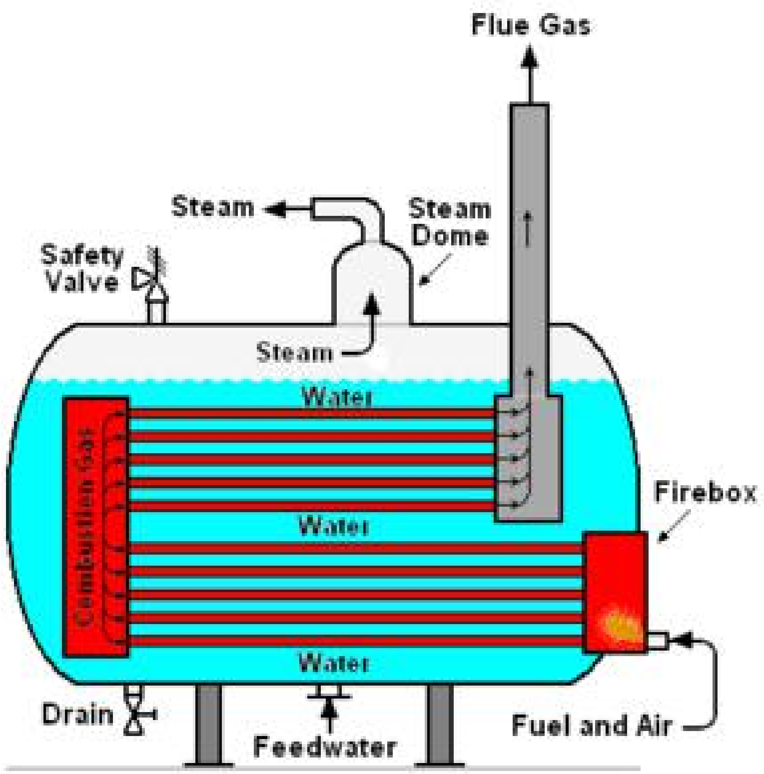


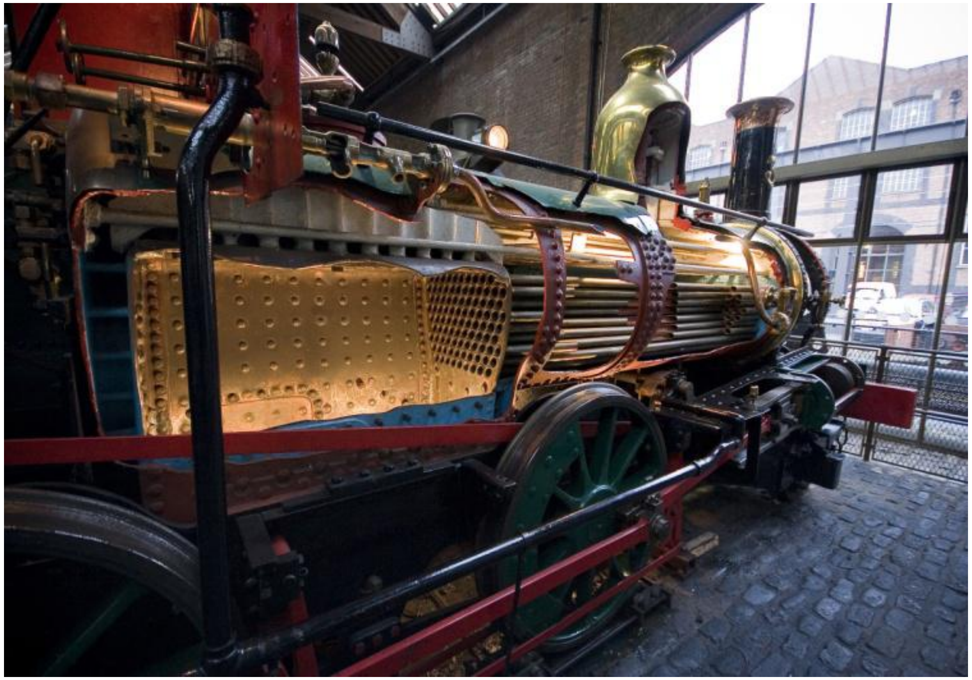
Fire tube boiler



Water tube boiler

Fire tube boilers





Cut-view of a steam locomotive boiler

Fire-tube boilers

a. Somewhat **similar to Shell-and-Tube heat exchangers**, with hot flue gases flowing through the tubes and **water and steam** confined to the **shell side**

b. They **typically produce saturated steam only** as boiling occurs inside the same compartment where there is water

c. The **outer shell** has to be designed **to withstand the steam pressure** – larger the pressure/capacity, larger will be the shell thickness

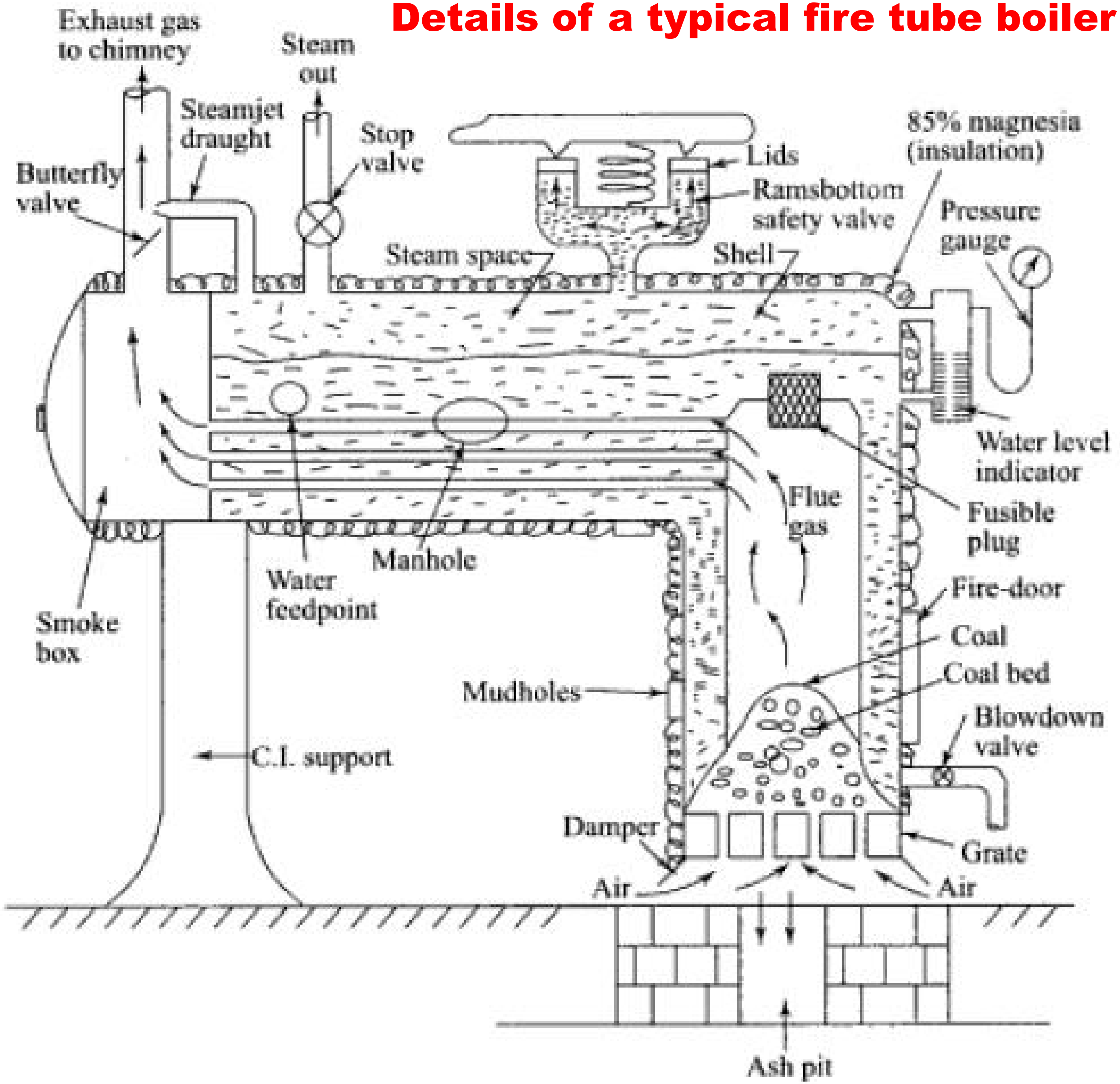
d. Used normally for **low pressure** ($\leq$ 18 bar) and **low capacities** (steam rate $\leq$ 6.3 kg/s)

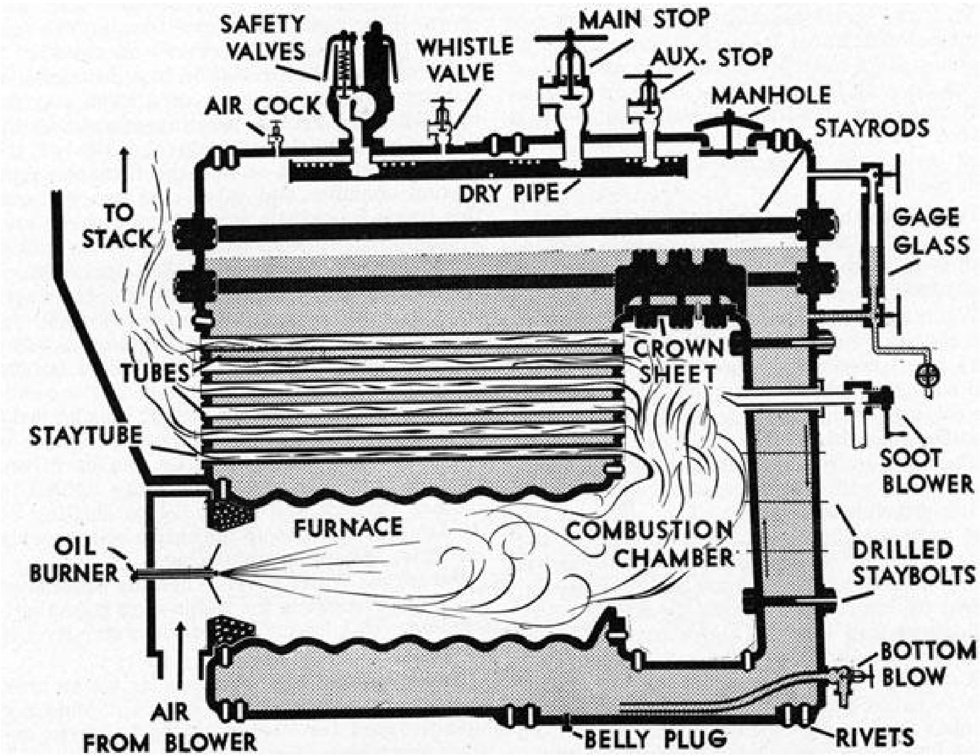
e. **Prone to explosions**

f. Once they were used in small power plants and steam locomotives

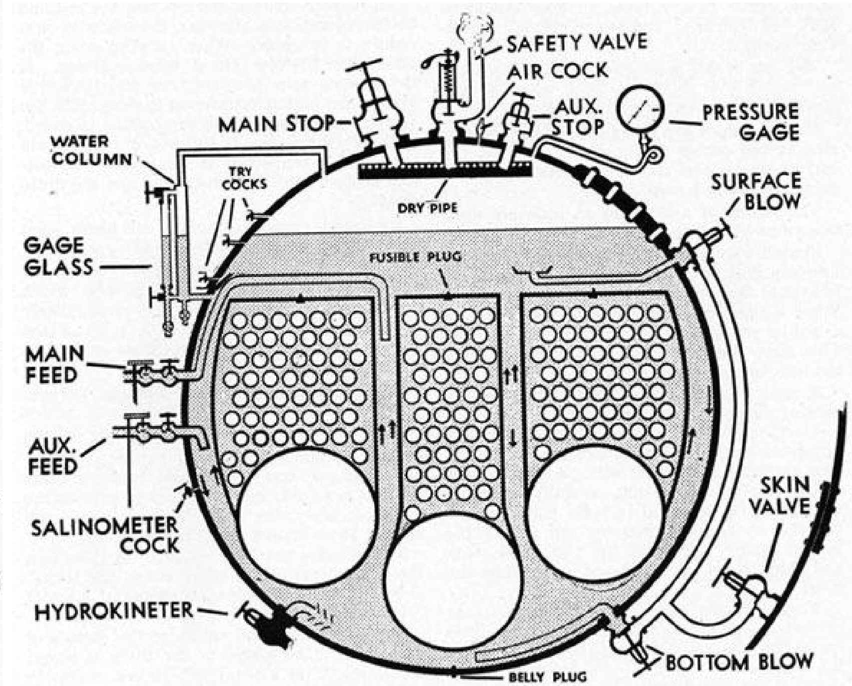
g. Currently they are used for industrial applications only, e.g. for hot water prduction

Details of a typical fire tube boiler



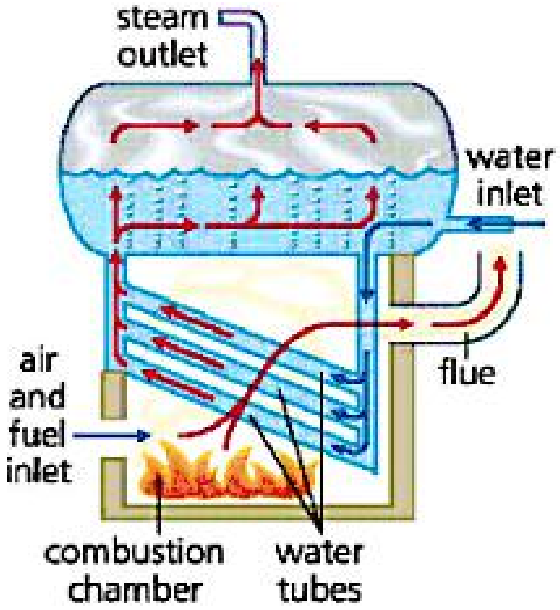


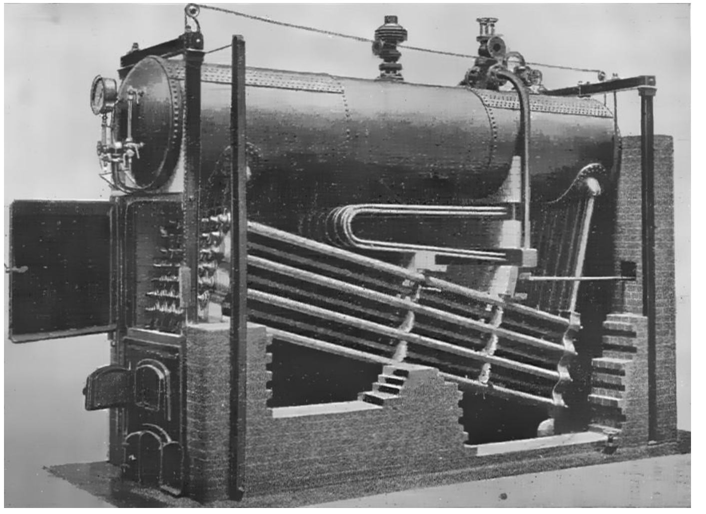
Scotch Marine Type Boiler (front view)



Scotch Marine Type Boiler (side view)

Water tube Boilers





Babcox & Wilcox Boiler

Modern water tube boilers

Water-tube boilers

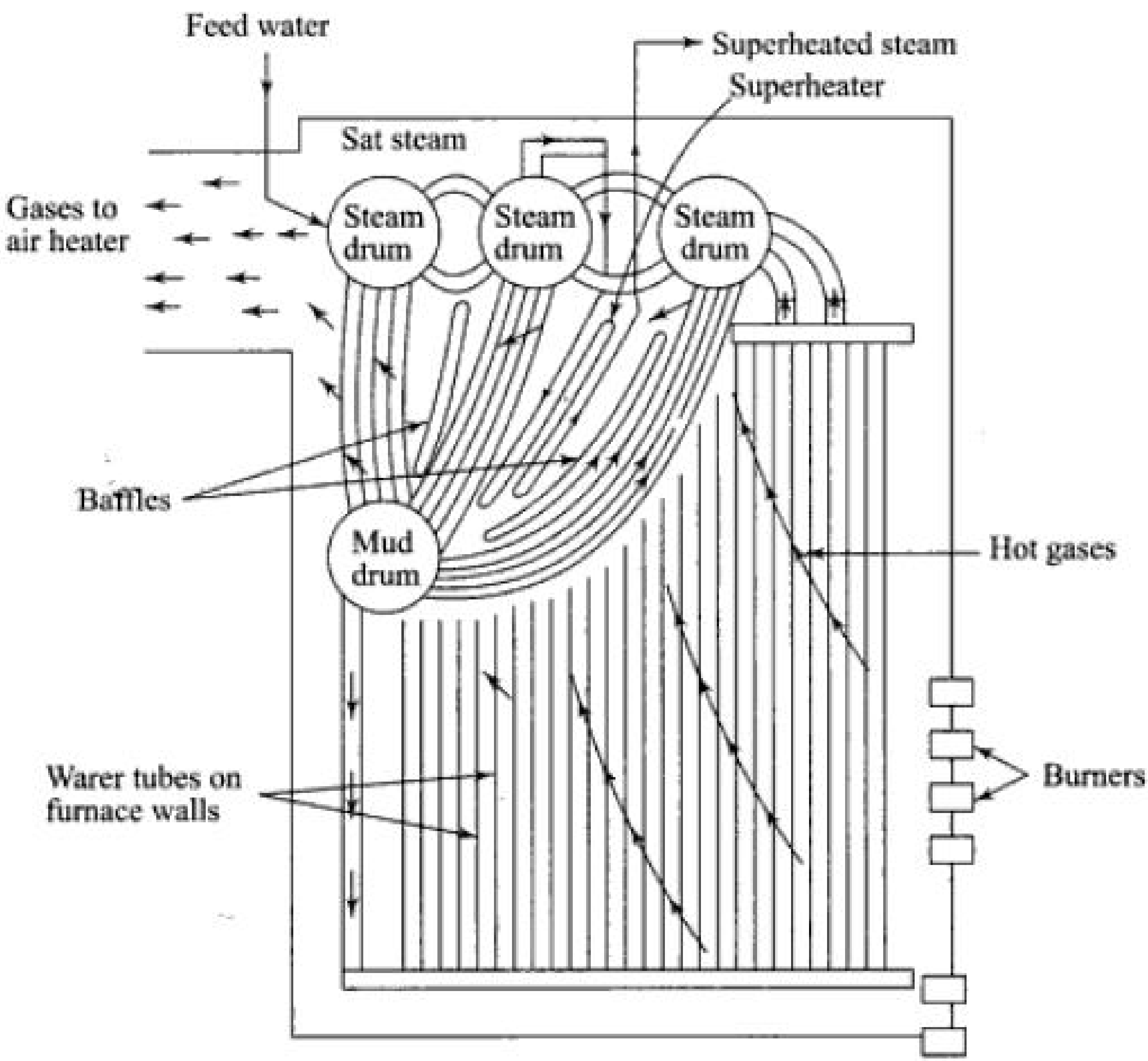
a. Pioneered by **Babcock and Wilcox** [1867], water-tube boilers are the **main type of boilers used in all steam power plants**

b. Here **pressurized water** flows **through the tubes**, while heating is provided by the flue gases flowing outside the tubes

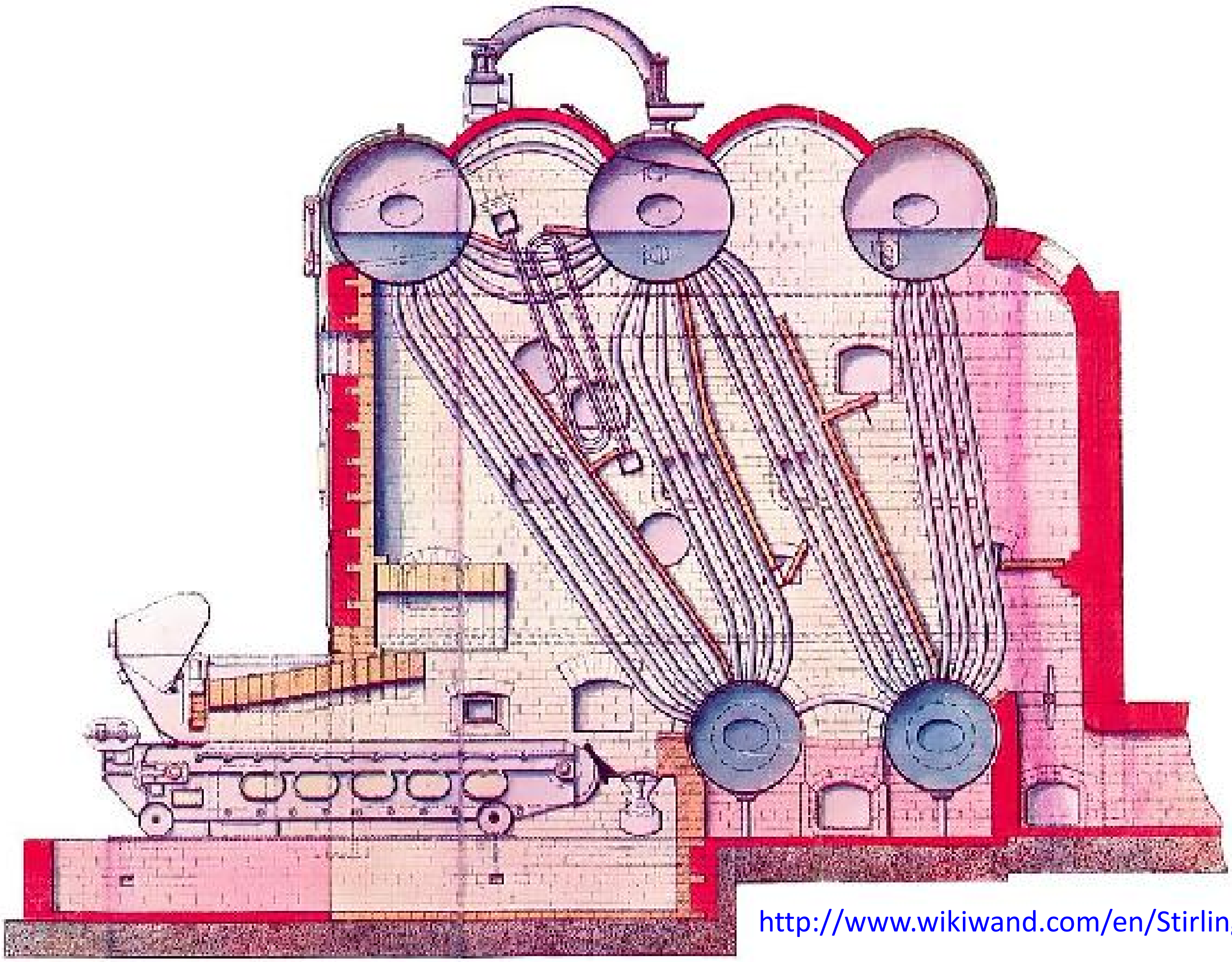
c. It is **possible to produce**, **high pressure and high capacity systems**, that are much safer

d. There are **many variants of water-tube boilers**, depending upon the type of circulation, geometry etc.

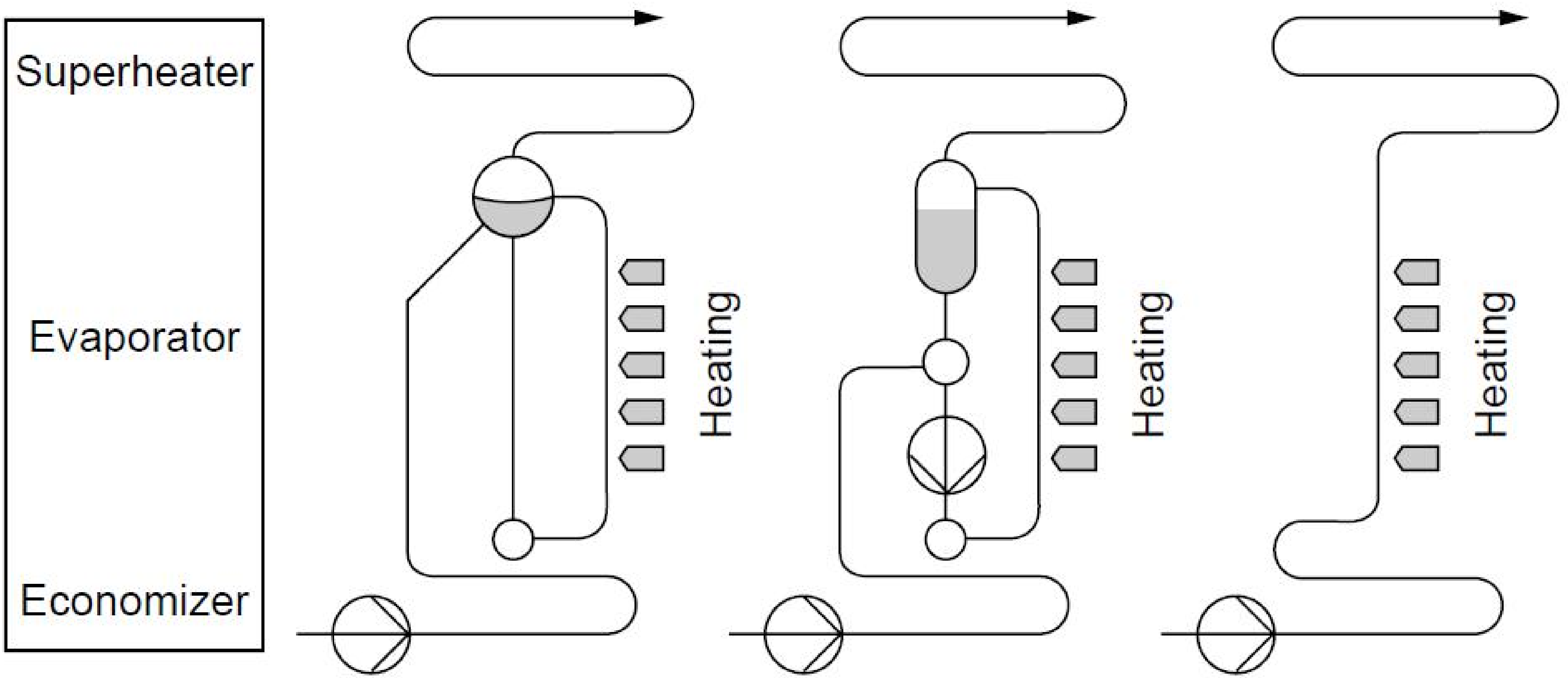
A 4-drum, bent tube boilers



A Stirling, 5-drum water tube boiler



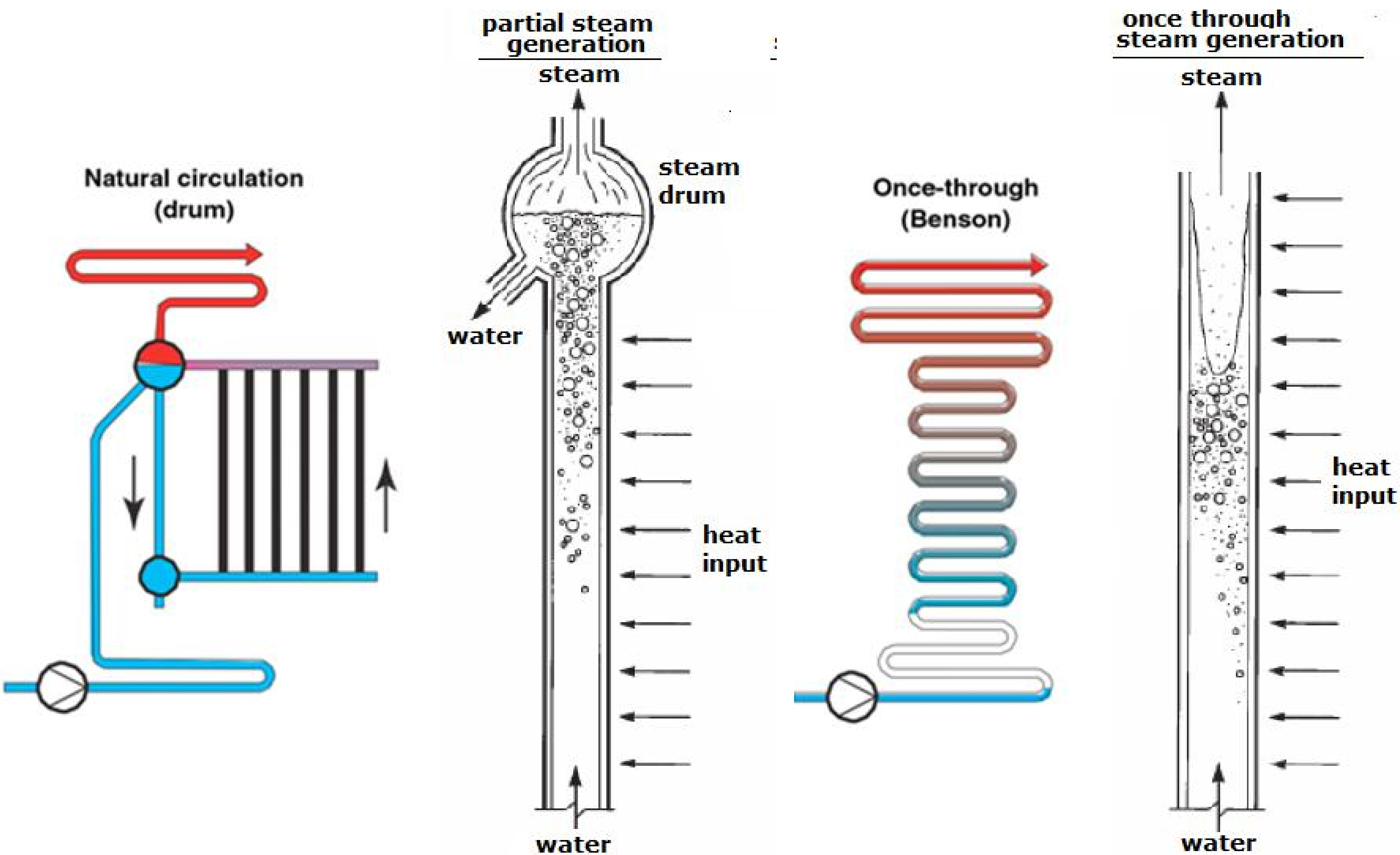
http://www.wikiwand.com/en/Stirling_boiler



Principle	Natural circulation(Drum)	Forced circulation	Once-through (Benson)
Operating pressure	Subcritical	Subcritical	Subcritical and supercritical

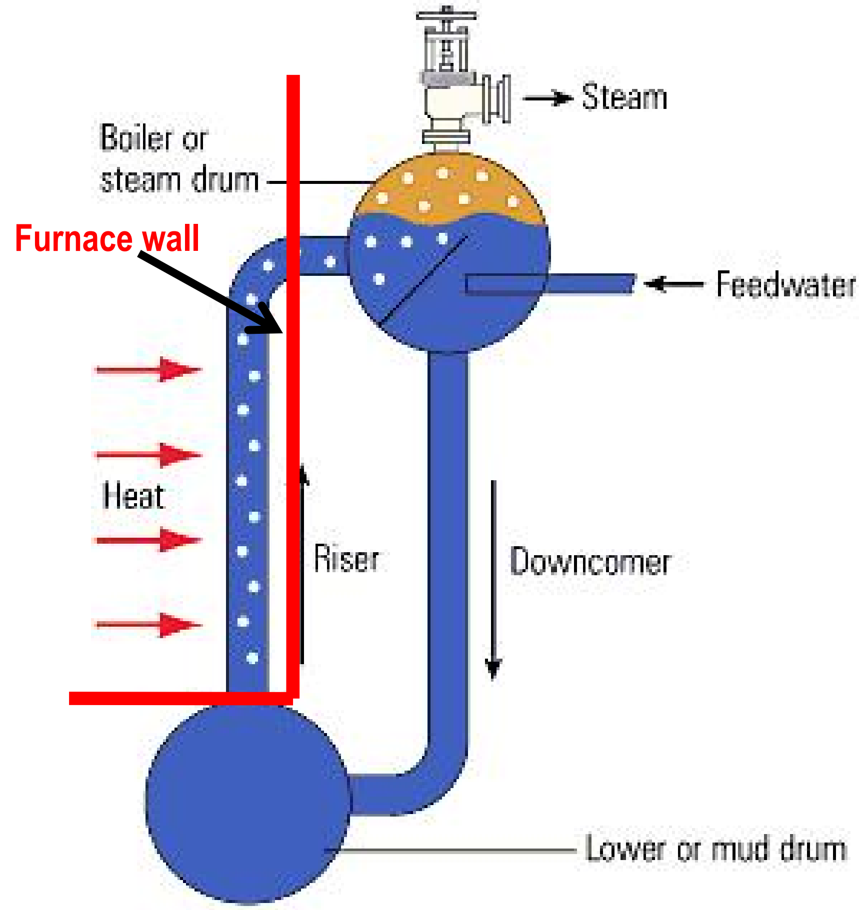
Principle of circulation in different types of boilers

Steam generation in circulation type vs once through type boilers



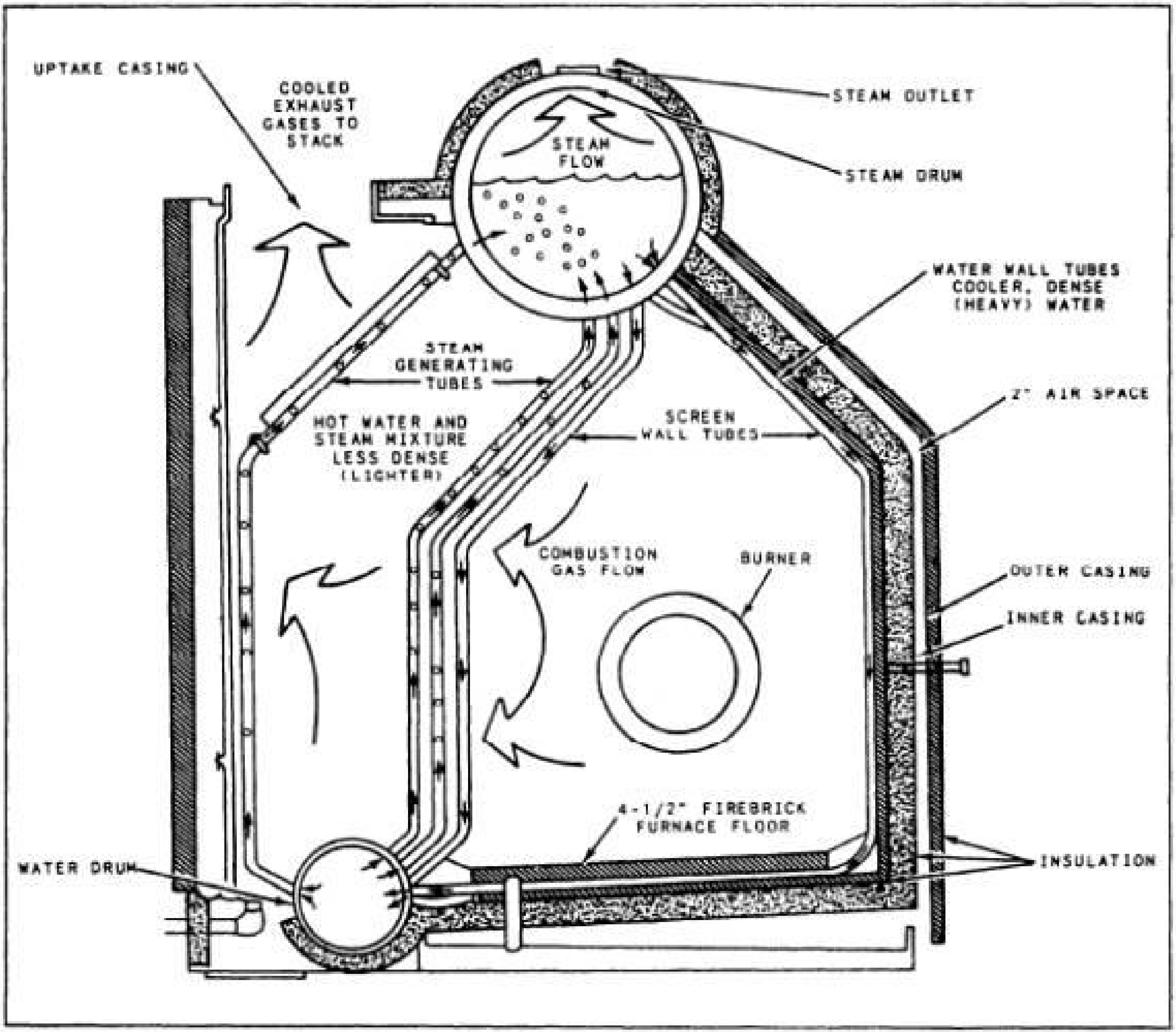
Natural circulation, drum type boilers

- **Circulation of water** is due to **density difference** between liquid water in the downcomer and 2-phase mixture in the riser
- **Design is reliable and simple**
- **Complete conversion** of **liquid into vapour** in the riser is **avoided** as it will lead to burn-out or film boiling problem
- This arrangement is **quite commonly used in large boilers**
- Better **tolerance for impurities in water** with **mud drum**

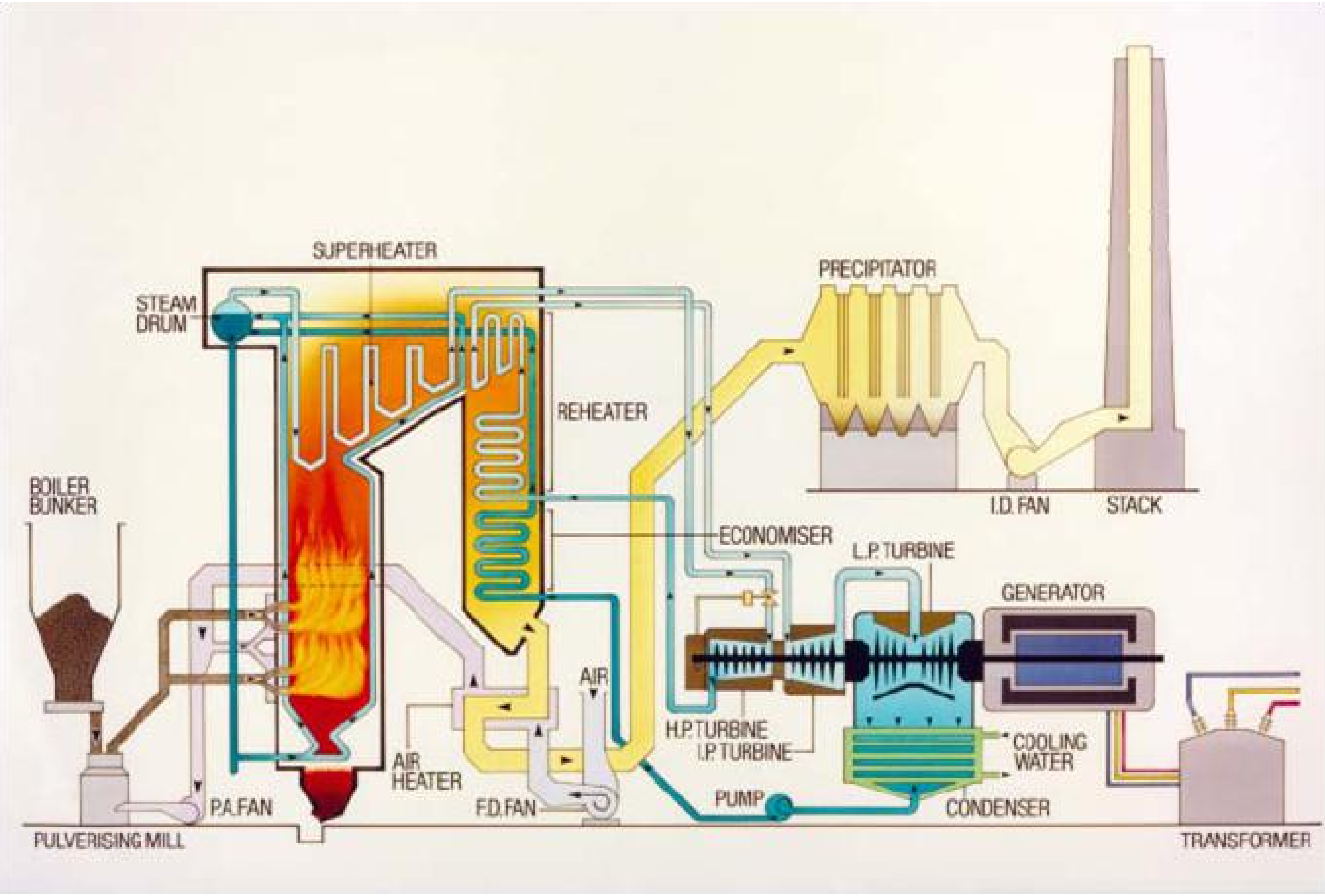


However, as the **operating pressure increases**, the density difference between liquid and vapour decreases, leading to **reduced buoyancy**

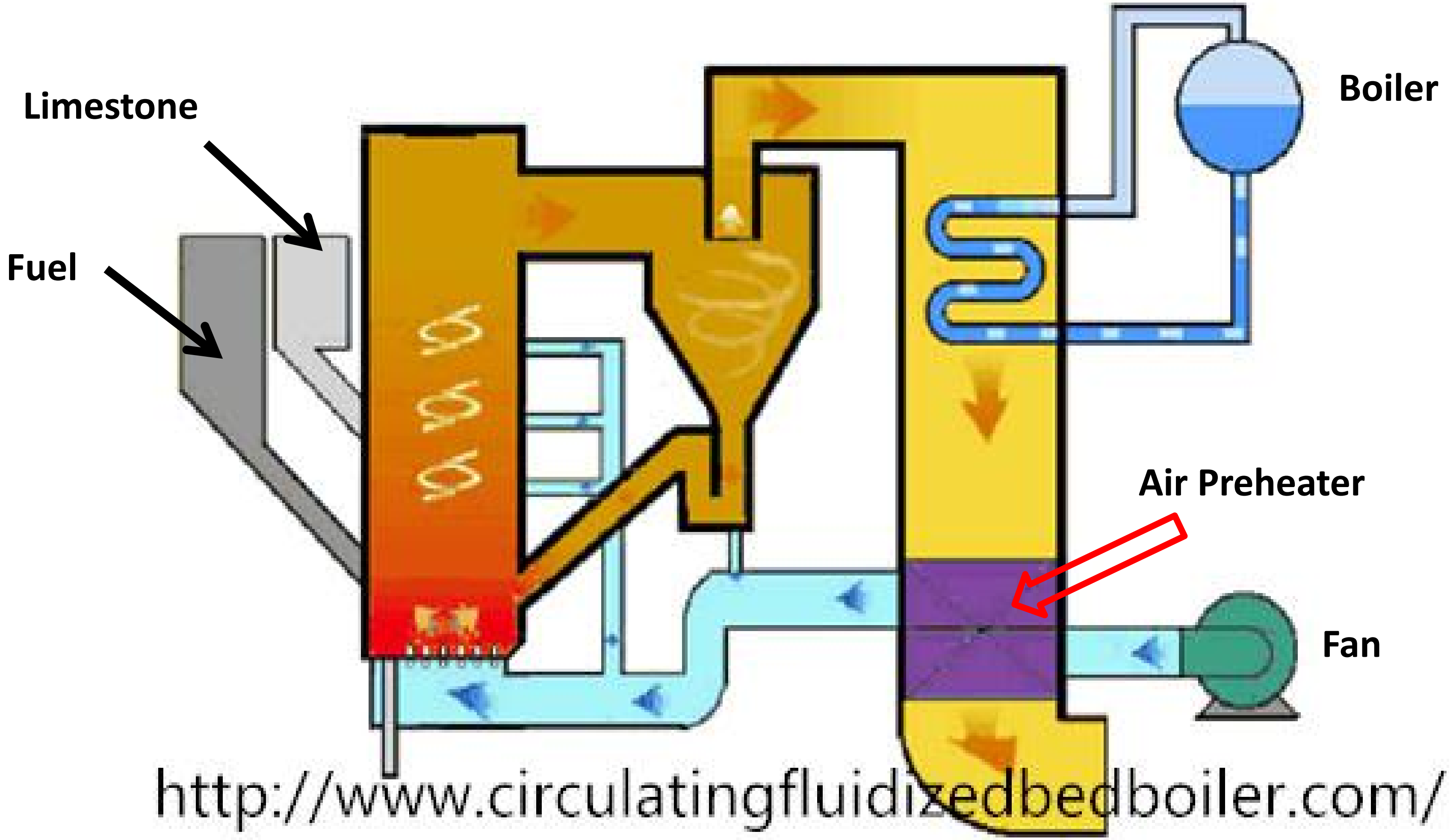
Drum type boiler



Pulverized coal boiler



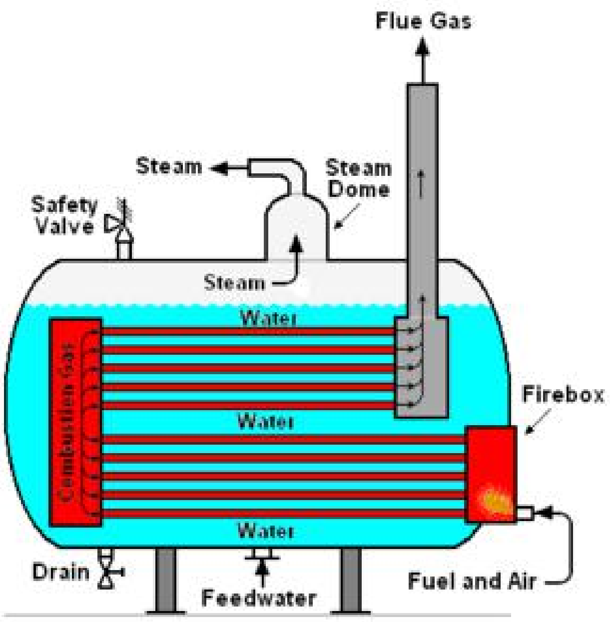
Circulating Fluidized Bed Boiler



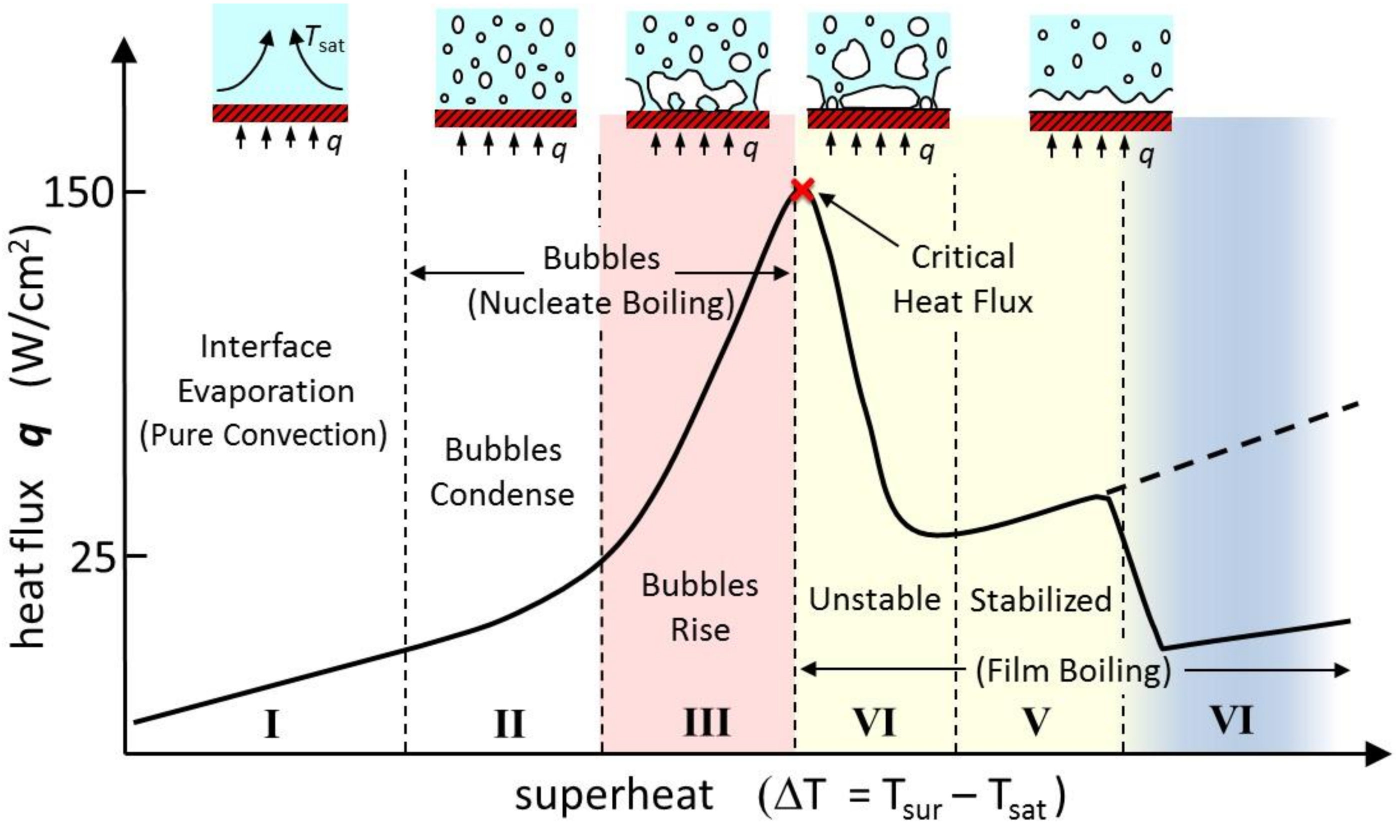
Pool boiling of water

- All liquids **boil** into vapours when they are **brought in contact** with a **surface** whose **temperature** is **more than** the **saturation temperature** of the liquid at **that pressure**
- When a **liquid boils**, **vapour bubbles** are formed, and the resulting **motion of the vapour bubbles** gives rise to **very high heat transfer coefficients**
- When **boiling** takes place with **no bulk fluid motion** then it is called as **pool boiling**

Pool boiling typically occurs in shell-and-tube type boilers with **boiling** taking place **on** the **shell side**, e.g. in a **fire tube boiler**



Pool boiling curve



Rohesnow's correlation for Pool boiling

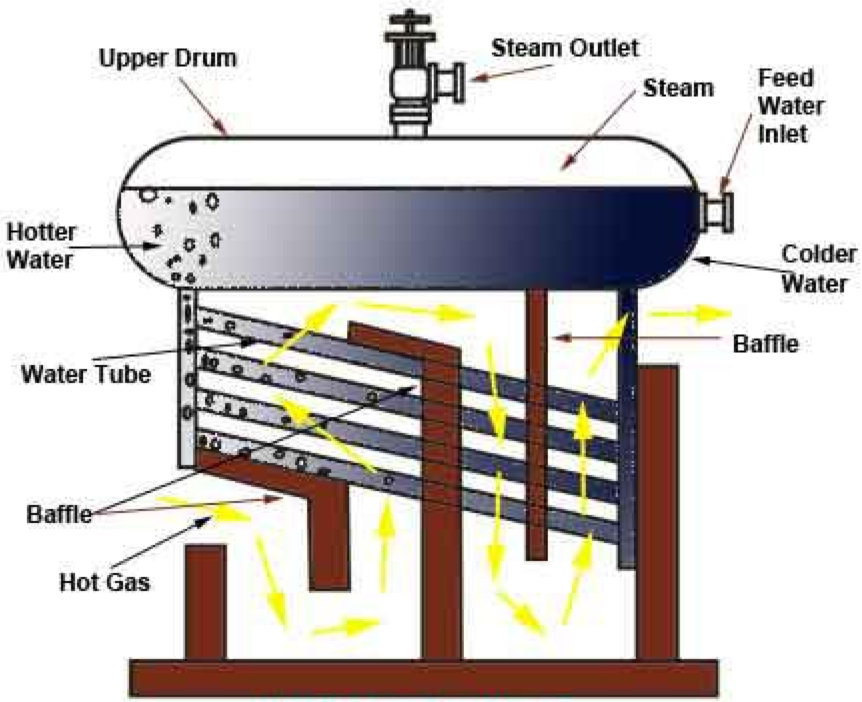
$$\frac{C_L\left(T_s - T_{sat}\right)}{H_{fg}} = C_{sf}\left(\frac{q}{\mu_L H_{fg}}\sqrt{\frac{\sigma g_c}{g\left(\rho_L - \rho_V\right)}}\right)^{0.33} \mathrm{Pr}^r$$

C_{sf} = Surface-fluid interaction factor, r = 0.8 to 2.0, L: Saturated Liquid; V: saturated vapour

Flow boiling of water

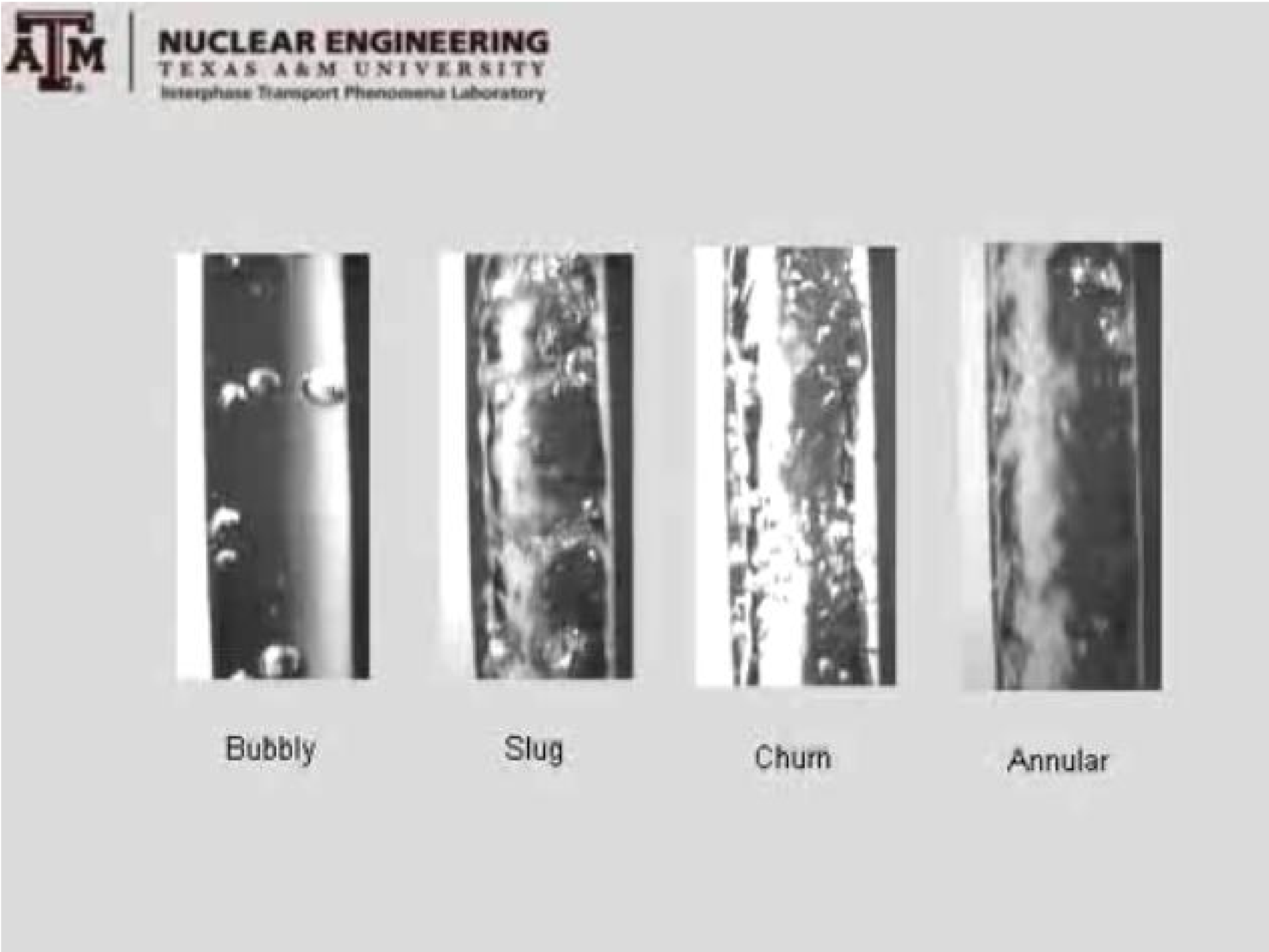
- When **boiling** takes place with **bulk fluid motion** then it is called as flow boiling
- **Flow boiling** typically occurs in shell-and-tube type boilers with **boiling** taking place inside the **tubes**, e.g. in a water tube boiler

The **heat transfer in flow boiling** is **more complex** compared to pool boiling as it depends on **several additional parameters** such as the **mass flux**, **orientation of the tube** etc.

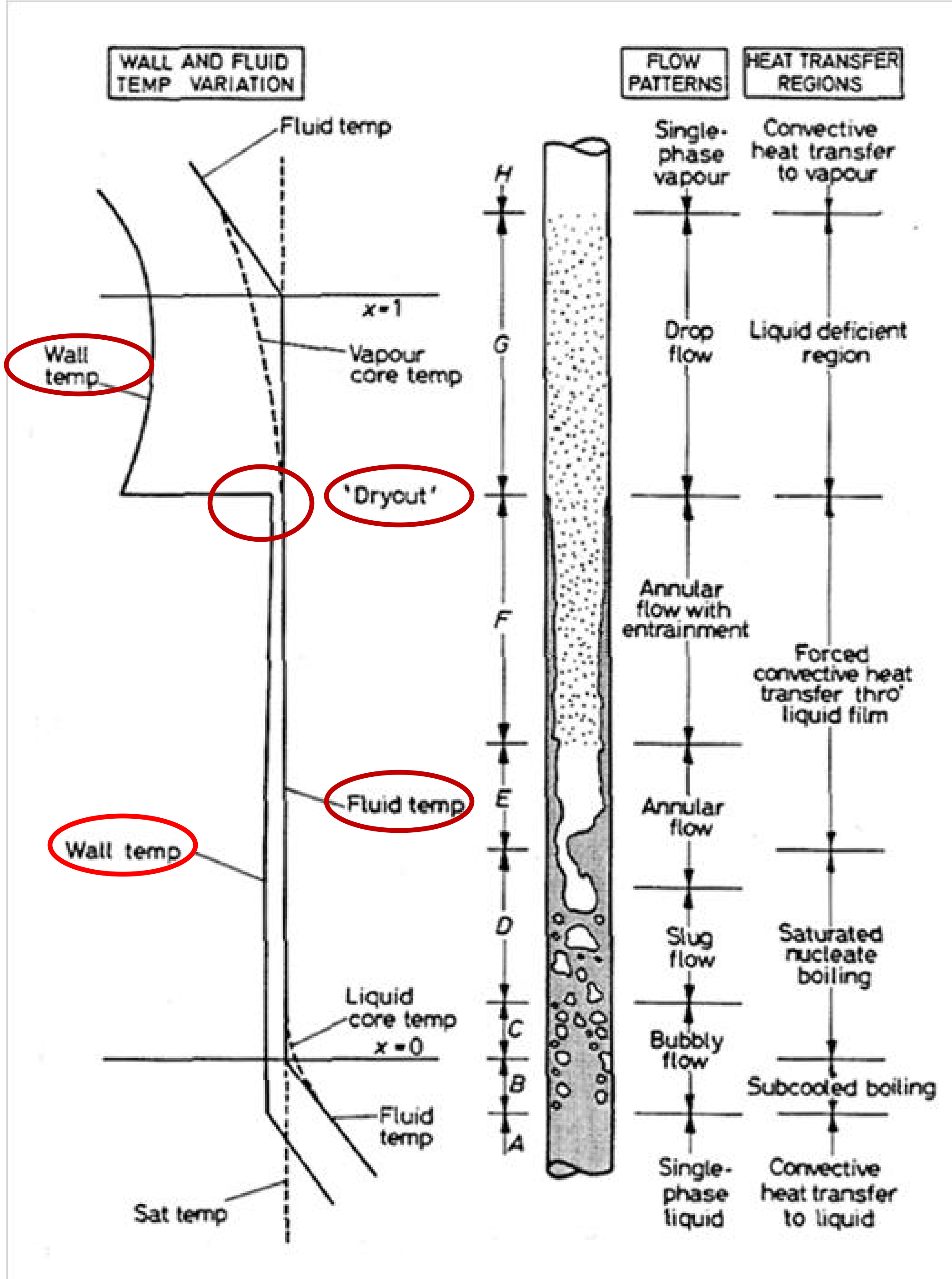


Longitudinal drum boiler

Flow Boiling



Flow boiling



Modeling of natural circulation type boiler

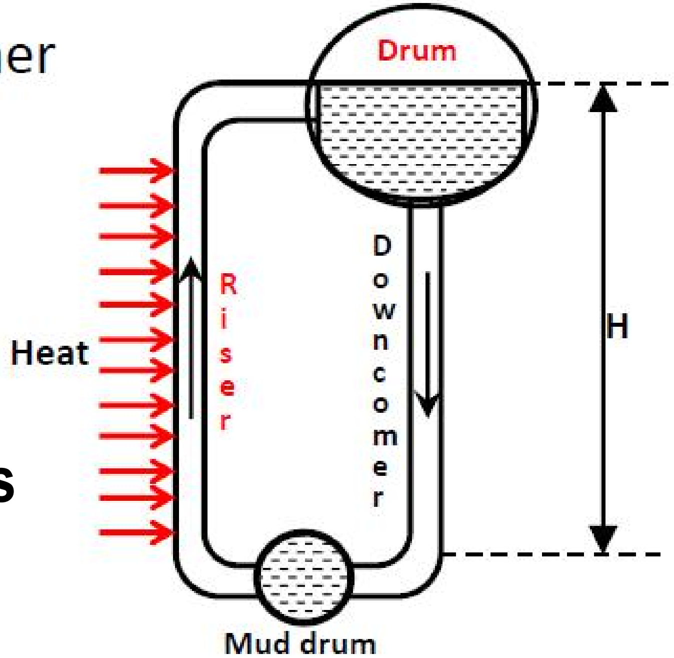
Driving Buoyancy pressure, $\Delta P_b = \left(\rho_D - \rho_{2-\varphi,R}\right) g H$

$\rho_{2-\varphi,R}$ = Density of liquid-vapour mixture in the riser

ρ_D = Density of liquid water in the downcomer

g = Acceleration due to gravity

H = Height of water level in the drum above the bottom header



The quality of the liquid-vapour mixture **varies continuously** along the riser due to heating

Hence the **density of 2-phase mixture**, $\rho_{2-\phi,R}$ **also varies** along the riser tubes

Modeling of natural circulation type boiler

The density of liquid-vapour mixture $\rho_{2-\varphi}$ is given by:

$$\rho_{2-\varphi} = (1-\alpha)\rho_f + \alpha\rho_g$$

Where, α is the void fraction and is equal to the **ratio of the volume** occupied by the **vapour** to the **total volume**

The void fraction α is related to the dryness fraction *x* as:

$$\alpha = \frac{1}{1 + \left[\frac{(1-x)}{x}\right]\psi}$$

Derive this equation!

$$\text{where } \psi = \frac{v_f}{v_g} S$$

$$\text{where } \bar{V}_{s,g} = \text{Avg. vapour velocity at any section}$$

$$\bar{V}_{s,f} = \text{Avg. liquid velocity at any section}$$

Modeling of natural circulation type boiler

Experimental studies show that the value of slip ratio lies between 1 to 10. When the operating pressures are high, then $S \rightarrow 1$

The average 2 − phase density over a height H is given by:

$$\bar{\rho}_{2-\varphi} = \frac{\int_0^H \rho_{2-\varphi(z)} \, .dz}{H}$$

Assuming uniform heat flux along the riser, the average density is shown to be equal to:

$$\bar{\rho}_{2-\varphi,R} = \rho_f - \frac{(\rho_f - \rho_g)}{(1-\psi)} \left\{ 1 - \left[\frac{1}{\alpha_e(1-\psi)} - 1 \right] \ln \frac{1}{(1-\alpha_e(1-\psi))} \right\}$$

Where α_e is the void fraction at the exit of the riser.

Modeling of natural circulation type boiler

At steady state the **buoyancy pressure head** should be **balanced by** the **total frictional and momentum pressure losses** in the loop, i.e,

$$\Delta p_B = \Delta p_{friction} + \Delta p_{momentum}$$

The **rate at which heat is transferred** to the riser is given by:

$$Q_{riser} = \dot{m}\Delta x h_{fg}$$

Where $\dot{m}$ is the mass flow rate of water through the loop,

Δx is the change in dryness fraction across the riser

h_{fg} is the latent heat of vapourization.

Natural circulation type boiler

Circulation Ratio, CR: It is defined as the ratio of **mass flow rate** of water through the downcomer to **mass flow rate** of steam at the **exit of the riser**

$$CR = \frac{m_w}{m_g} = \frac{1}{x_e}$$

Where x_e is the dryness fraction at the exit of the riser.

The **Circulation Ratio** depends upon the **heat transfer rate** to each of the riser tubes and **may vary from tube to tube**

Generally the **circulation ratio** is maintained between **6 to 25**

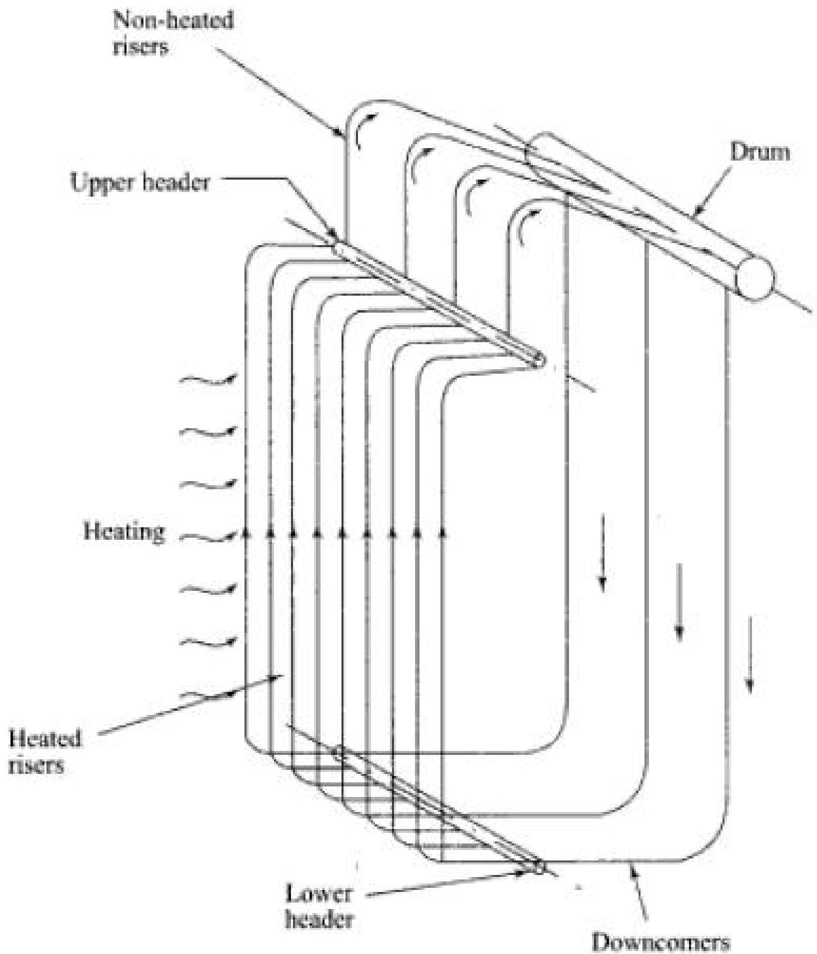
A **lower circulation** ratio may lead to **overheating and melting of tubes** due to local **dry-out** or **film boiling**

A **higher circulation** implies **improper utilization** of **riser tube area** for heat transfer

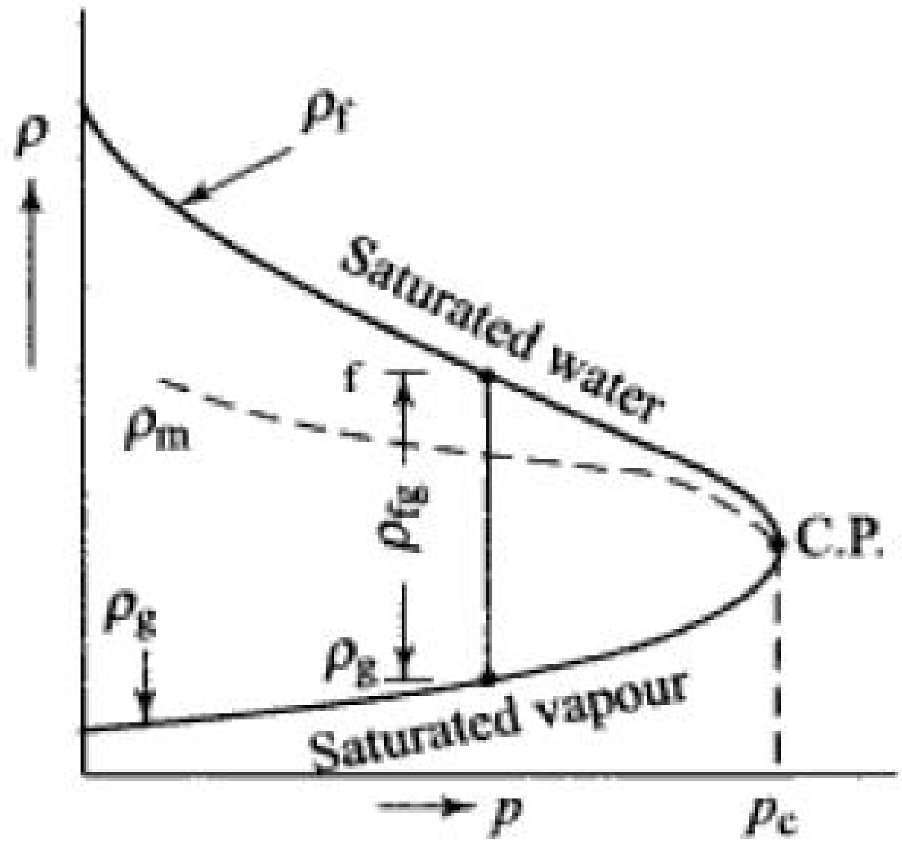
Natural circulation type boiler

Normally, the there are **fewer number** of **larger size downcomer** tubes (diameter between **150 mm to 200 mm**) **to reduce frictional pressure drop**

There are **more number** of **smaller diameter** (**62 to 76 mm**) **riser tubes** for more heat transfer area



Variation of liquid and vapour density with pressure



If the boiler pressure is **180 bar or higher**, then the **density difference** between liquid and vapour becomes **too small** to provide **sufficient natural circulation**

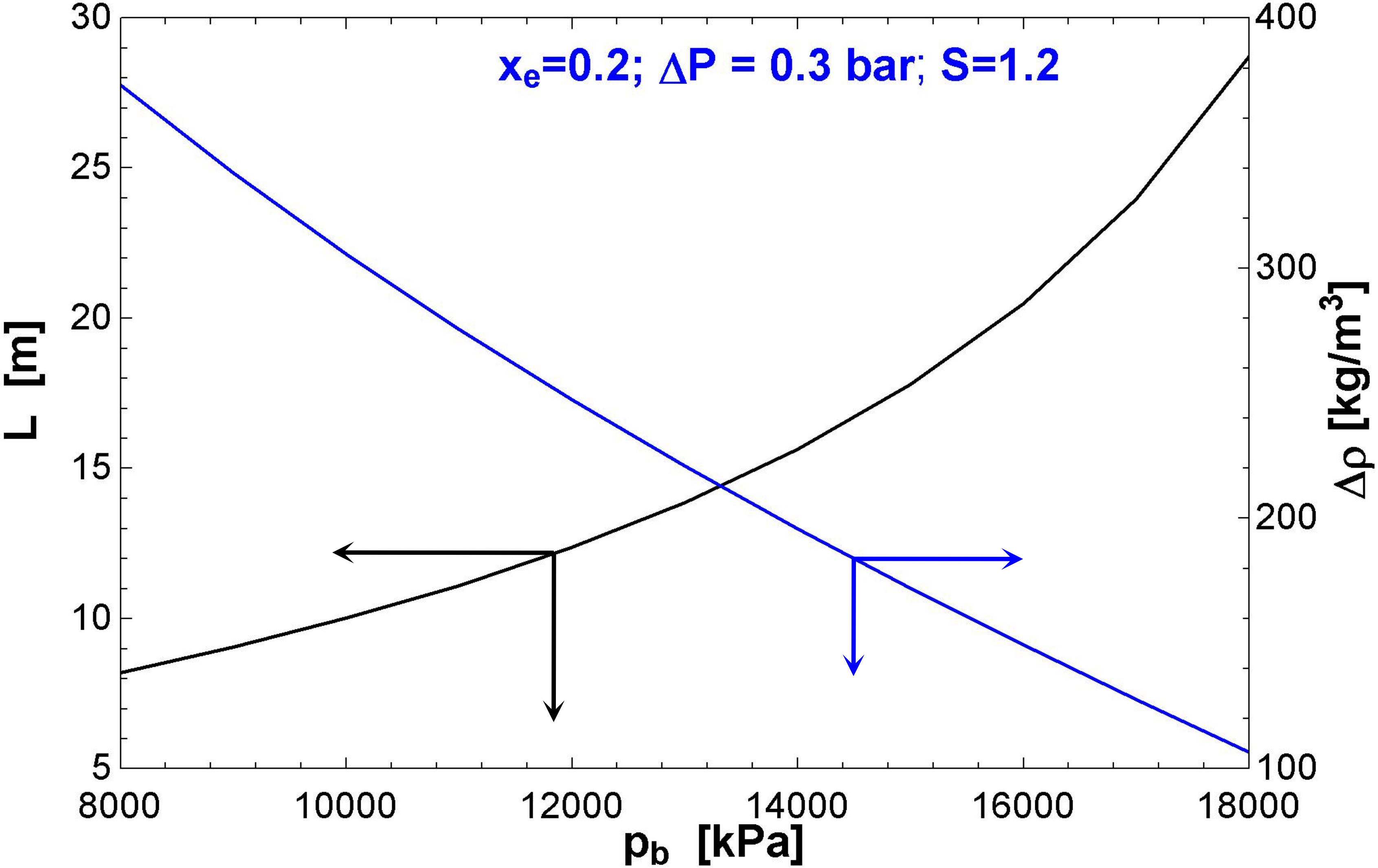
Hence, under these conditions, **forced circulation** is used by employing a **pump**

Example 1

- A natural circulation type boiler operates at a pressure of **120 bar**. The **quality** of water at the inlet to the riser is zero, while that at the exit of the riser is **0.2**. A) What should be the height of the system so that the buoyancy head required to overcome the losses is **0.3 bar**?
- B) **Show** how the **required height varies** with **boiler pressure** in the range of **80 to 180 bar**
- Take the value of **S** as **1.2**.
- **Given:**
- At **120 bar**, v_f = **0.001526 m³/kg**, v_g = **0.01426 m³/kg**

Ans: A) 12.37 m (at 120 bar)

B) Effect of boiler pressure on boiler height



Example 2

- A **12 m** tall, natural circulation boiler operates at **100 bar**. The **quality** of water at the inlet to the riser is **0.0**, while that at the exit of the riser is **0.15**. The flow rate of water through the downcomer is **45 kg/s.** If the frictional pressure drop through the downcomer is **50 %** of the total pressure drop, find a) the diameter of the downcomer, and b) the rate at which heat is transferred to the riser. The value of **S = 2.0**.

- **Given:** At **100 bar**, v_f = **0.001452 m³/kg**, v_g = **0.01803 m³/kg**

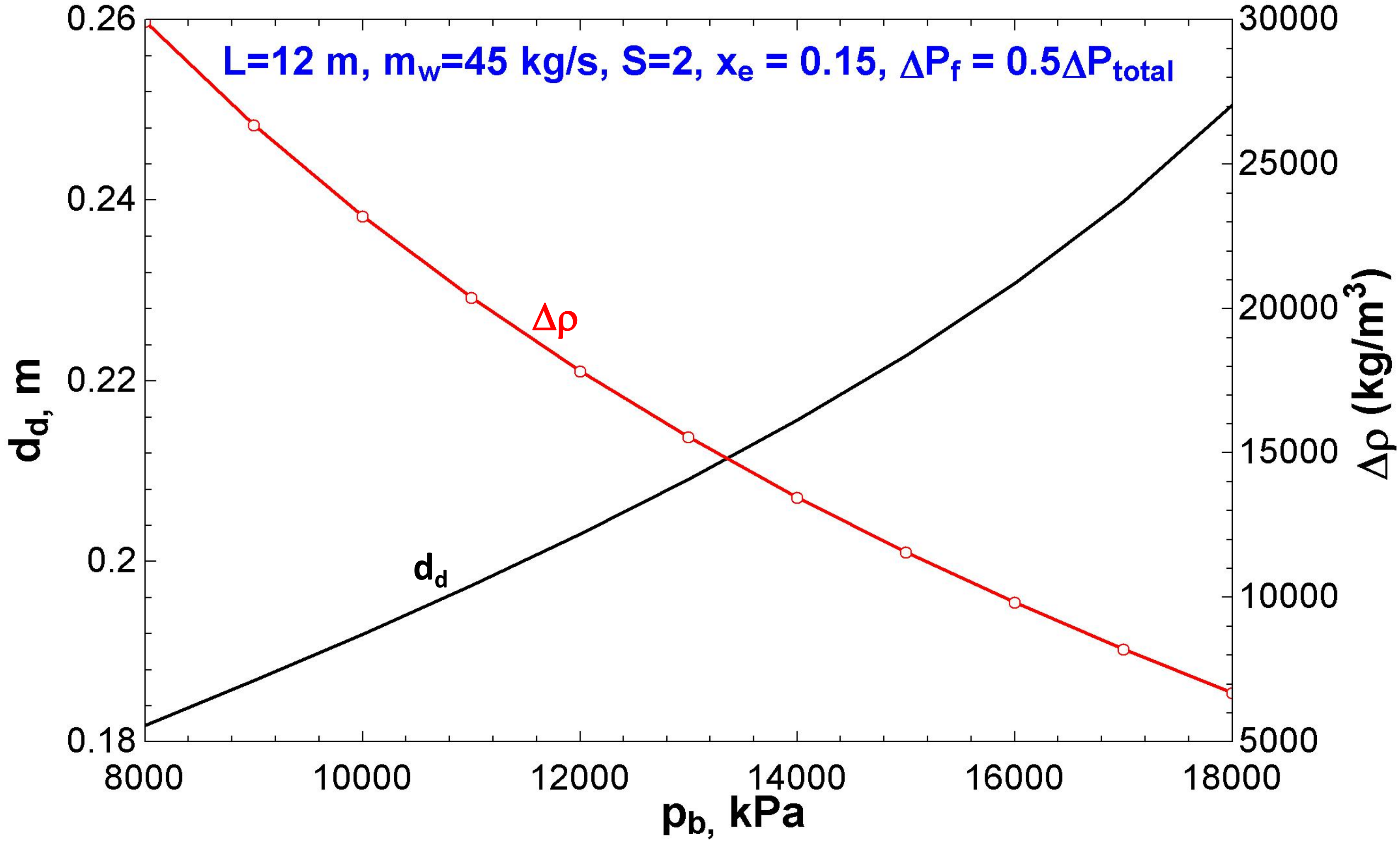
- h_f = **1407 kJ/kg**, h_g = **2725 kJ/kg,** μ_f = **81.83 x 10⁻⁶ kg/m.s**

Use the following equation for frictional pressure drop (take $k_s = 0.0015$ m):

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{k_s}{3.7D} + \frac{2.51}{(Re_D)\sqrt{f}}\right]$$

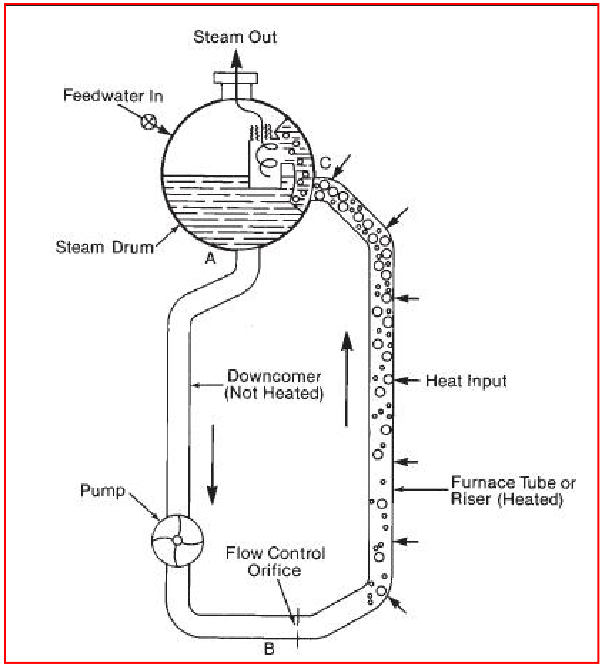
Ans: **a) 0.192 m** **b) 8.89 MW**

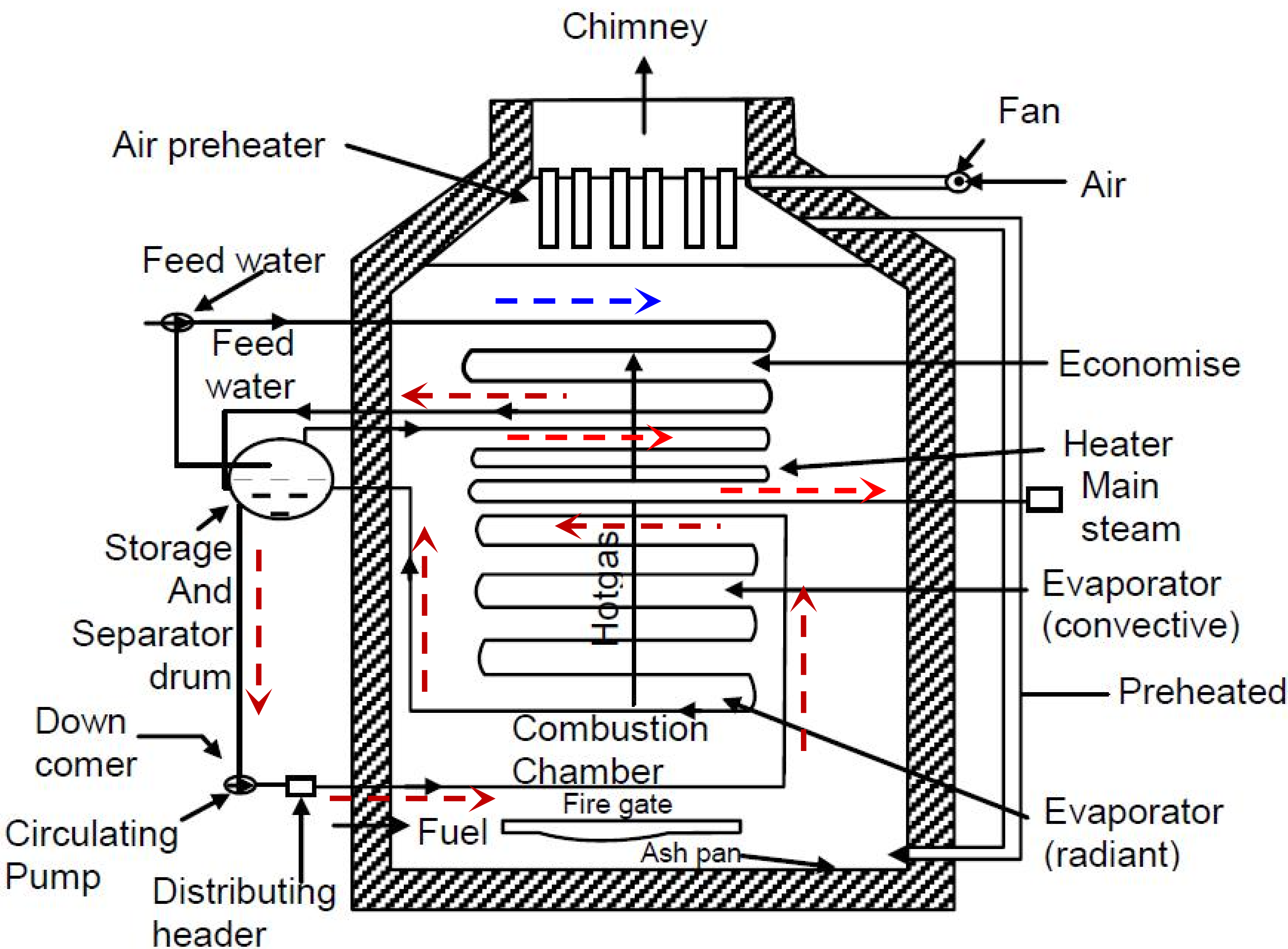
B) Effect of boiler pressure on downcomer diameter



Controlled or forced circulation type boilers

- **Circulation of water** is maintained by a pump installed in the downcomer
- **Large heights** are **not needed** and **position** and **orientation** are **flexible**
- **Circulation ratios can be low**
- Due to reduced density difference between liquid and vapour at high pressures, these boilers are **favoured for high pressure applications**
- The **pump** provides an **additional margin of safety** – stand-by pumps are needed
- Also **forced circulation** provides **higher fluid velocities** and hence **better heat transfer** coefficients and hence more **compact** design
- However, **less reliable**, **need good quality water**





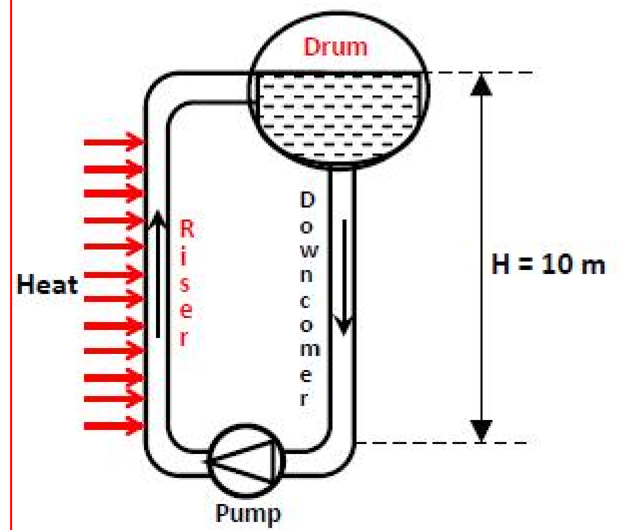
The La Mont Boiler (Forced circulation type)

Example 3

- The following data is available for a controlled circulation type boiler:

a. Boiler pressure = 180 bar
b. Height of the boiler = **10 m**
c. Diameter of the downcomer = **150 mm**
d. Number of downcomer tubes = **6**
e. Velocity at the exit of downcomer = **3 m/s**
f. Slip Ratio, S = **1.2**
g. Void fraction at the exit of riser tubes = **0.8**
h. Total pressure drop = **0.5 bar**
i. Pump efficiency = **80%**

- **Find the required power input to the pump.**



Ans.: 11.75 kW

Given: At **180 bar**, v_f **=0.00184 m³/kg**, v_g **= 0.0075 m³/kg**

Example 4

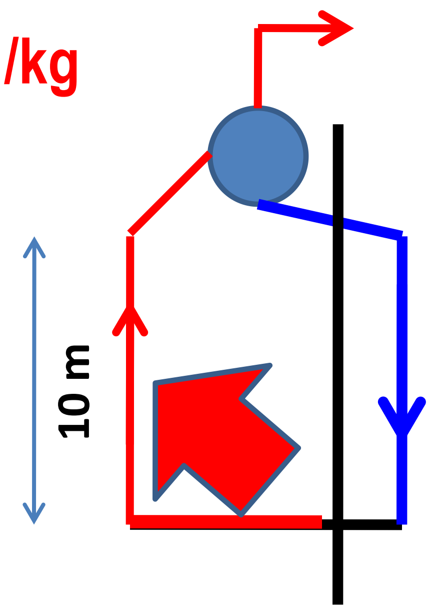
- For the problem discussed in Example 3, find the **number of riser tubes required**, if the heat flux (assumed to be uniform) is not to exceed **1 MW/m²**. Assume that **only the vertical projected area** is available for heat transfer in the riser. **Outer diameter of riser tubes is 80 mm.**

  Given: At **180 bar;** h_f **= 1732 kJ/kg**; h_g **= 2510 kJ/kg**

Ans.: 91 tubes

What **difficulty** arises when **only the projected area** of riser is considered **for heat transfer**?

Is there a contradiction?



Example 5

- A **12 m tall**, **7.5 cm dia**. Steam generator tube receives saturated water at a velocity of **1.8 m/s** and a pressure of **180 bar**. **Heat is added uniformly to the tube**. The slip ratio **S** is **1.8**. Find the maximum heat flux (**in kW/m²**) that the tube can be subjected to, if the exit void fraction (α_e) is not to exceed **0.5**.

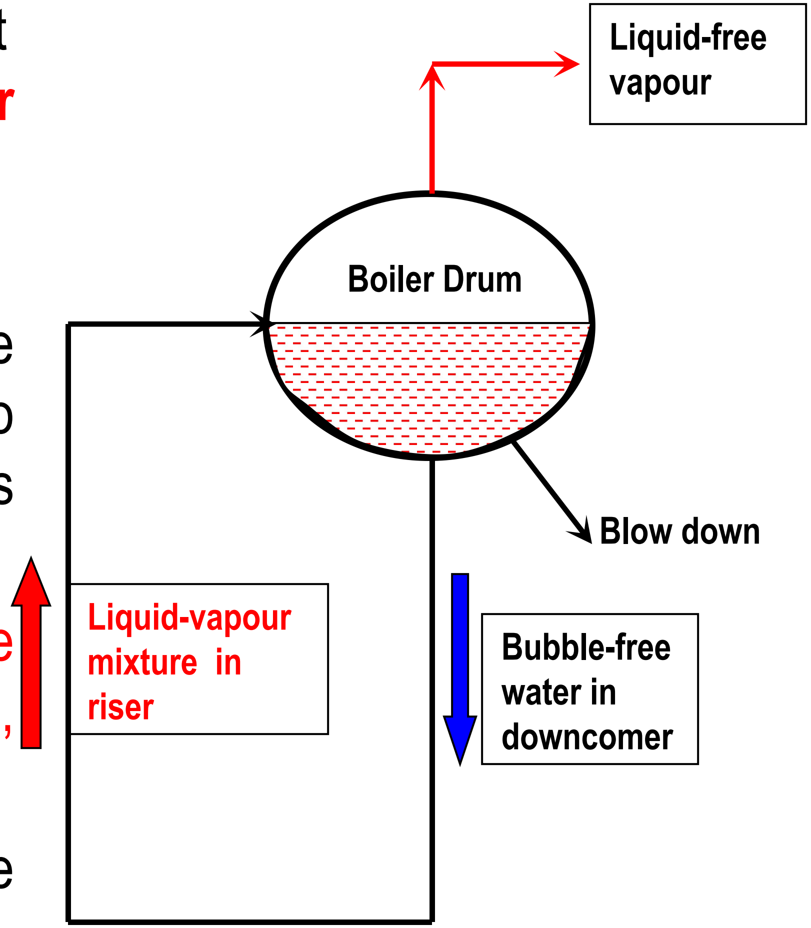
Given: At **160 bar:** ρ_f= **543.5** kg/m^3, ρ_g = **133.3** kg/m^3

h_f= **1732** kJ/kg, h_g= **2510** kJ/kg

Ans.: 388.2 kW/m²

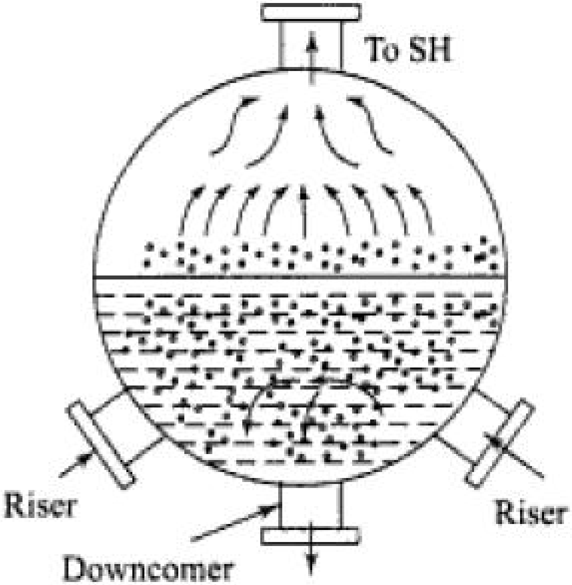
Boiler drum

- The **boiler drum** should be **so designed** that **only liquid-free vapour** leaves the drum **for superheater**, and
- **Bubble-free liquid** enters the **downcomer**
- **Presence of liquid** in vapour leaving the drum and entering the superheater leads to **deposition of scale** in superheater tubes and eventually its **melt-down**
- (Superheater is the most expensive component among the heat exchangers, **why**?)
- **Presence of bubbles** in **liquid** entering the downcomer **weakens buoyancy effect**

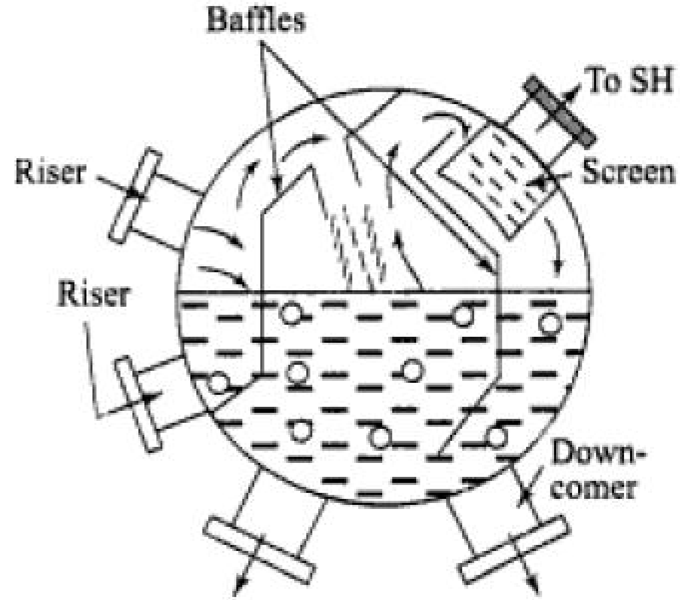


- **Continuous blow down** in boiler drum may be needed to ensure that the **concentration of total dissolved solids** (TDS) in boiler drum is **within acceptable limits**

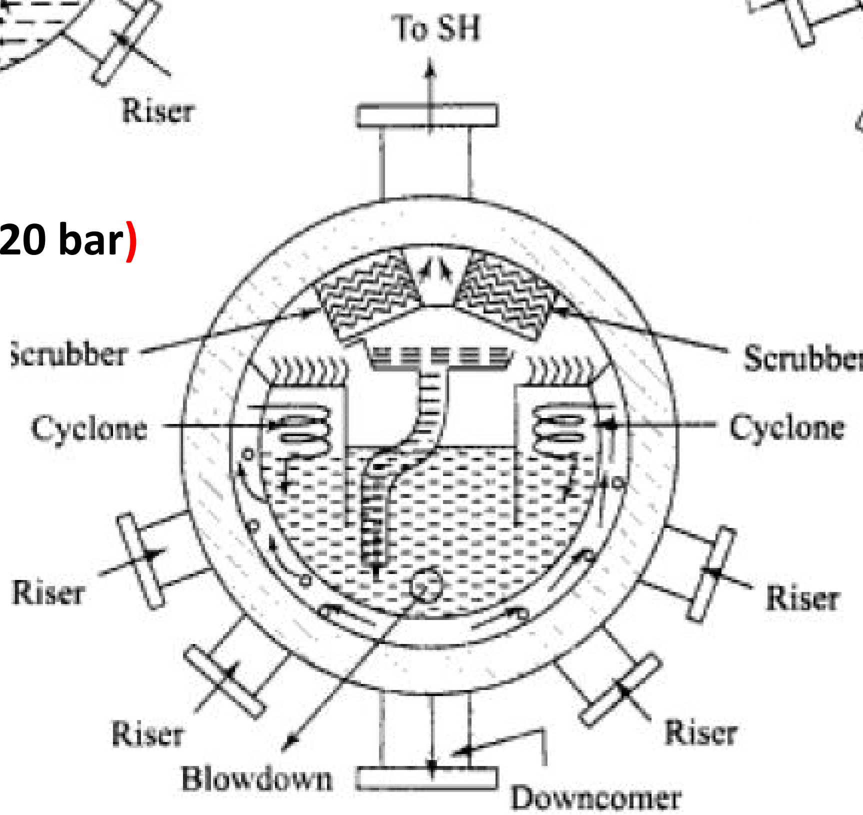
Various boiler drum configurations



Use of gravity (p_b < 20 bar)

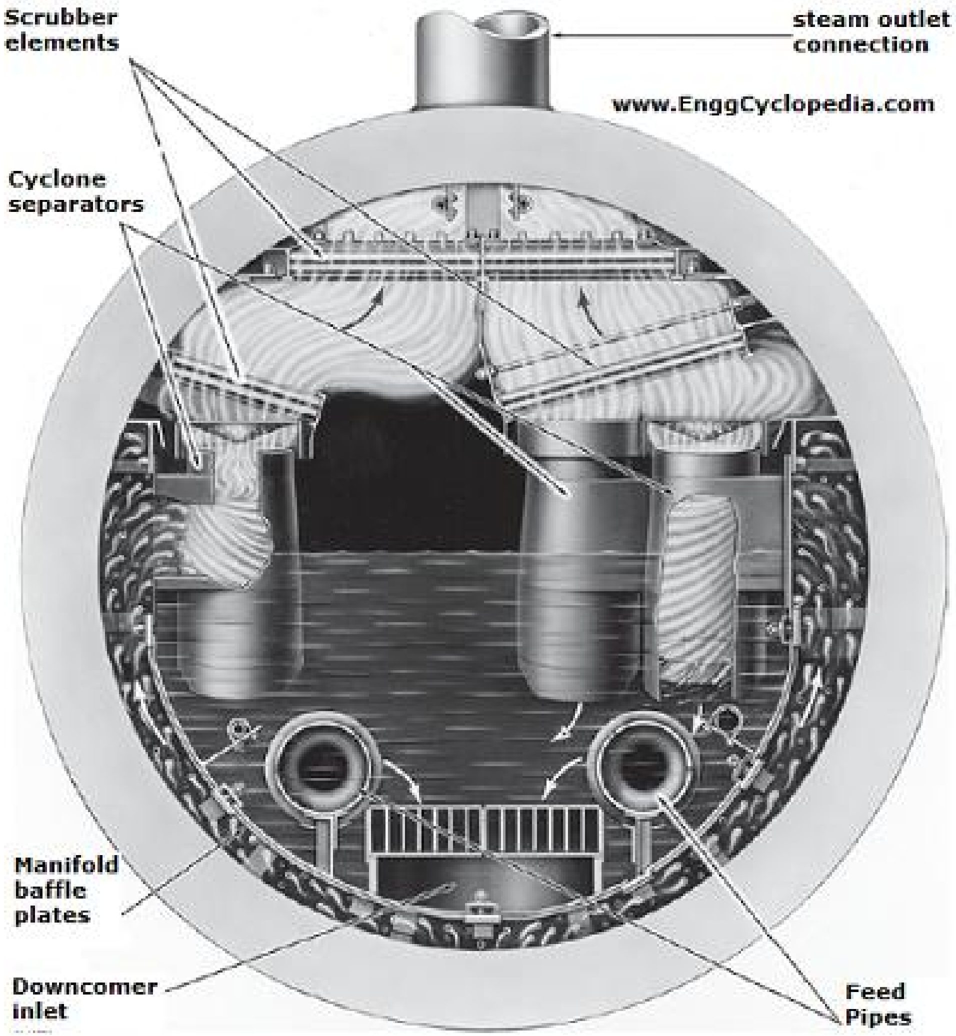


Use of baffles and screen



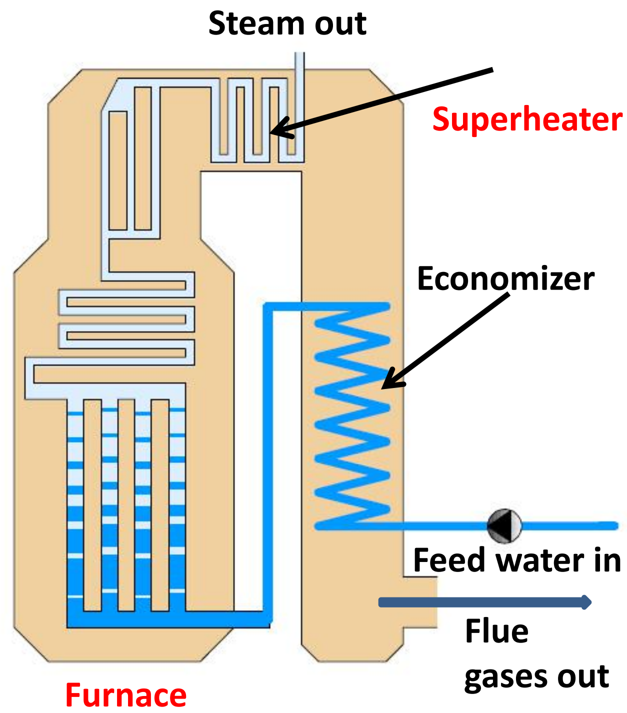
Use of cyclone separator & scrubber (for high pressures where density difference is small)

Inner details of a modern boiler drum

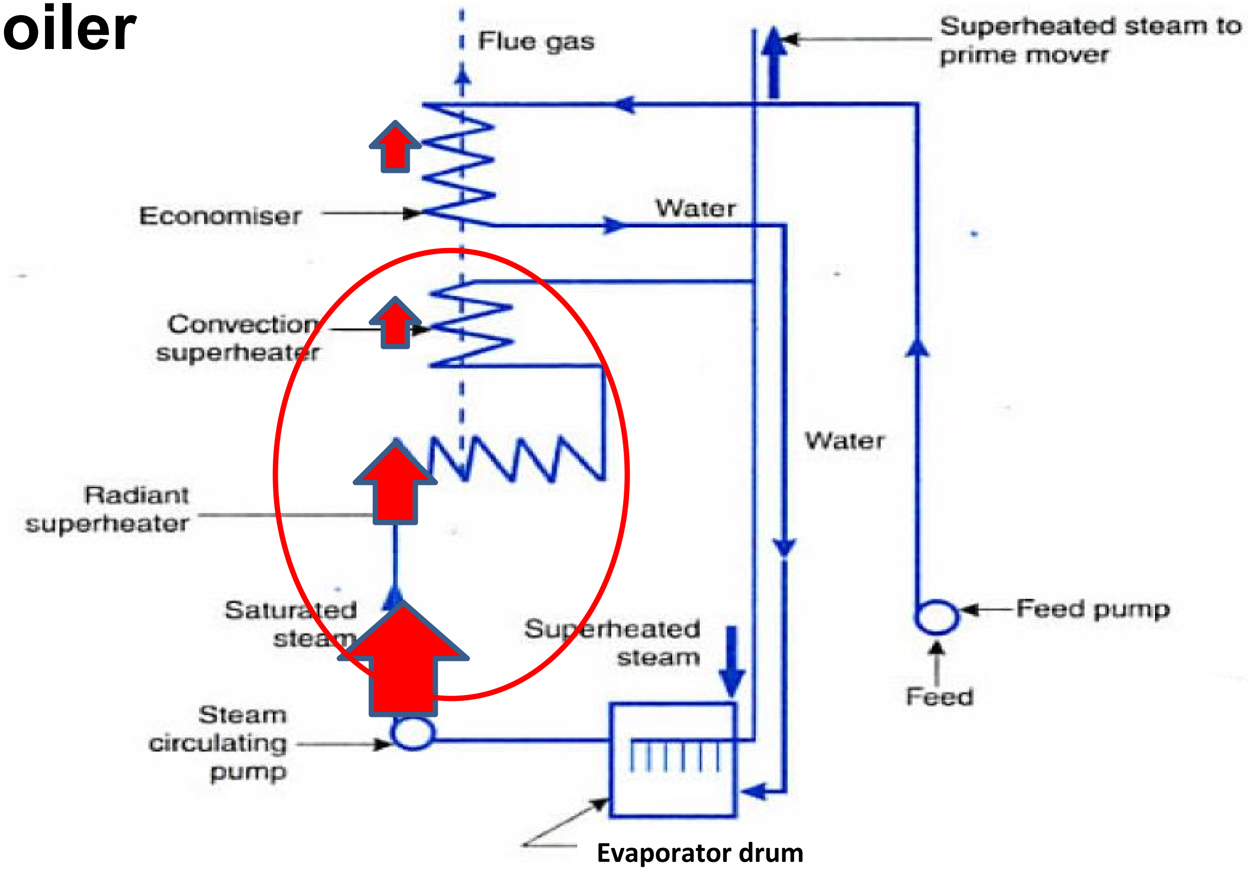


Once through type boilers

- Also called as **Benson** or **universal pressure boiler** as it can be used for all temperatures and pressures, i.e., subcritical or supercritical
- No steam drum is required as there is no recirculation of water
- Due to **absence of steam drum**, this is the **only boiler** that can be used **to produce supercritical steam**
- Economical for high pressure (upto **320 bar**) and high capacity (upto **1500 kg/s**) plants
- **Initial cost** is **marginally higher** compared to other types of boilers



Loeffler Boiler



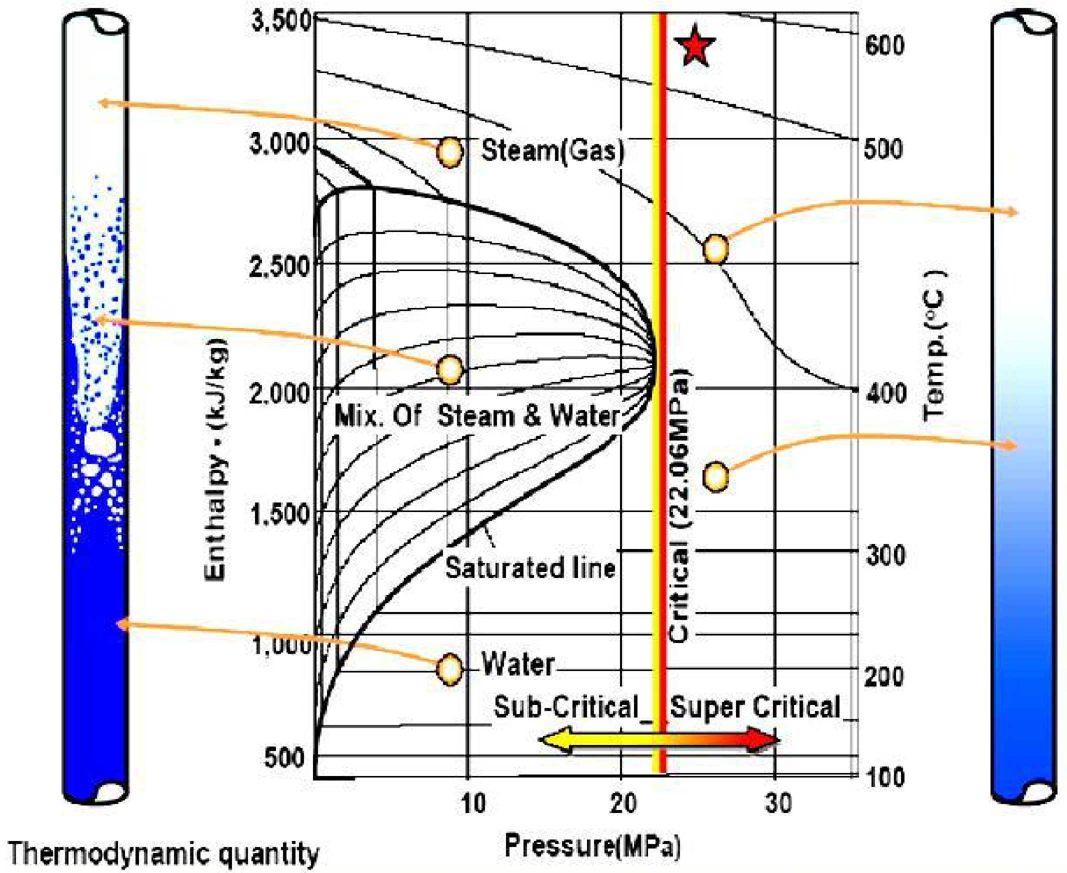
Presence of **liquid** water in boiler tube is **prevented** by **generating** saturated steam from the **feedwater**, using **superheated steam** in the evaporator drum

Since there is no phase change inside the steam generator, this type of boiler can tolerate higher amounts of salt in the water

Can be used for both land and sea applications

Supercritical boilers

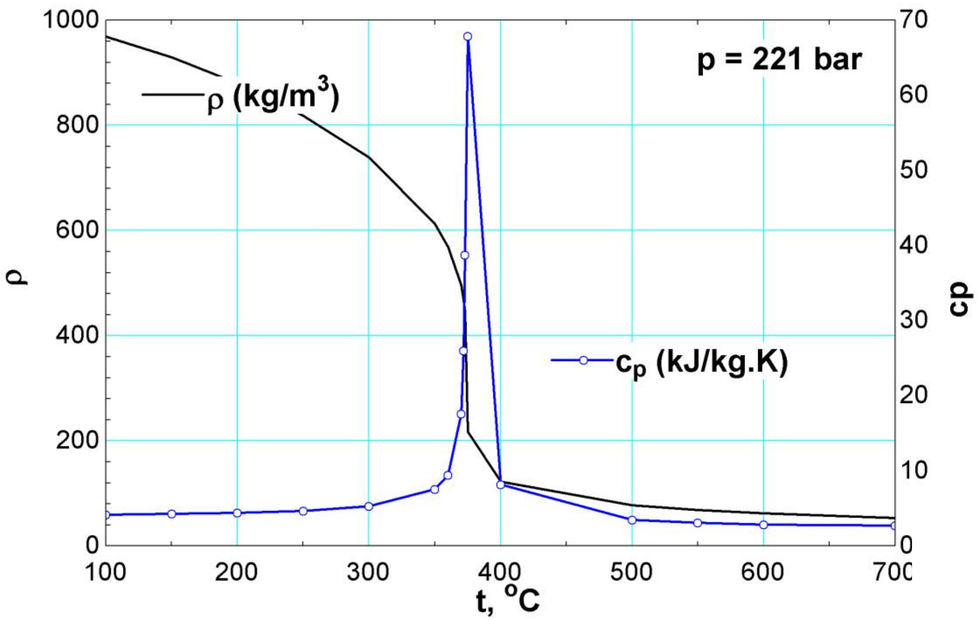
In supercritical region there is no clear distinction between the liquid and the gaseous phase



There is no surface tension in a supercritical fluid, as there is no distinct phase boundary

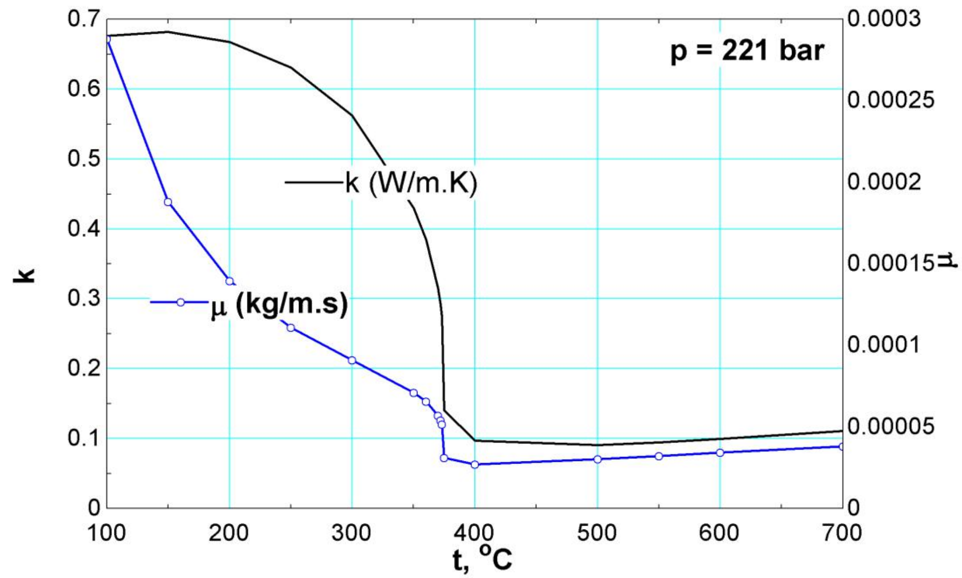
Supercritical region

Critical point is the point of discontinuity on the vapour dome where abrupt changes in properties occur



For water,
Critical pressure = 221 bar, and
Critical temperature = 374.15 °C

Abrupt property variation near critical point affects the design of heat exchangers, boilers etc. significantly



Supercritical steam generator

Benefits

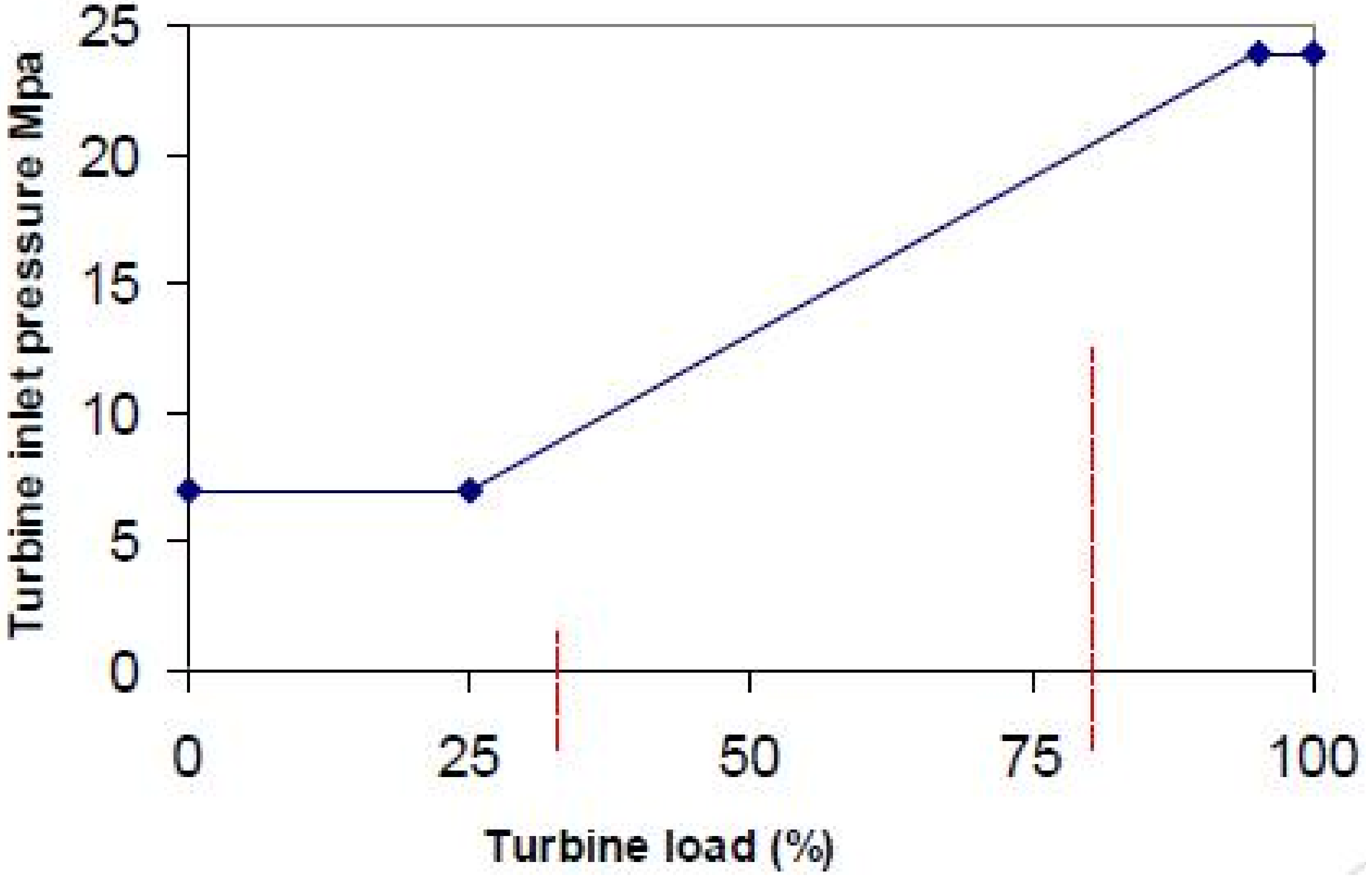
- When boiler pressure > **220 bar,** it becomes a supercritical boiler.
- **Steam becomes a single phase fluid** with homogeneous properties and there is no need to separate liquid from vapour – no drum!
- Since there is **no thick-walled steam drum**, the **start up time and ramp rates for a once through unit can be significantly reduced** from that required for a drum-type unit – **fast start-up and fast load variations**
- This is **ideal for sliding pressure operation** which has much more flexibility in load changes and controlling the power grid

Supercritical steam generator

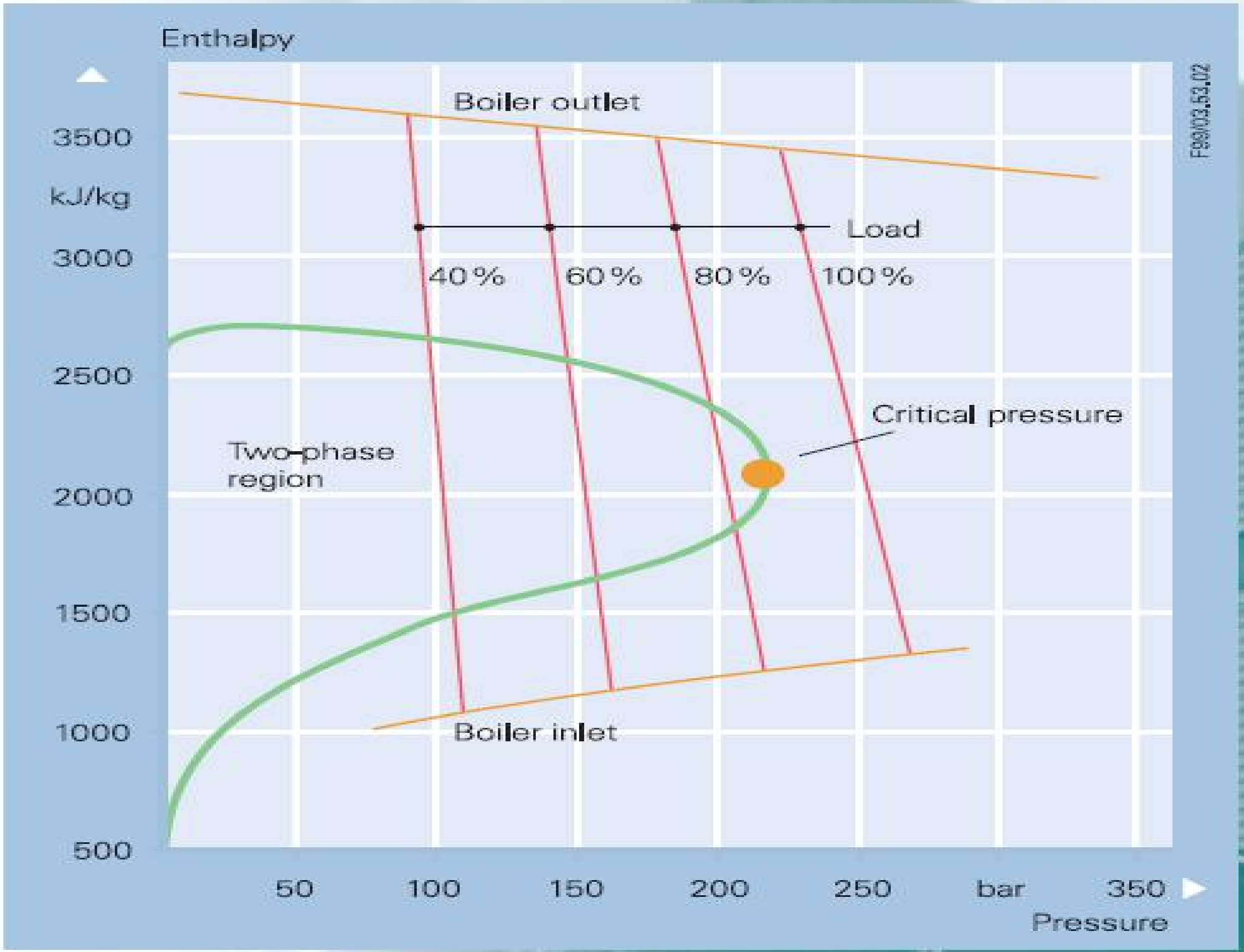
Concerns

- As there is no mud drum, in supercritical units the water entering the boiler has to be of extremely high levels of purity
- If the entering water quality is not good, carry over of **impurities** can result in **turbine blade deposits and damage**
- Though there is no steam drum, a **separator is required during start-up**
- Require special high grade materials for the boiler tubes.
- The **turbine blades** are **also of improved design and materials**.

Sliding Pressure

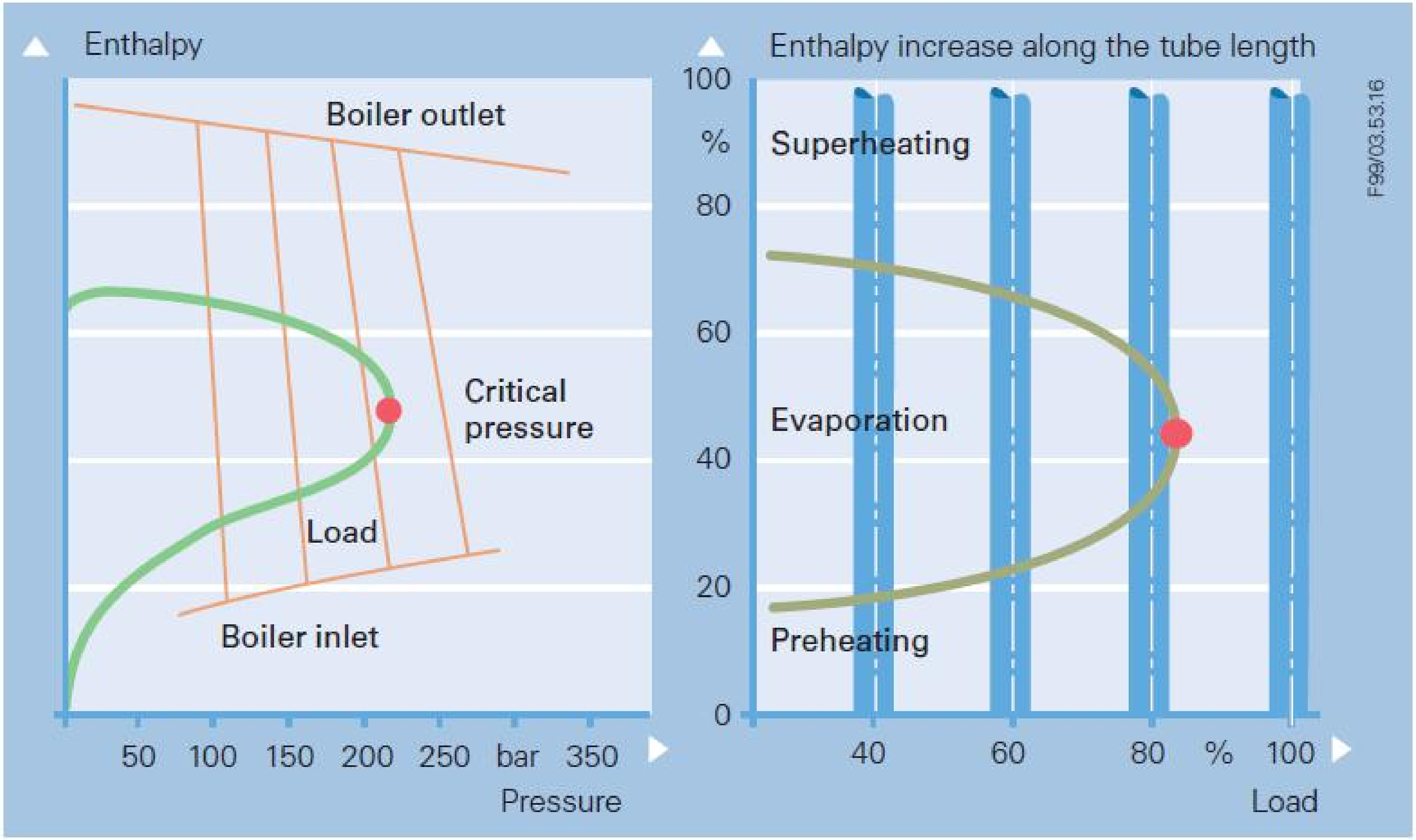


Sliding pressure operation in Benson Boilers



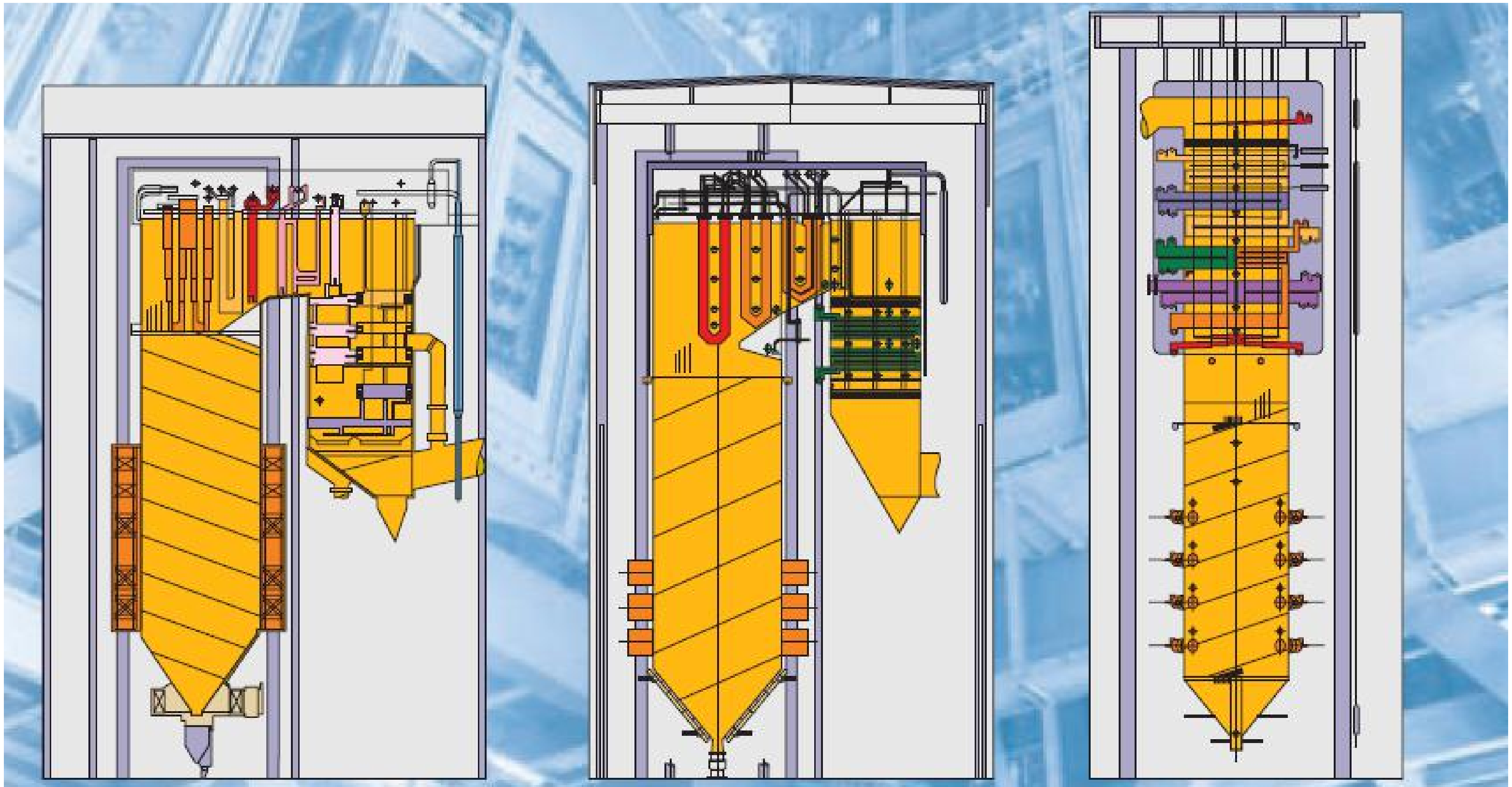
A BENSON boiler which is designed for supercritical pressures can be operated at any pressure, i. e. also at subcritical pressure.

Sliding pressure operation in Benson Boilers



The fractions for preheat, evaporation and superheat change with pressure in the boiler (left). In sliding-pressure operation, the size of the heating surfaces automatically adapts to these conditions (right).

Typical Benson once through Boilers



Hekinan power plant, Japan

639 kg/s - imported coal
255 bar/543°C/569°C
Manufacturer:
Babcock-Hitachi

Hemweg power plant, Netherlands

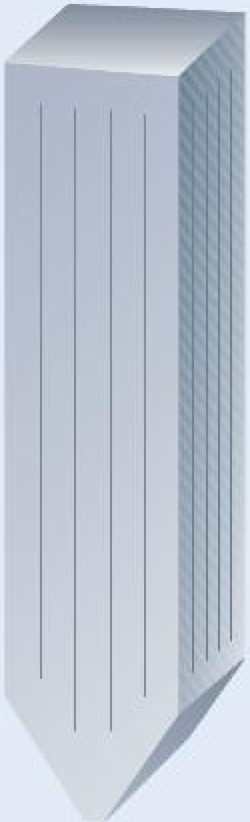
530 kg/s - imported coal
261 bar/540°C/540°C
Manufacturer:
Mitsui Babcock Energy/Stork

Nordjyllandsvaerket power plant, Denmark

270 kg/s - imported coal
310 bar/582°C/580°C
Manufacturer:
Burmeister & Wain

Rifled tube steam generators in Benson Boilers

Advantages of the BENSON boiler with vertical rifled tubes



Vertically tubed BENSON boiler

Rifled tube

Compared to a once-through boiler with a spiral configuration of furnace tubes, a vertically tubed BENSON boiler exhibits a number of advantages in terms of its design and operation:

- Straightforward and maintenance-friendly design for highest efficiency levels,
- Cost-effective manufacture and assembly,
- Welded-on support straps are not required,
- Simple startup system, a startup circulation pump is not required,
- Lowest part loads down to 20% are possible while maintaining high main steam temperatures,
- Reduced slagging of furnace walls,
- The evaporator pressure drop is reduced from 10 bar to 5 bar, low auxiliary power needed for feed pump.

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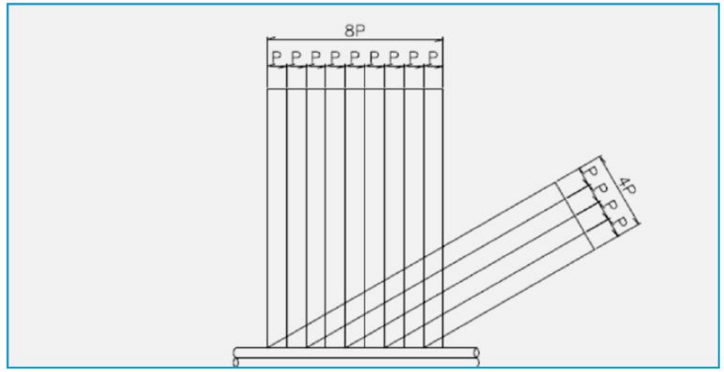
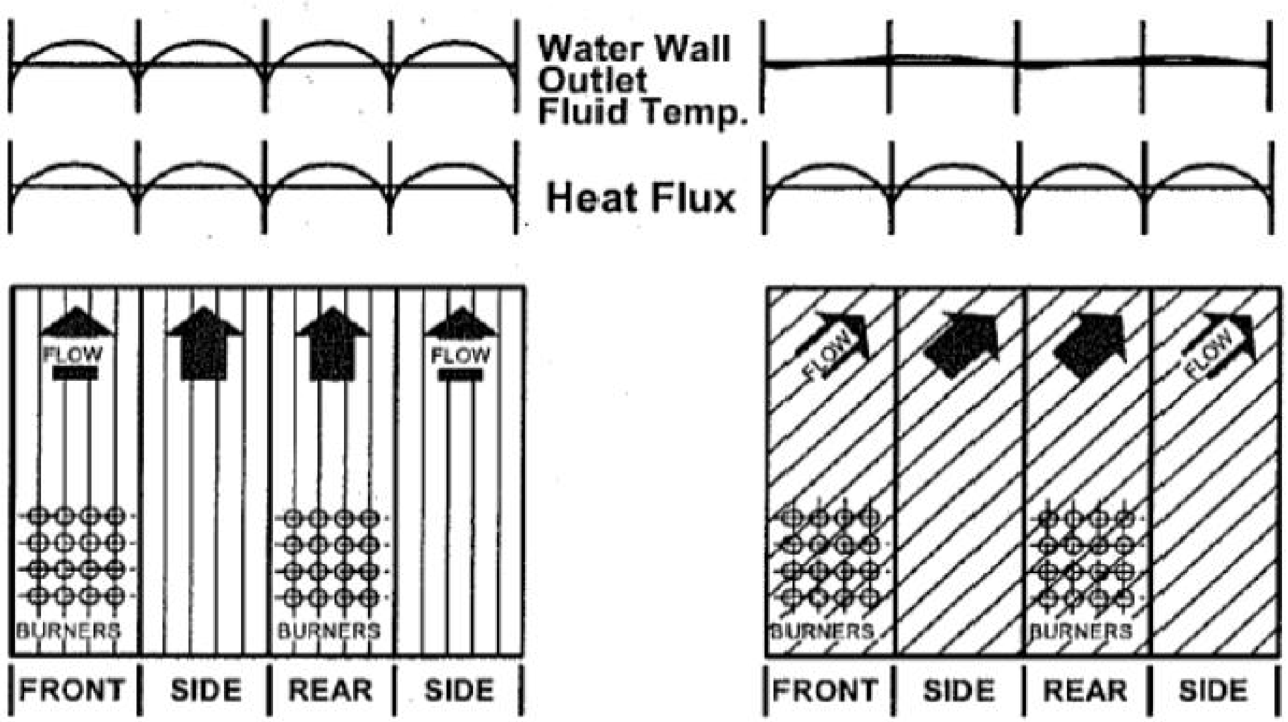
The BENSON boiler with vertical rifled tubes combines the advantages of the BENSON boiler with spiral-wound furnace tubes with the simple design of the drum boiler.

Vertical vs spiral water walls





Vertical Type Water Wall

Spiral Type Water Wall

Heat transfer in steam generator

Heat transfer inside a steam generator **involves** all **possible modes**, i.e.,

Sensible heat transfer

Convection

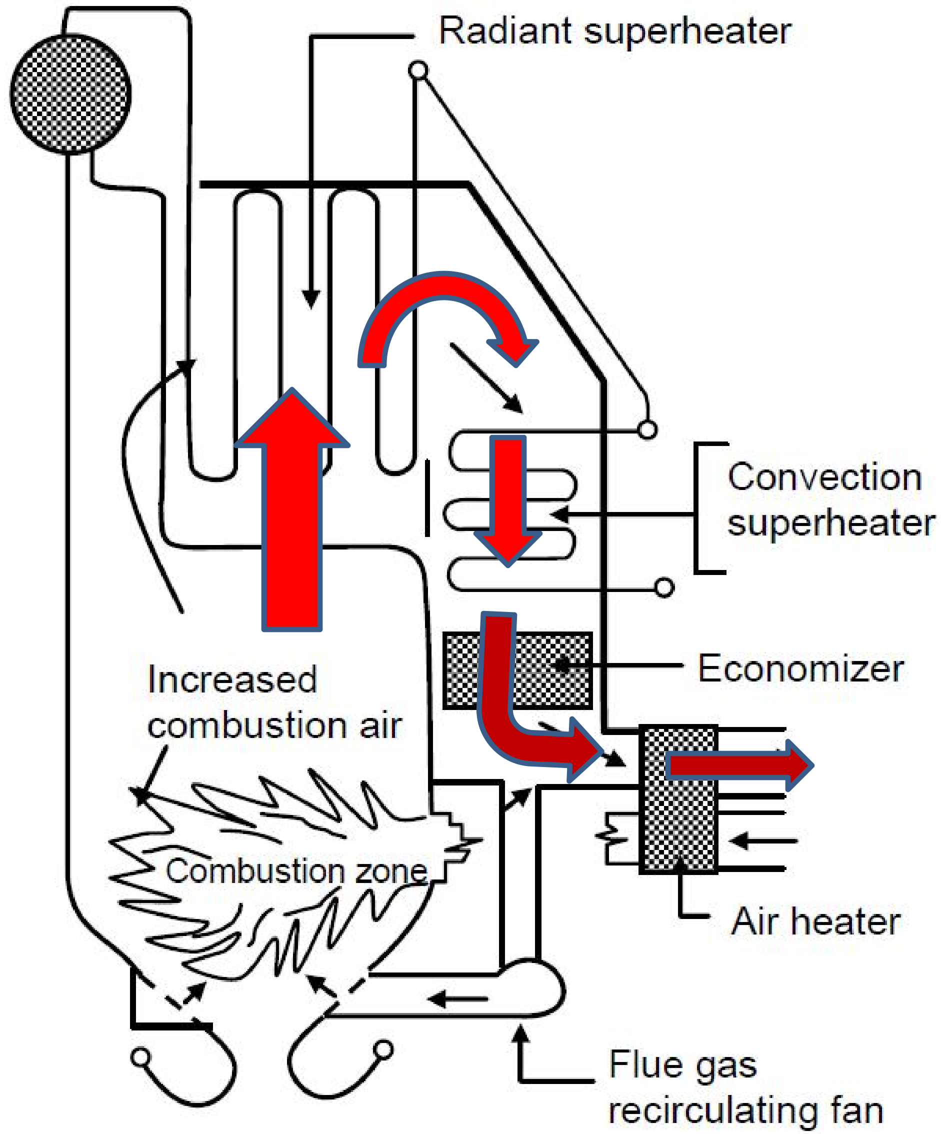
Radiation

Conduction

Latent heat transfer

In the boiler region

May consist of both **recuperative** as well as **regenerative** type heat exchangers



Steam Generator Heat Transfer Equipment

- In steam generator equipment, heat transfer is **between** flue gases and water/steam, **except** in air preheater where heat transfer is between flue gases and incoming air
- **Fins** are **not generally employed** on flue gas side due to **possibility of blockage** with **soot** and or softened ash!
- **Arrangement** can be parallel flow or counter flow or **cross flow**
- **The main heat transfer equipment are:**

1. **Boiler tubes** (radiative or **convective** or combination)
2. **Superheaters** (radiative or **convective** or combination)
3. **Reheaters** (**convective**)
4. **Economizers** (**convective**)
5. **Air preheaters** (**convective**)
   - **recuperative** or **regenerative**

- **Convection heat transfer** is sensitive to **fluid flow rates** on the flue gas as well as on steam sides
- Heat transfer coefficient **increases** as the **fluid flow rate** increases, however the change is generally non linear ($h \propto m^{0.6}$ *or* $m^{0.8}$)
- Heat transfer rate for a given flow rate is approximately proportional to the temperature difference between flue gases and steam ($h \propto t_g - t_s$)
- When the **steam generator tubes** are placed **closer** and **in the direct view** of the furnace walls, then the dominant mechanism of heat transfer is radiation
- **Heat transfer rate** is approximately proportional to the **4th power** of flue gas temperature
- **Convective heaters** are used in low temperature systems, while, **radiant heaters** are mainly used in high temperature systems

Example 6

- The following data pertains to a **convective superheater** in which **steam** flows through a **tube bundle**, while flue gases flow outside the tube bundle:

1. **Steam flow rate = 25 kg/s**
2. **Allowable mass flux = 540 kg/m²**
3. **State of steam**: **Inlet:** t_i = 299°C; h_i = 2740 kJ/kg

   Exit: t_e = 538°C; h_i = 3478 kJ/kg
4. **Flue gas**: **Inlet:** $t_{g,i}$ = 982°C; **Exit:** $t_{g,e}$ = 627°C
5. **Heat Transfer coefficient**: Flue gas: **57 W/m².K**

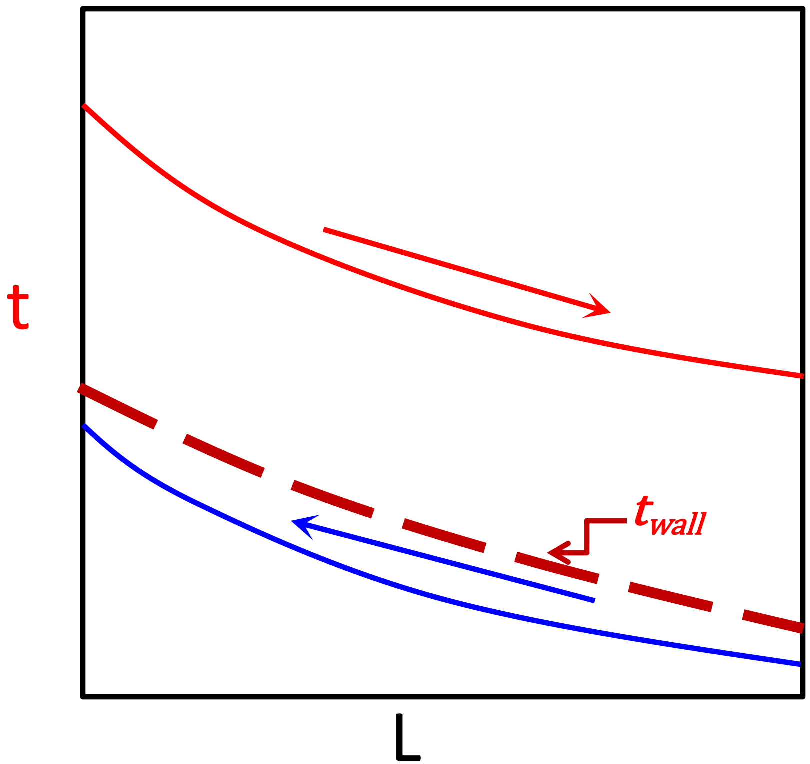
   Steam: **456 W/m².K**
6. **Tube diameter**: Inner: **41.6 mm**; Outside: **50.8 mm**
7. **Wall thermal conductivity**: **35 W/m.K**

Example 6 (contd.)

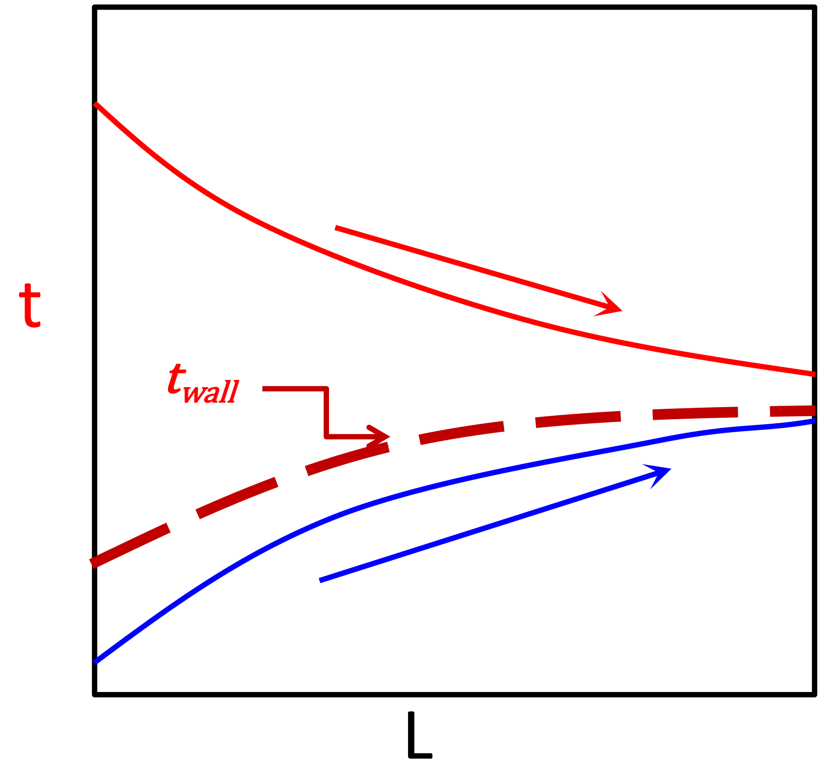
- From the data given, find:
  1. **Number of tubes required**
  2. **Length of each of the tube of the tube bundle**
  3. **Maximum wall temperature**
- Perform the calculations for both **counterflow** and **parallel flow** arrangements

	Counterflow	Parallel flow
No. of tubes required	**34**	**34**
Length of each tube, m	**180.4**	**237.2**
Maximum wall temperature, ^{o}C	**599.5**	**550.3**

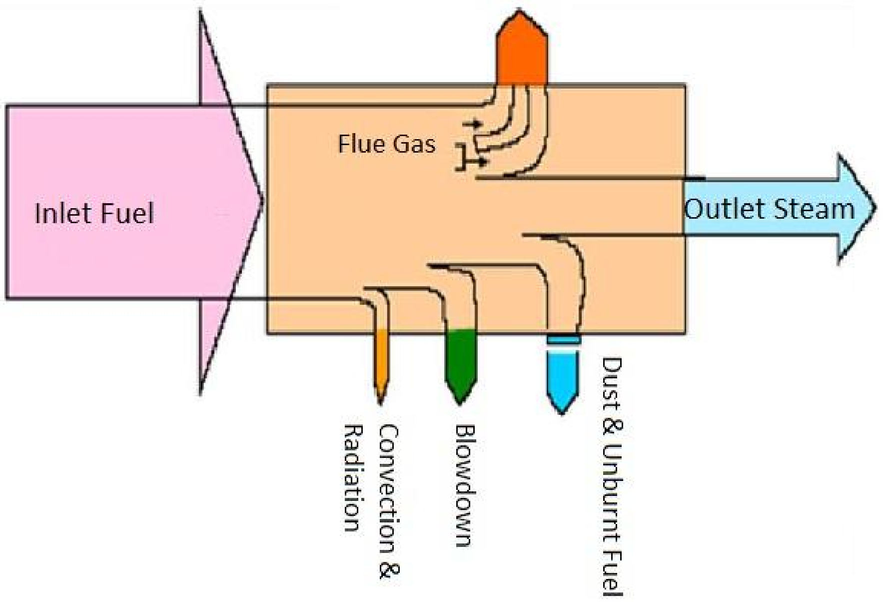
Counter flow



Parallel flow



Boiler energy balance



Boiler energy balance

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{E}_{in} = \dot{E}_{fuel} + \dot{E}_{air} + \dot{E}_{feed\,water}$$

$$\dot{E}_{out} = \dot{E}_{flue\ gases} + \dot{E}_{steam} + \dot{E}_{ash} + \dot{E}_{blowdown} + \dot{E}_{losses}$$

Blowdown losses:

Some amount of **water** is **bled from the boiler**, either **intermittently or continuously**, to **maintain the impurity level** of boiler water below a certain acceptable level

The **losses** that take place due to the bleeding of hot water from the boiler are called as **blowdown losses**

Depending upon the impurity levels of boiler feed water, the blowdown losses can vary from **1 to 3 % of the fuel input**

Boiler energy balance - Example

Perform energy balance on a boiler that receives **480 short tons** (**1 short ton = 907.1874 kg**) of coal per day.

The heating value of the coal is **30.238 MJ/kg**.

Feed water at a flow rate of **47.25 kg/s** enters the steam generator at **172 bar and 232°C** and leaves as steam at **165.5 bar and 538°C**.

Combustion air enters at **26.7°C** and leaves at **177°C**.

The refuse (ash + other matter) generated at a rate of **45 short tons per day** has an internal energy of **1861 kJ/kg**.

The **air/fuel ratio** to the steam generator is **20:**1 (by mass).

The blowdown losses are **3%** of the heat input. What is the thermal efficiency of the boiler?

Use the property data given below:

Enthalpy of water(kJ/kg): a) 172 bar & 232°C: **1004**; b) 165.5 bar & 538°C: **3398**

c_p of air and flue gases = **1.12 kJ/kg.K**

Boiler energy balance – Example (contd.)

Ans.:

$$Q_{coal} = m_{coal} \times h_{f,coal} = 152397 \text{ kW}$$

$$Q_{blowdown} = 0.03 \times 152397 = 4572 \text{ kW}$$

$$Q_{air} = m_{air} c_p (t_{air,out} - t_{air,in}) = 16934 \text{ kW}$$

$$Q_{steam} = m_{steam}(h_{out} - h_{in}) = 113127 \text{ kW}$$

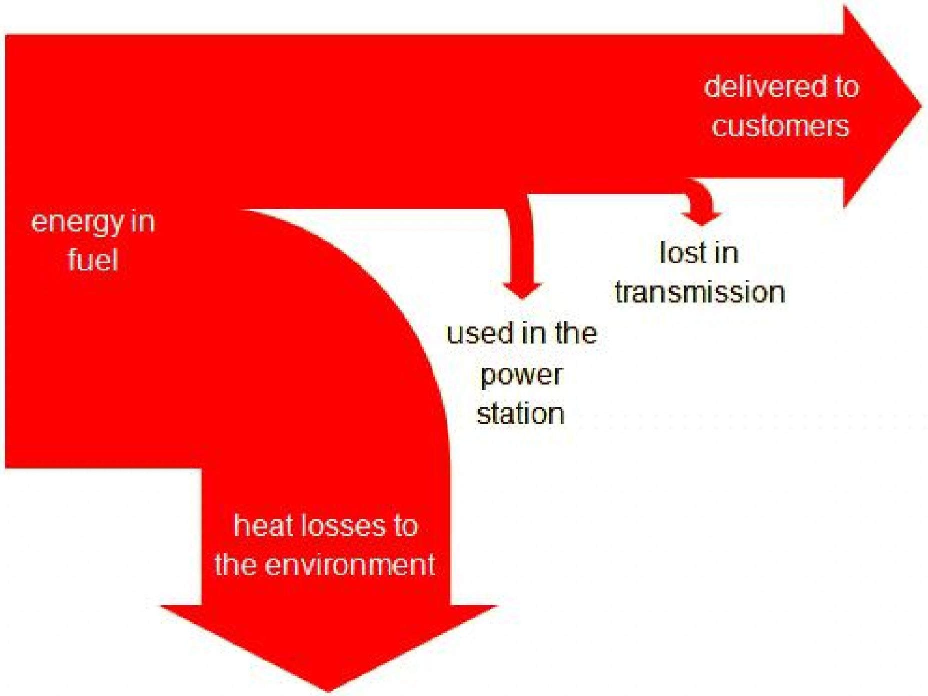
$$Q_{ash} = m_{ash} u_{ash} = 879.2 \text{ kW}$$

$$Q_{heat\ loss} = Q_{coal} - Q_{blowdown} - Q_{air} - Q_{steam} - Q_{ash} = 16885 \text{ kW}$$

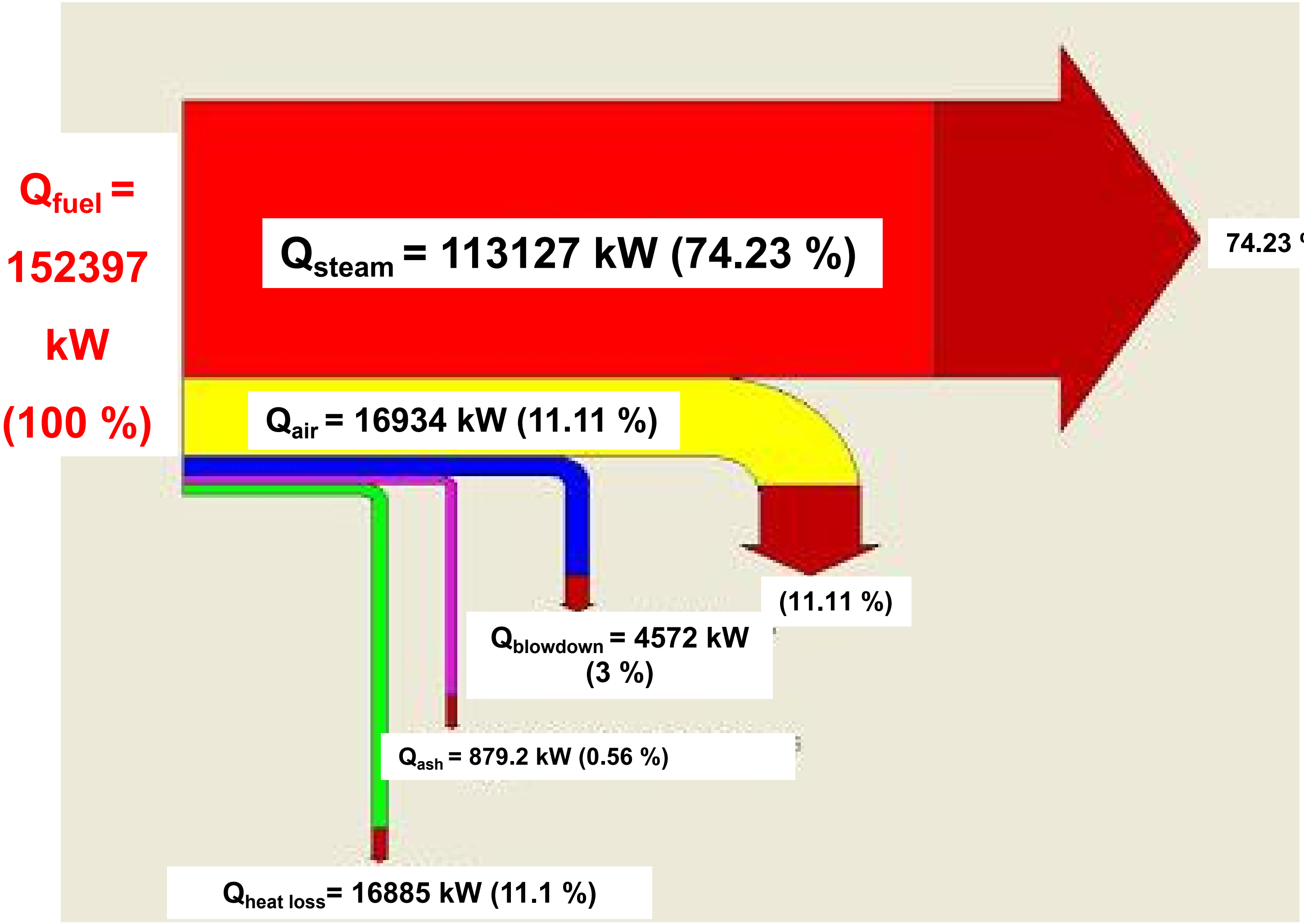
$$\Rightarrow \eta_{boiler} = 100 \times (Q_{steam} \div Q_{coal}) = 74.23\ \%$$

The Sankey diagram of the steam boiler

- **Sankey diagrams** are a specific type of flow diagram, in which the width of the arrows is shown proportionally to the flow quantity
- They are typically used to visualize energy or material or cost transfers between processes
- They are named after Irish Captain Matthew Henry Sankey, who used this type of diagram in 1898 in a classic figure showing the energy efficiency of a steam engine
- (source: wikipedia)



The Sankey diagram of the example steam boiler



Control of steam generator

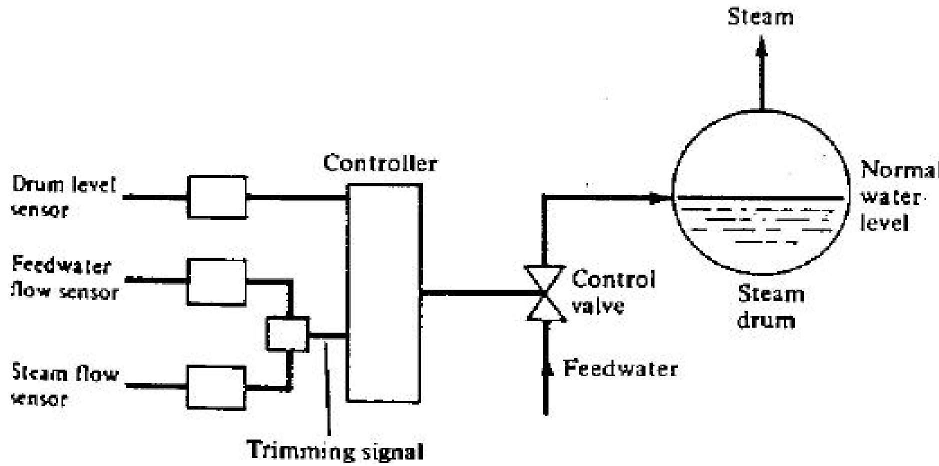
- Control of steam generator to ensure proper operation of the power plant is extremely important and involves highly complex processes
- The control system involves **elaborate and sensitive instrumentation, data processing** and is required to ensure:

1. **Start-up** and **shut-down** of the power plant
2. Control of **combustion** process
3. Control of **water level** in the steam drum
4. Control of **steam flow rate**
5. Control of **steam pressure** and **temperatur**e etc.

However, the **basic controls** involve:

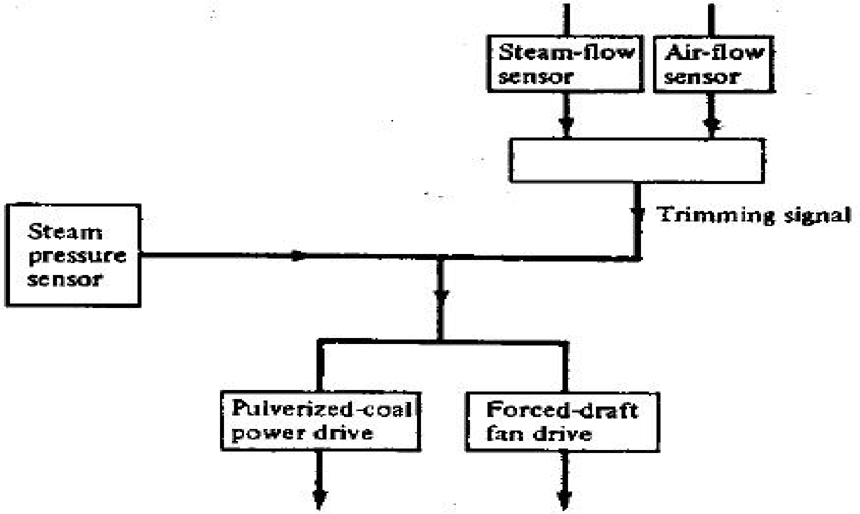
1. **Feedwater** and **steam drum level** control
2. **Steam pressure** (Boiler Master) control, and
3. **Steam temperature** control

1. Steam drum level control



- **Feedwater flow rate** is **controlle**d to **meet the load** on the **turbine**
- For **satisfactory operation**, it is essential to **maintain the water level** in the steam drum within narrow limits
- To maintain the water level, the **feedwater flow rate** into the steam drum must **match** with the **steam consumption rate** by the turbine
- The **drum level sensor** responds to difference between actual drum level and set point, and thereby controls the feedwater valve
- To make the response fast, **sensors** are installed to sense the **feedwater** and **steam flow** rates
- These sensors anticipate the drum level and send signals to the controller which actuates the valve

2. Steam pressure (Boiler Master) control



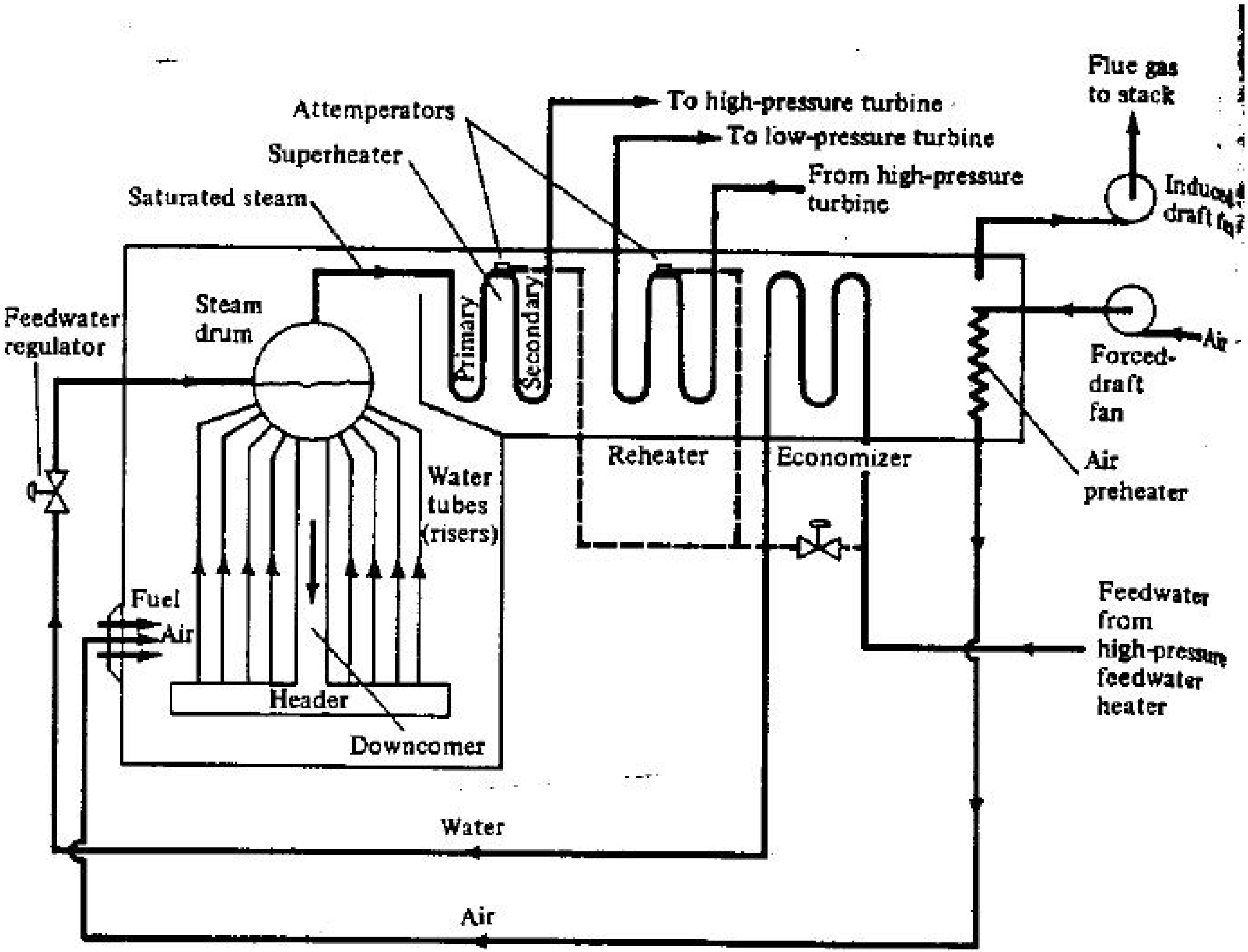
- **Steam pressure** is **controlled** by adjusting **fuel** and **combustion air flow rates**
- Both the **flowrates increase** as the **boiler pressure drops**
- The **steam pressure sensor acts directly** on **pulverized coal power drive** and **forced draft fan**
- A **trimming signal** from fuel and air flow sensors **maintains** proper **fuel-air ratio**
- Since it is **difficult** to accurately **measure and control** fuel flow rates (e.g. coal), sometimes a **steam flow sensor** is used as a **substitute for fuel flow sensor** (if steam flow rate decreases then fuel flow rate is increased)
- A **delay** of about **5 seconds** is allowed between the fuel and air flow rate changes **to prevent** a **momentary rich mixture** and thus ensure a smoke free combustion

3. Steam temperature control

- **Temperature of steam** at the exit of the steam generator (inlet to the turbine) is to be controlled for **proper operation** of the power plant
- Steam temperatures **vary due to** variation in **turbine load**
- Steam temperatures may **also vary due to** deposition of **slag or ash** on the heat transfer surfaces
- **Too low a temperature** affects the power **plant effici**ency, while **too high a temperature** is detrimental to the **materials of construction**
- **Temperature** of saturated steam leaving the **steam drum** remains **constant** as long as the boiler pressure is controlled
- However, the **temperature** of steam at the exit of **superheater** and **reheater** can vary **independent of pressure**
- Steam temperature can be **maintained** within **narrow limits** using a suitable combination of **convective and radiative superheaters** in series
- In addition, **more active temperature controls** are also employed

3. **Steam temperature** control

- **Attemperation:** Reduction of steam temperature by using low temperature liquid water from the economizer or boiler water



3. Steam temperature control (contd.)

- Attemperation can be of **indirect co**ntact, e.g. use of a shell-and-tube type heat exchanger, or
- **Direct contact**, where in **water** is directly **sprayed** into the steam
- From energy balance, for **direct contact attemperation**;

$$m_s h_{s1} + m_w h_w = (m_s + m_w) h_{s2}$$

where m_s = steam flow rate (kg/s)

m_w = water flow rate (kg/s)

h_{s1}, h_{s2} = enthalpy of steam at the inlet and exit of attemperator

h_w = enthalpy of liquid water

- Use of **separately fired superheater** with independent burner, combustion chambers, controls are also used in some plants for temperature control
- **Tiltable burners**, **exhaust gas recirculation**, hot gas bypass are some of the other methods used for the control of steam temperature

Example on steam generator heat exchanger

- At a particular load condition, saturated steam at **347.4°C** enters a convective type superheater and leaves at **480°C**. Find a) the exit temperature of steam, and b) % increase in heat transfer rate, if both the **steam and flue gas mass flow rates are doubled**. The flue gas temperature remains constant at **2000**°C.

Assume:

1. The convective heat transfer coefficients on gas (h_g) and steam (h_s) sides are proportional to $m^{0.8}$, where m is the mass flow rate of gas and steam
2. The overall heat transfer coefficient U of the superheater is proportional to $[(1/h_g)+(1/h_s)]^{-1}$
3. The heat transfer rate **Q** is proportional to $U[T_g - 0.5(T_{s,i} + T_{s,o})]$
4. The heat transfer rate **Q** is proportional to $m_s(T_{s,o} - T_{s,i})$

Where $T_{s,i}$ and $T_{s,o}$ are steam inlet and outlet temperatures, m_s is the mass flow rate of steam

Ans.: a) **463.43°C**, b) **75%**

End of Module 3A