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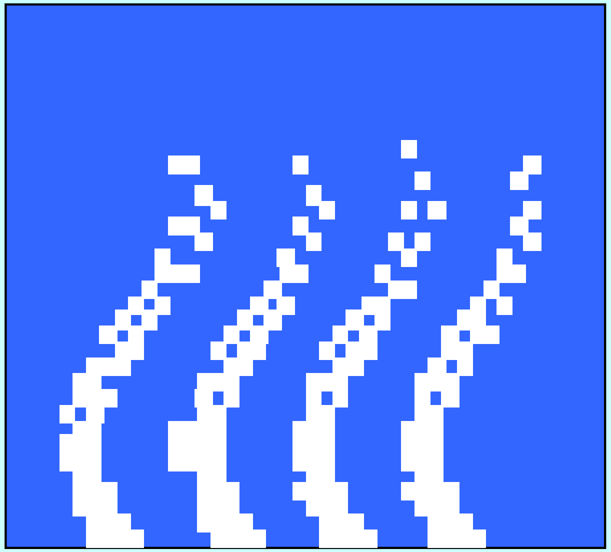

Steam Systems

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Contents

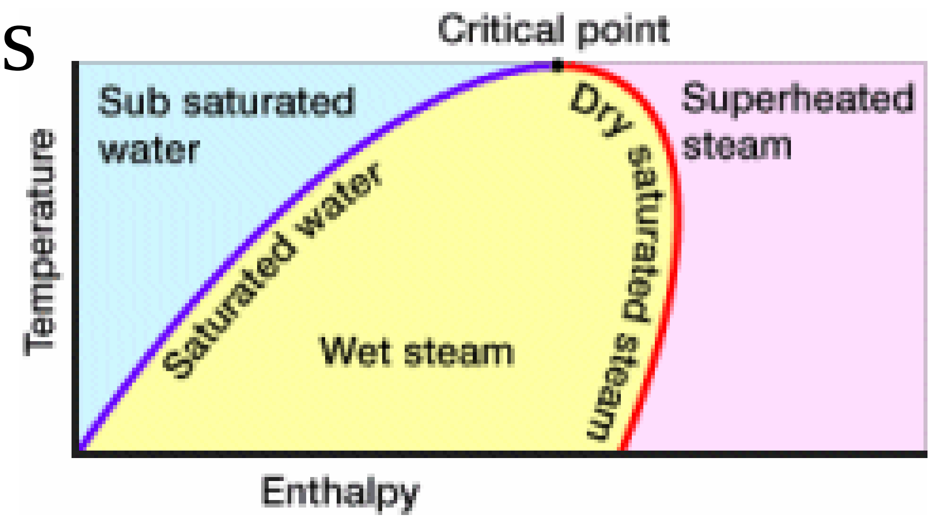
- Properties of steam
- Uses of steam
- System components
- Design considerations

Properties of steam

- Basic thermodynamics
  - Steam: water heated to vaporisation
  - At atmospheric pressure, temperature = 100 ^oC
- Three types of heat in steam calculation:
  - Specific heat of water (h_f)
  - Specific enthalpy of evaporation (h_{fg})
  - Specific enthalpy of steam (h_g)

Properties of steam

- Assume you understand thermodynamics well
  - Such as pressure, specific volume, density, temperature, internal energy, enthalpy, entropy and specific heat
  - Review relevant text books if you have questions
- Key fundamental concepts
  - Steam tables
  - Dry steam and wet steam
  - Superheated steam



Properties of steam

- Steam tables
  - To determine various steam properties
    - Pressure
    - Temperature
    - Specific enthalpy
    - Specific volume (inverse of density)
    - Specific heat capacity
  - Published tables in databooks, such as CIBSE Guide C, Section 4, or IOP Guide
  - Total enthalpy, $h_g = h_f$ (sensible) + h_{fg} (latent)

Do you know how to use these steam tables?

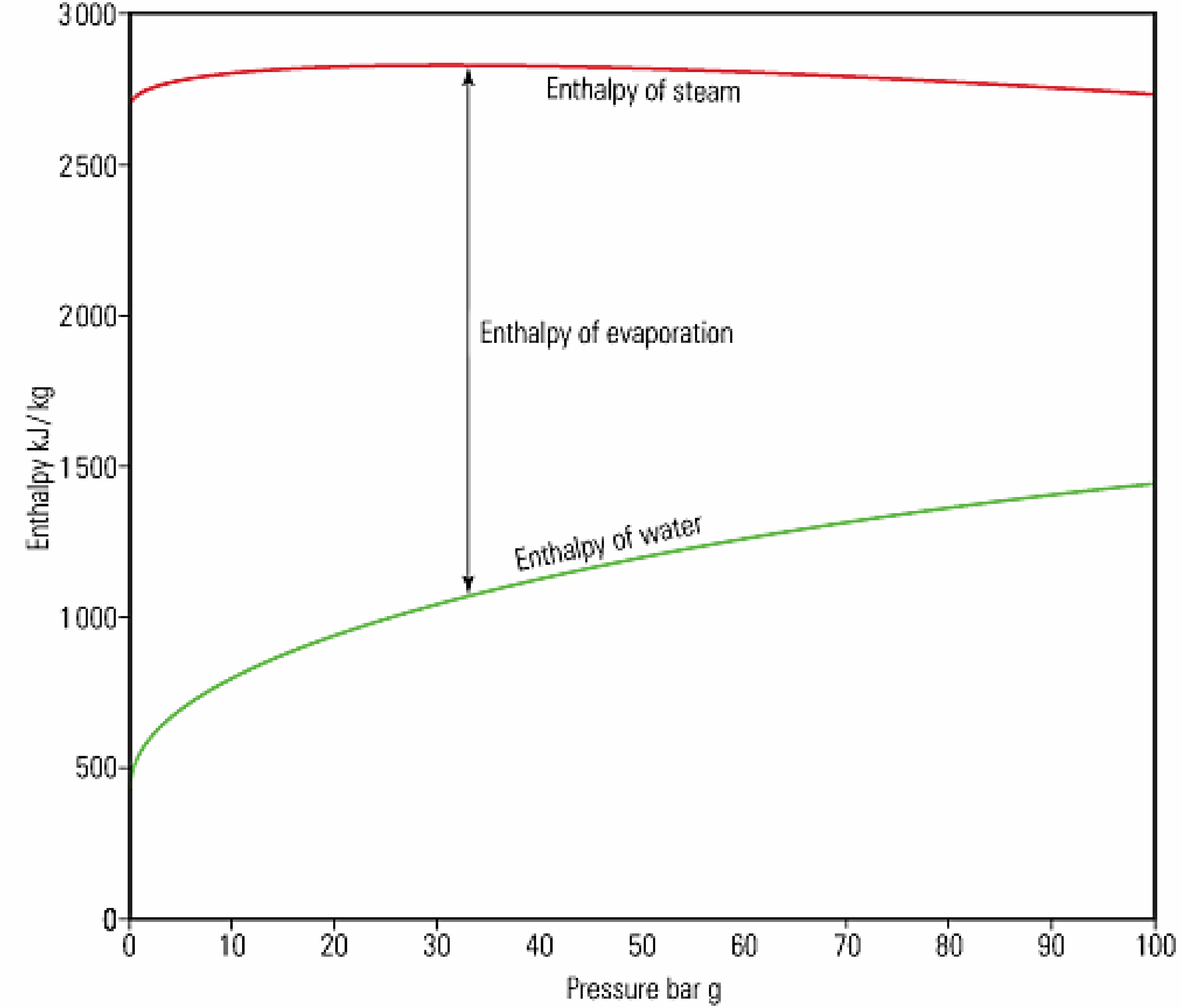
Extract from the saturated steam tables

Pressure bar g	Saturation temperature °C	Enthalpy kJ/kg Water h_f	Enthalpy kJ/kg Evaporation h_{fg}	Enthalpy kJ/kg Steam h_g	Volume of dry saturated steam m^3/kg
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

Extract from superheated steam tables

Absolute pressure bar a	Units	Temperature (°C)					
		150	200	250	300	400	500
1.013	v_g (m^3/kg)	1.912	2.145	2.376	2.604	3.062	3.519
	u_g (kJ/kg)	2 583	2 658	2 734	2 811	2 968	3 131
	h_g (kJ/kg)	2 777	2 876	2 975	3 076	3 278	3 488
	s_g (kK/kg)	7.608	7.828	8.027	8.209	8.537	8.828

(Source: www.spiraxsarco.com/learn)



The enthalpy/pressure diagram

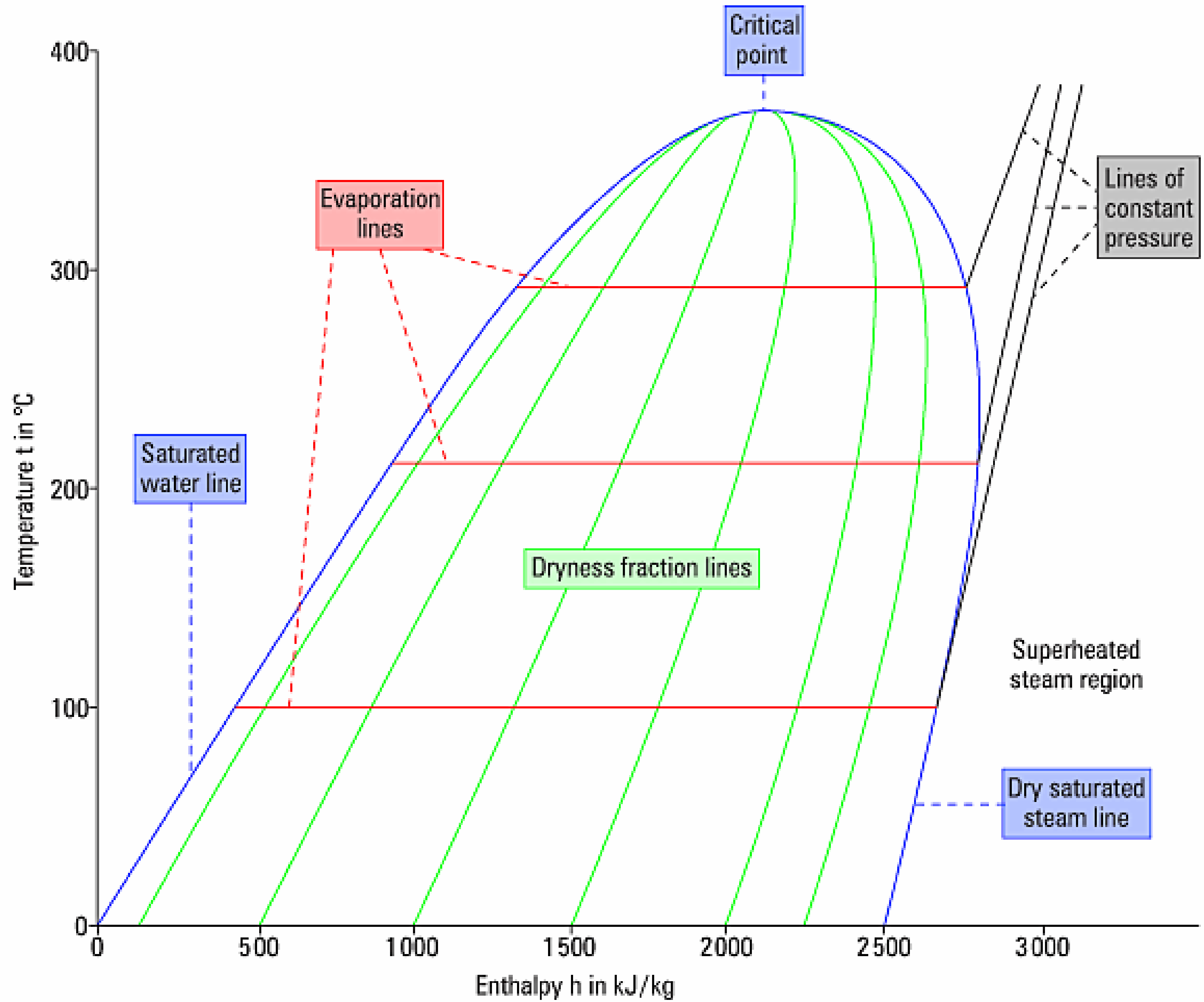
(Source: www.spiraxsarco.com/learn)

Properties of steam

- Dryness of steam
  - Steam often carries tiny droplets of water
  - *Dryness fraction (χ)* = proportion of completely dry steam present in the steam-moisture mixture
  - Wet steam has a heat content substantially lower than that of dry saturated steam at the same pressure
    - Actual enthalpy of evaporation = $h_{fg} . (\chi)$
    - Actual total enthalpy = $h_f + h_{fg} . (\chi)$

Properties of steam

- <u>Superheated steam</u>
  - If the saturated steam produced in a boiler is exposed to a surface with a higher temperature, its temperature will increase above the evaporating temperature → <u>*Superheated*</u>
  - When superheated steam gives up some of its enthalpy, a fall in temperature without condensation until the saturation temperature has been reached (condensation occurs in saturated steam)



The temperature/enthalpy diagram

(Source: www.spiraxsarco.com/learn)

Uses of steam

- Steam is used:
  - As a heating medium for industrial process, heating & hot water in buildings, cooking
  - To produce electrical power in power plants
- Common applications:
  - As a primary medium for distributing heat in factories, hospitals and hotels
  - Means of sterilizing, cooking (Chinese restaurants)
  - Space heating
  - Hot water supply (via calorifiers)

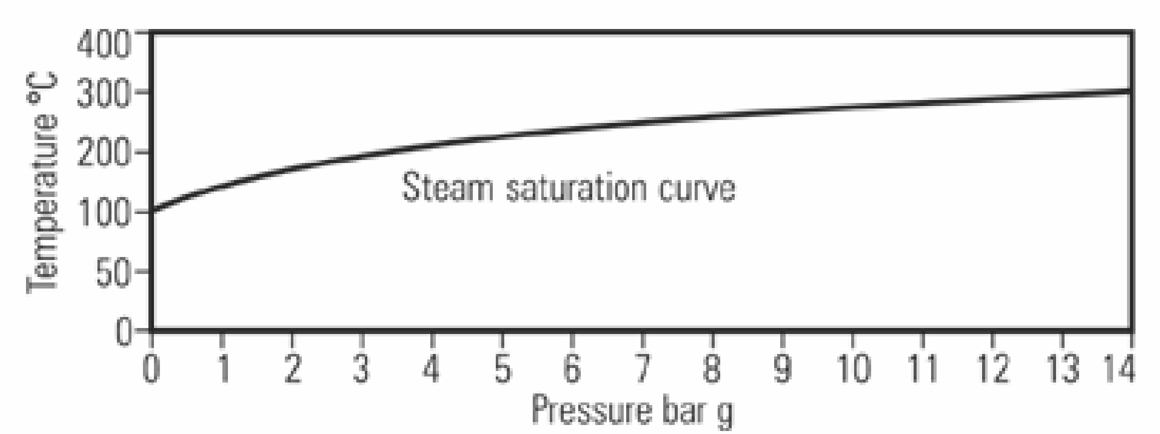
Industries and processes which use steam

Heavy users	Medium users	Light users
Food and drinks	Heating and ventilating	Electronics
Pharmaceuticals	Cooking	Horticulture
Oil refining	Curing	Air conditioning
Chemicals	Chilling	Humidifying
Plastics	Fermenting	
Pulp and paper	Treating	
Sugar refining	Cleaning	
Textiles	Melting	
Metal processing	Baking	
Rubber and tyres	Drying	
Shipbuilding		
Power generation		

(Source: www.spiraxsarco.com/learn)

Uses of steam

- Heat transfer
  - Latent heat of evaporation = 2257 kJ/kg at atm pressure
  - Sensible heat of water = 419 kJ/kg (0 to 100 ºC)
- Flow at high velocity (24-36 m/s) and high temperature (100-198 ºC)

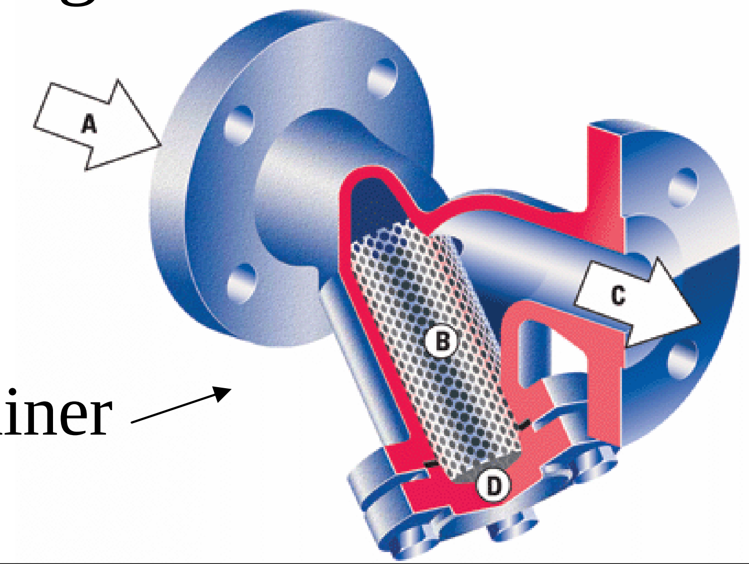


Uses of steam

- Advantages of steam over hot water systems:
  - No pumps needed: steam flows through system unaided
  - Smaller heat emitters
  - Low density: steam can be used in tall buildings where water systems create excessive pressure
  - Terminal units can be added/removed easily
  - Steam components can be repaired or replaced just by closing the steam supply (no associated draining and refilling a water system)
  - Steam system temperature can be controlled by varying either steam pressure or temperature
- Disadvantages:
  - More complicated, more maintenance & supervision

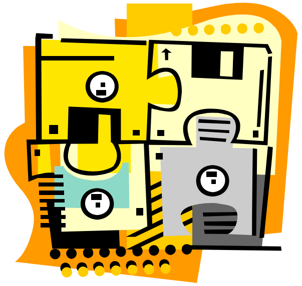
Uses of steam

- 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
  - Clean
  - Dry

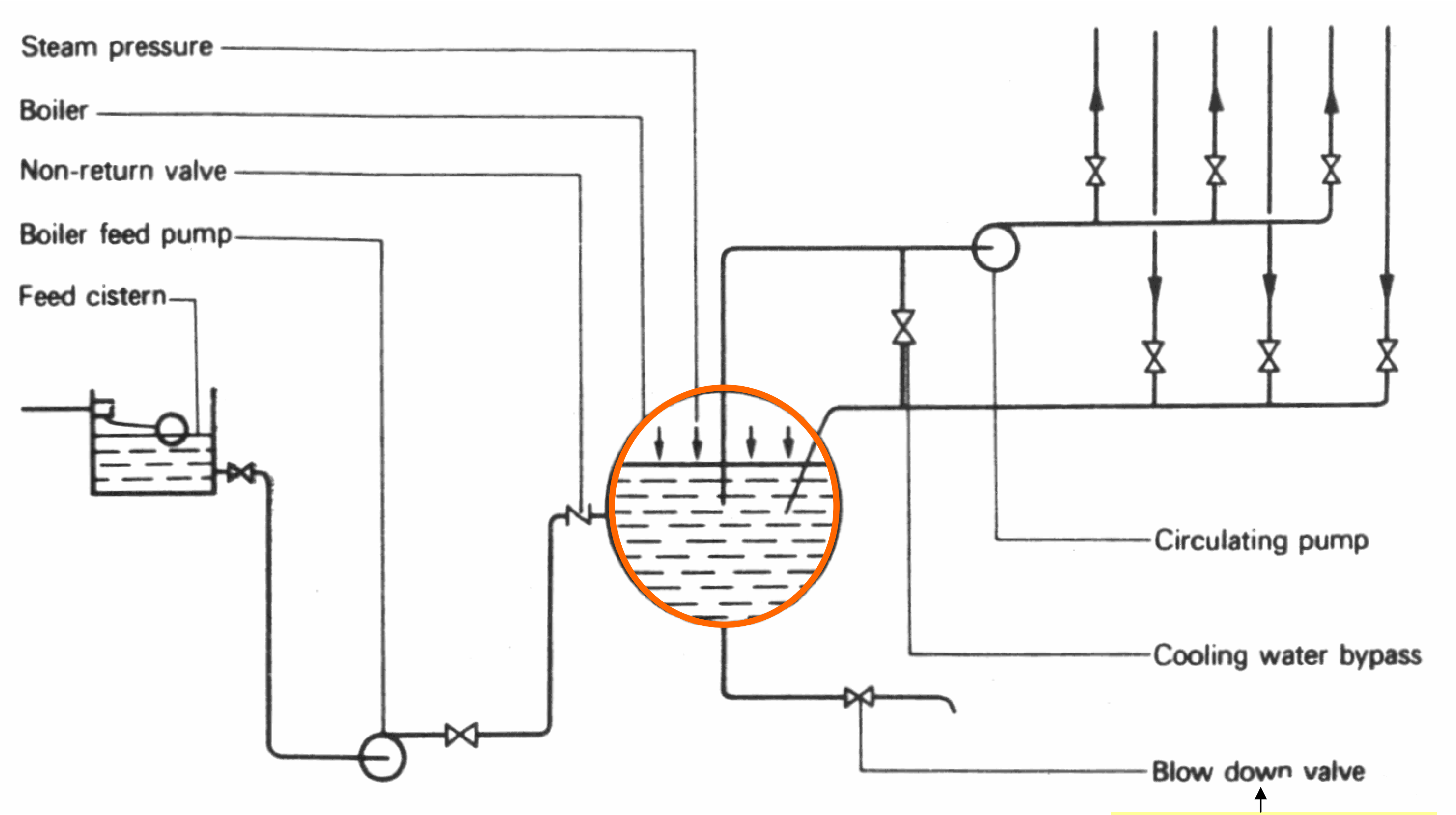


Pipeline strainer

System components



- Basic arrangements
  - Boiler plant using steam pressurisation
    - Hot water boiler (w/ steam maintained inside)
    - Boiler feed pump & cistern
    - Circulating pump & pipework
    - Cooling water bypass (mixing to control the pressure)
  - Steam & the water are at saturation temperature

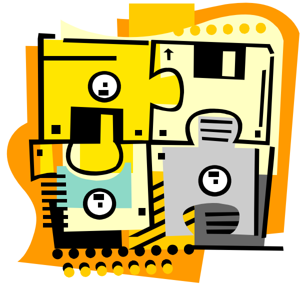


Why blow down?

Boiler plant using steam pressurisation

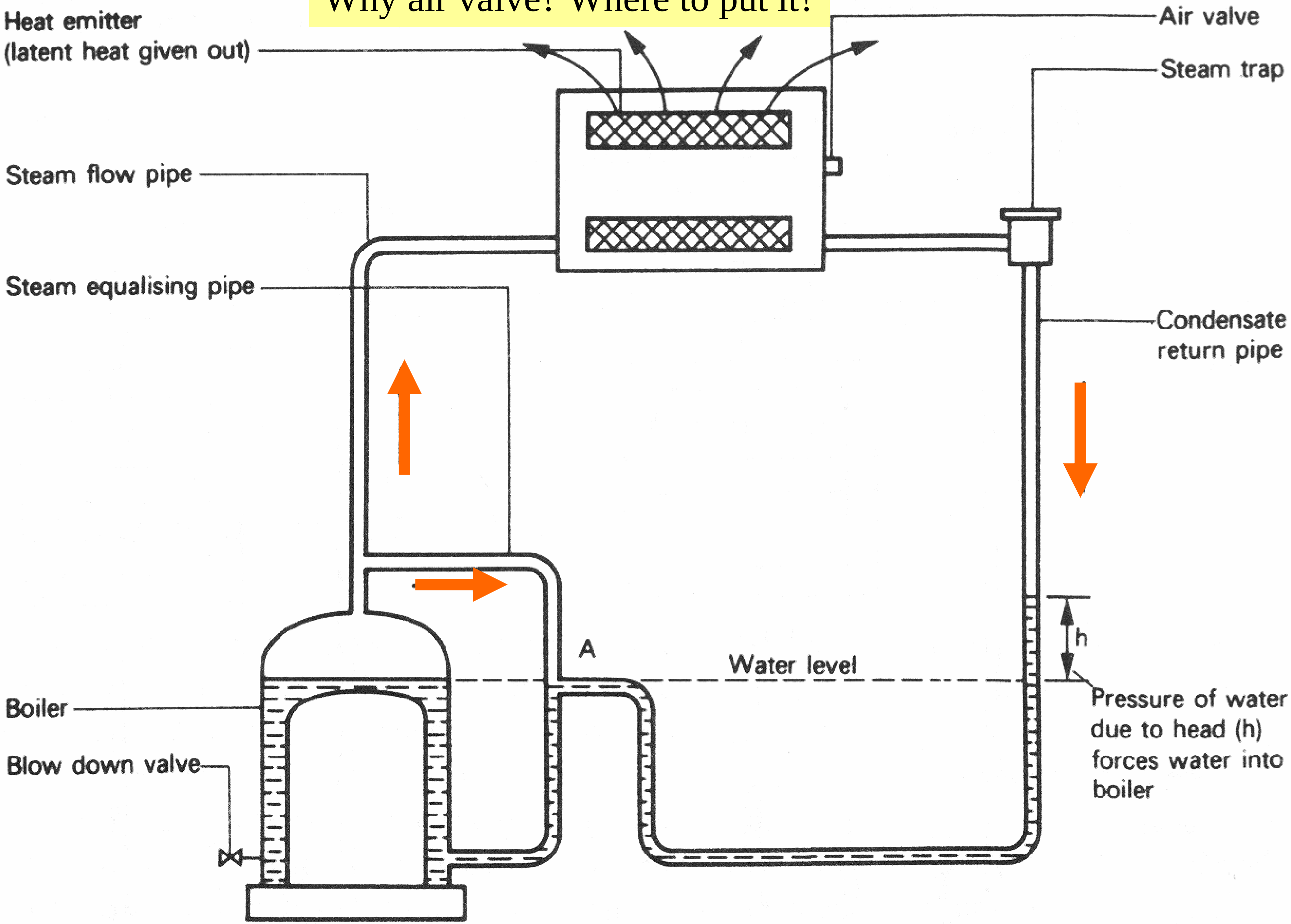
(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

System components



- Use steam directly for heating
  - Low pressure: up to 35 kPa
  - Medium pressure: 140 to 550 kPa
  - High pressure: 550 to 1400 kPa
- Low pressure steam
  - It has a higher heat content
  - Causes less risk of noise and wear
- Medium or high pressure
  - For large installations with long steam mains
  - Requires pressure-reducing set for appliances

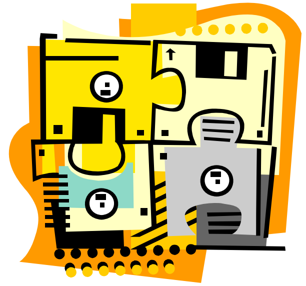
Why air valve? Where to put it?



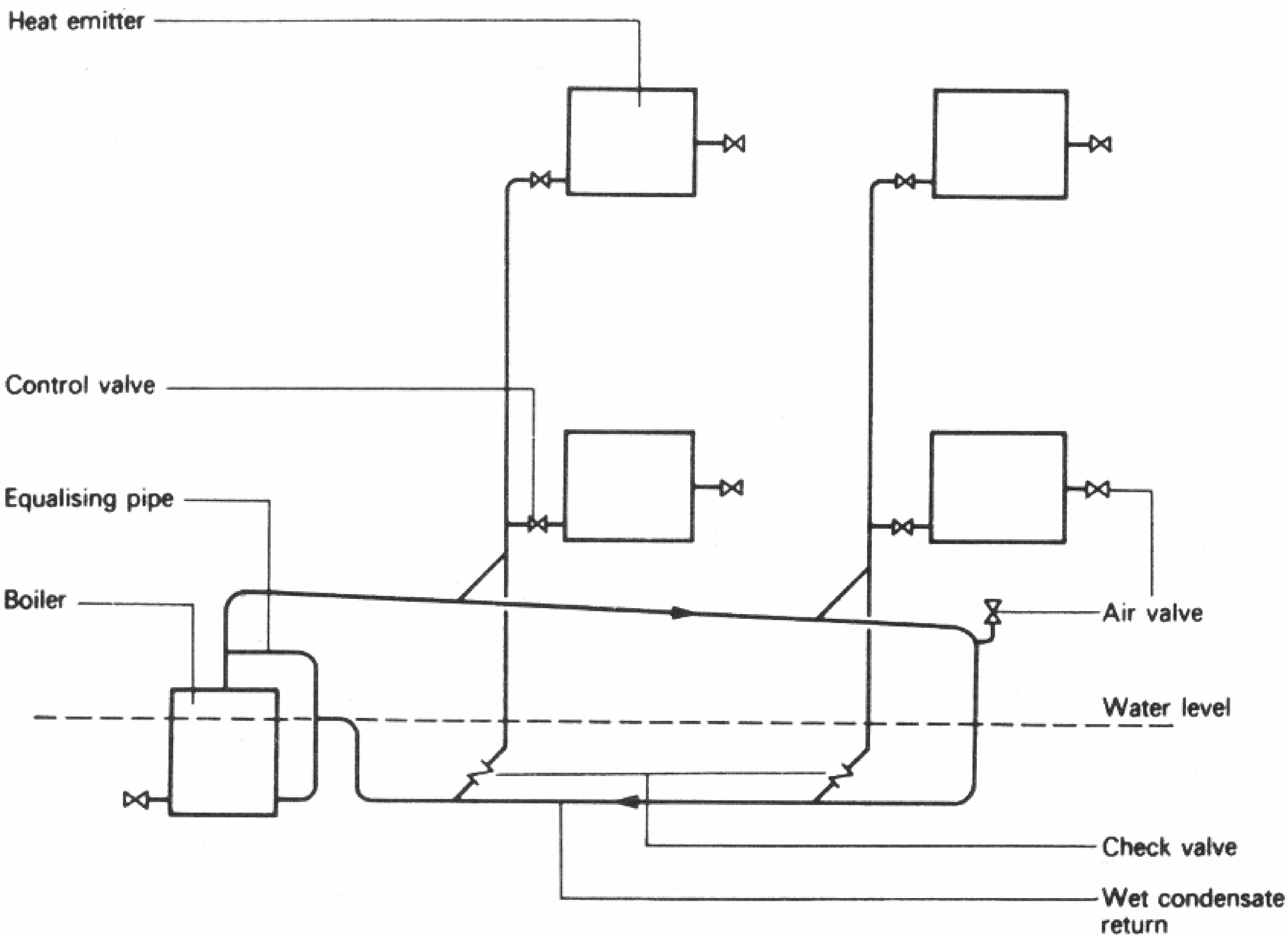
Operating principle of steam heating

(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

System components



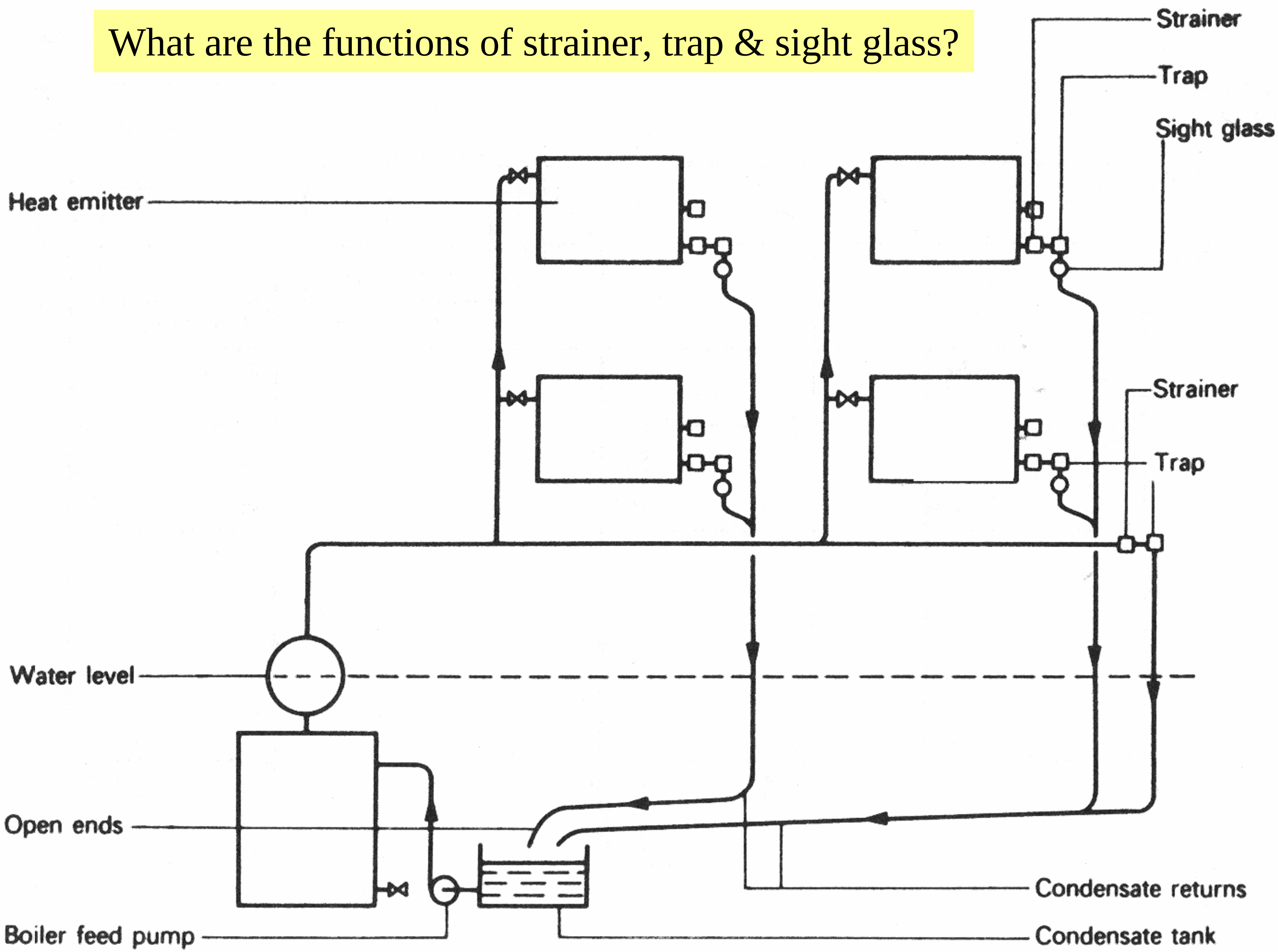
- Classification of steam systems:
  - By method of condensate return
    - Gravity
    - Mechanical
  - By pipe layout
    - One pipe or two pipe
    - Up-feed or down-feed



One-pipe gravity steam heating system

(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

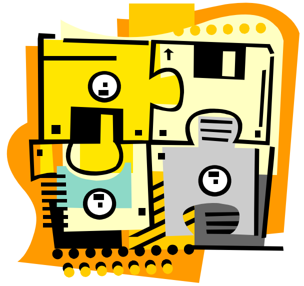
What are the functions of strainer, trap & sight glass?



Two-pipe mechanical steam heating system

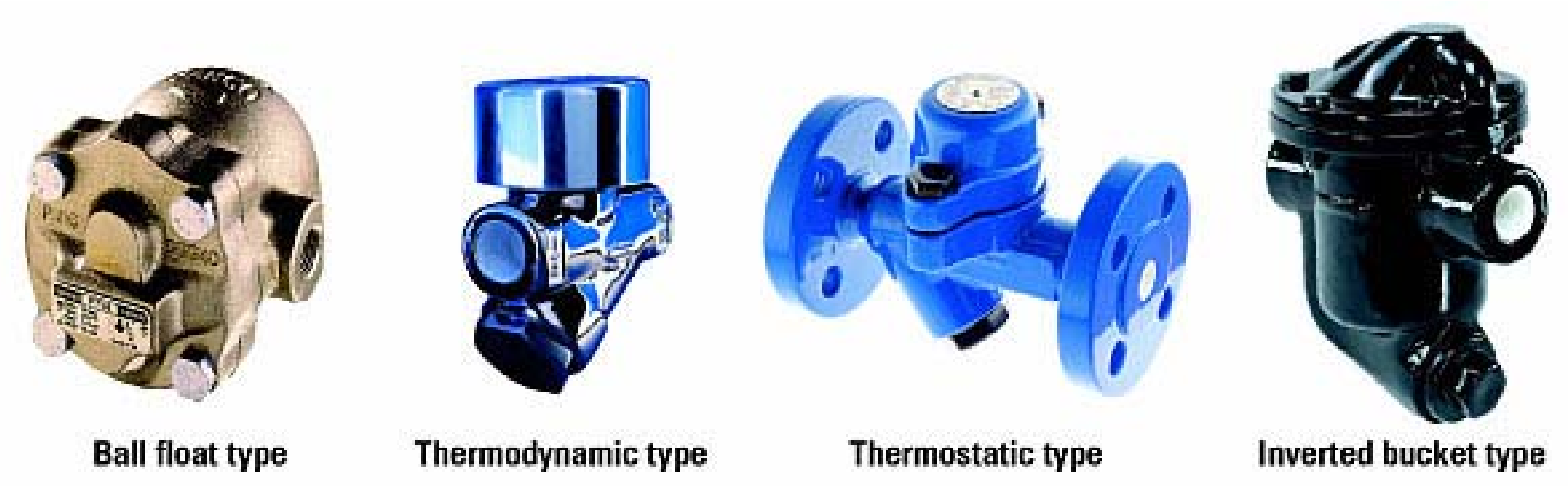
(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

System components



- Steam traps
  - Purpose: to remove condensate inside appliances, pipelines or heat exchangers
  - Condensate returns to boiler
    - By gravity (runs back to boiler)
    - By automatic pump (pumped back to boiler)
    - By condensate lifting trap
  - Three main groups of steam traps: thermostatic, mechanical and thermodynamic

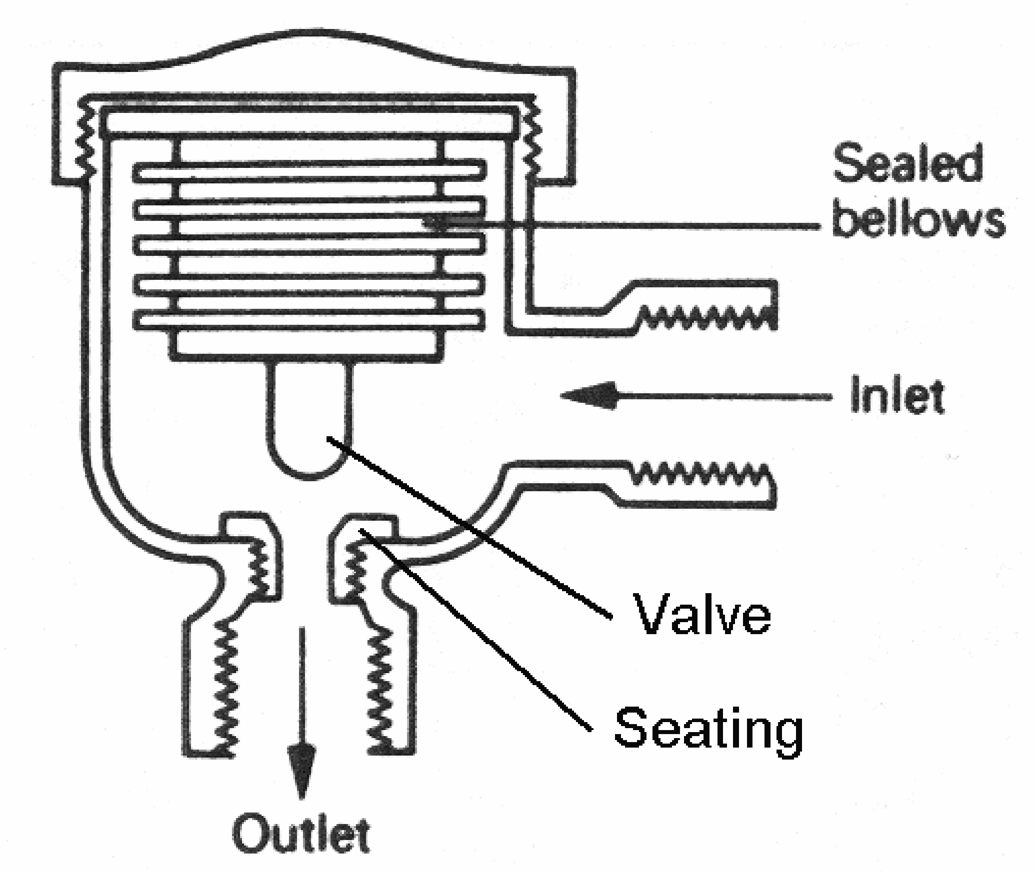
"The duty of a steam trap is to discharge condensate while not permitting the escape of live steam"



Typical types of steam traps

(Source: www.spiraxsarco.com/learn)

Thermostatic



Thermostatic steam trap

Operating principle:

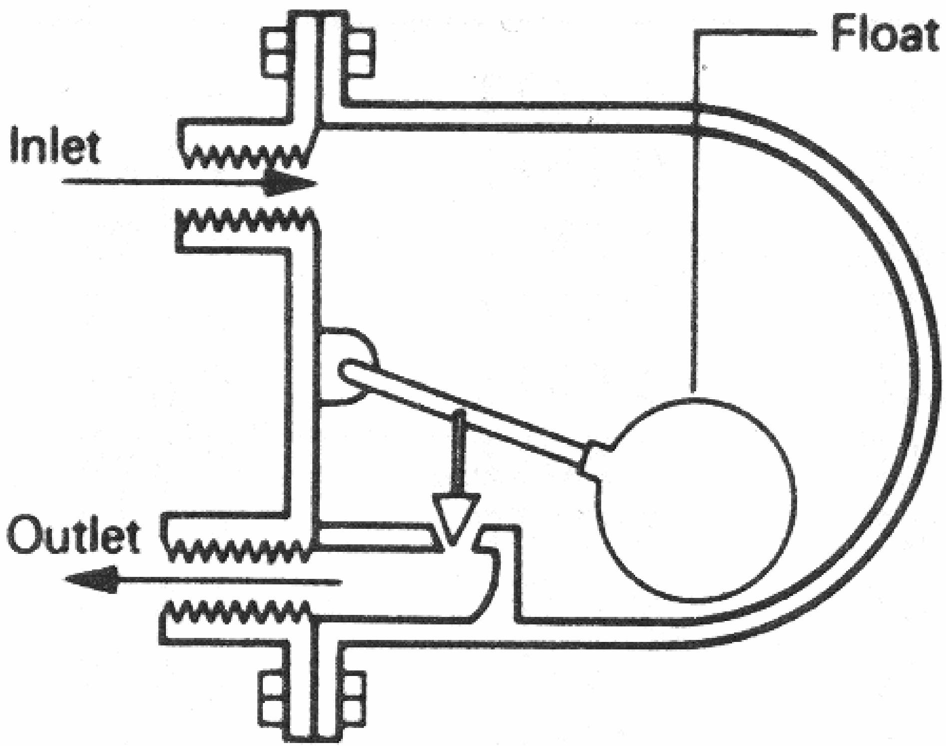
- The closed bellows contains a volatile spirit which has a boiling point suiting the temperature

- When steam enters the traps, the volatile spirit expands → open the bellows, close the valve

- Water (condensate) enters the traps at a temperature lower than steam, the spirit contracts and closes the bellows → open the valve + allow water to flow back to boiler

(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

Mechanical



Ballfloat steam trap

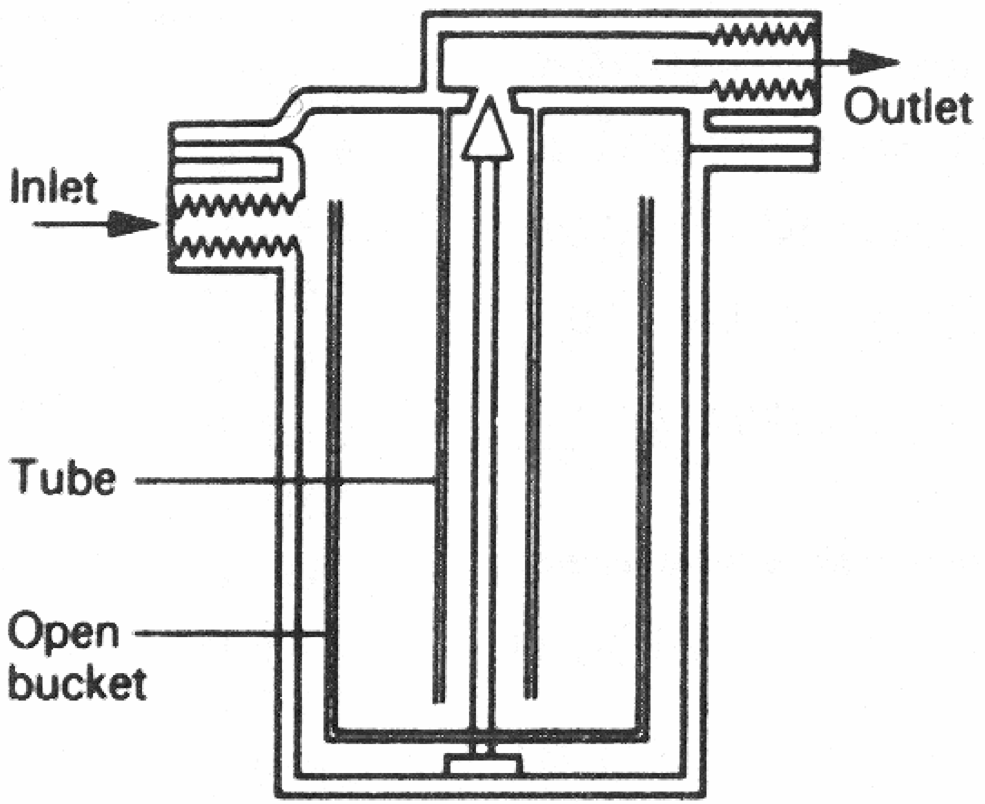
Operating principle:

- Steam enters the trap → ball float valve suspended → weight of float keeps outlet valve close

- Water (condensate) enters trap → float buoyant →opens valve → allow water flowing back to boiler

(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

Mechanical



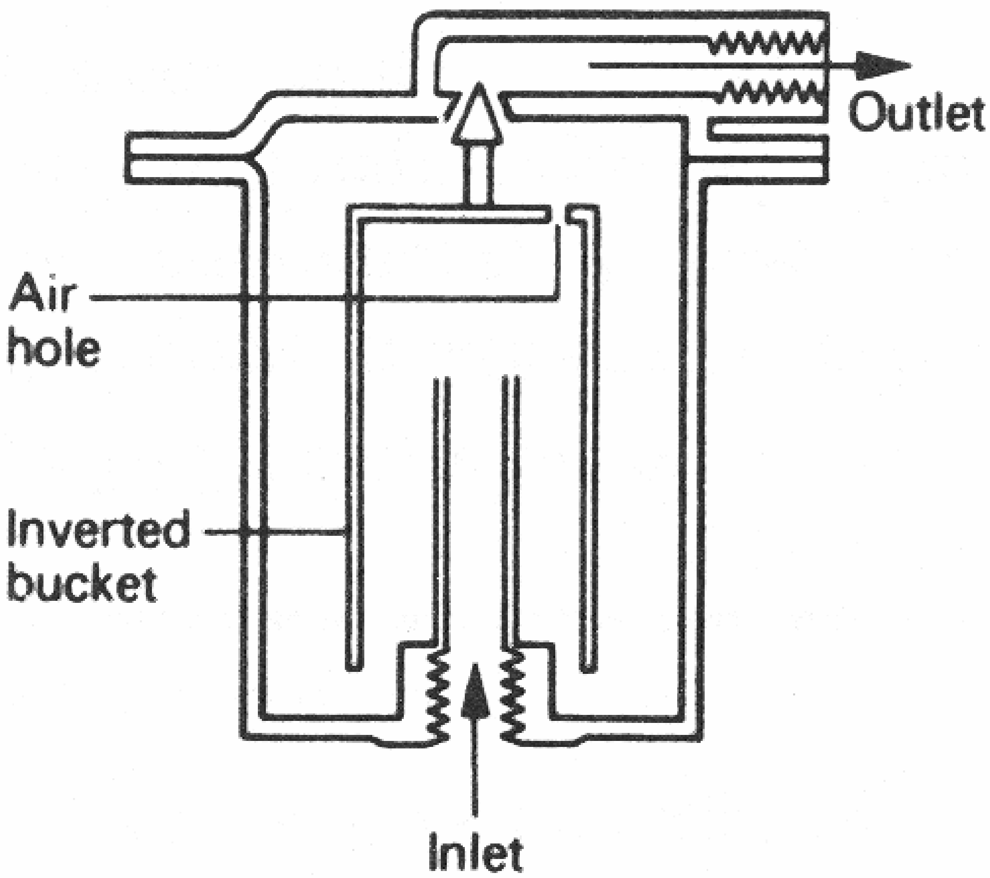
Open bucket steam trap

Operating principle:

- Bucket floats → outlet valve close
- Water (condensate) enters trap →overflows into bucket → bucket to sink → open the valve
- Steam forces water out of bucket through the tube → bucket is buoyant → closing the valve

(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

Mechanical



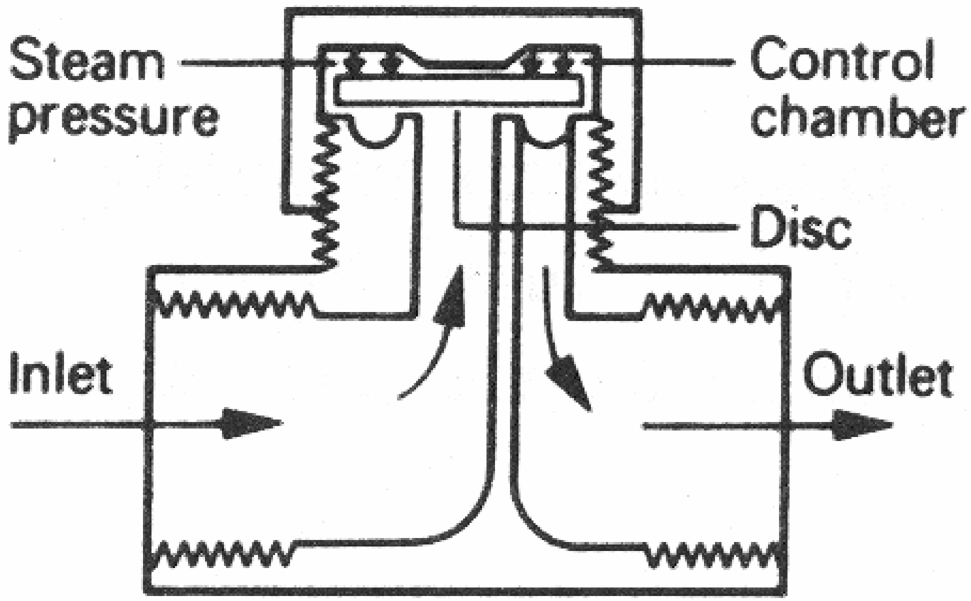
Inverted bucket steam trap

Operating principle:

- Steam enters the trap → bucket is lifted → valve is closed
- Water (condensate) enters trap → bucket fails under its own weight → valve opens → steam pressure forced water out

(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

Thermodynamic



Thermodynamic steam trap

Bernoulli principle:
kinetic pressure + potential energy = constant

Operating principle:

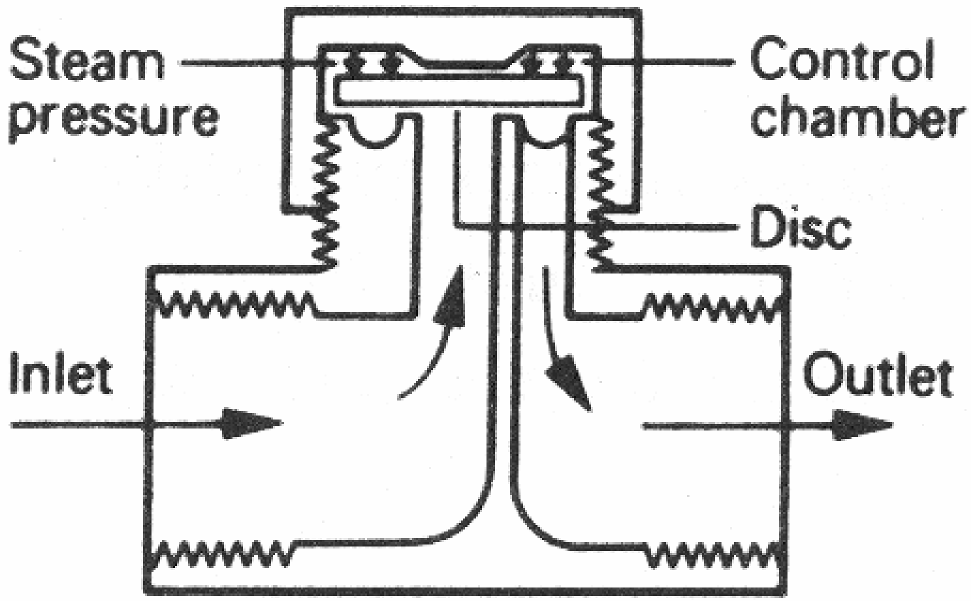
- Steam flows through trap → increase kinetic energy between disc & seating → reduce pressure energy at this point → disc moves nearer the seating until kinetic energy decreases

- Reduction in kinetic energy → increase pressure energy → lift the disc from seating (prevented from doing so by the steam pressure acting upon the top of the disc in the control chamber)

- Area at the top of the disc > area at inlet underneath → the upper pressure forces the disc firmly on to its seat

(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

Thermodynamic



Thermodynamic steam trap

Bernoulli principle:
kinetic pressure + potential energy = constant

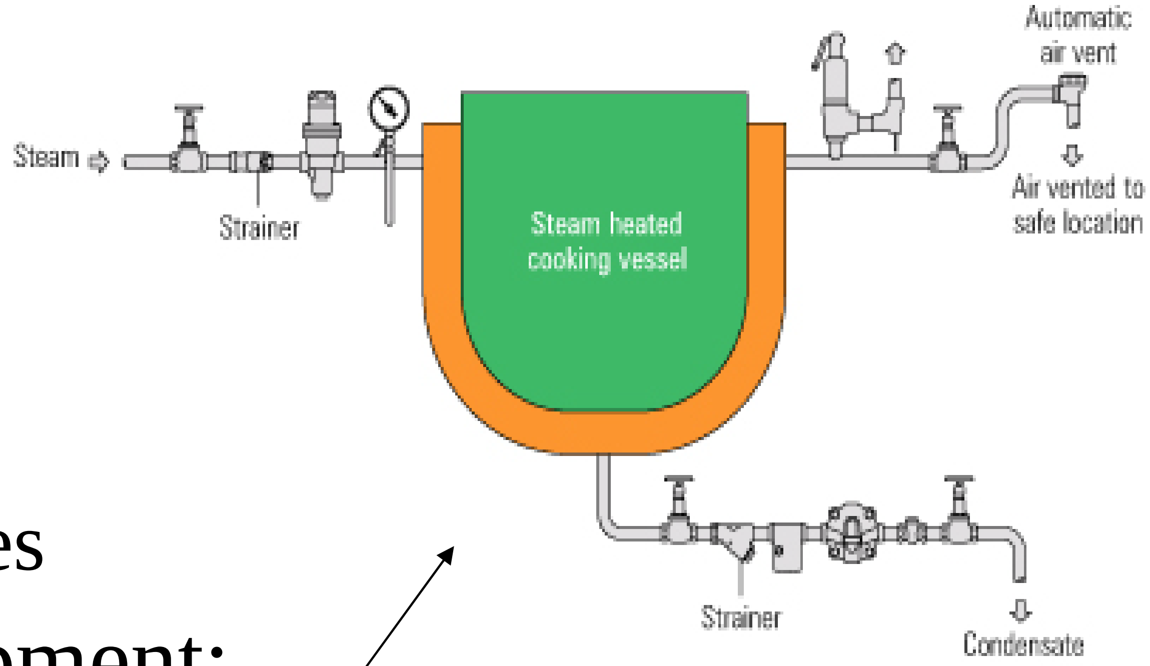
Operating principle (cont'd):

- Water (condensate) enters trap → steam above disc condenses → reduce pressure → disc forced up→ water flow through trap
- Water (condensate) flows through trap at a lower velocity than steam → insufficient reduction in pressure below the disc → traps remains open until steam enters

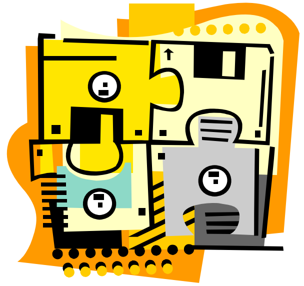
(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

System components

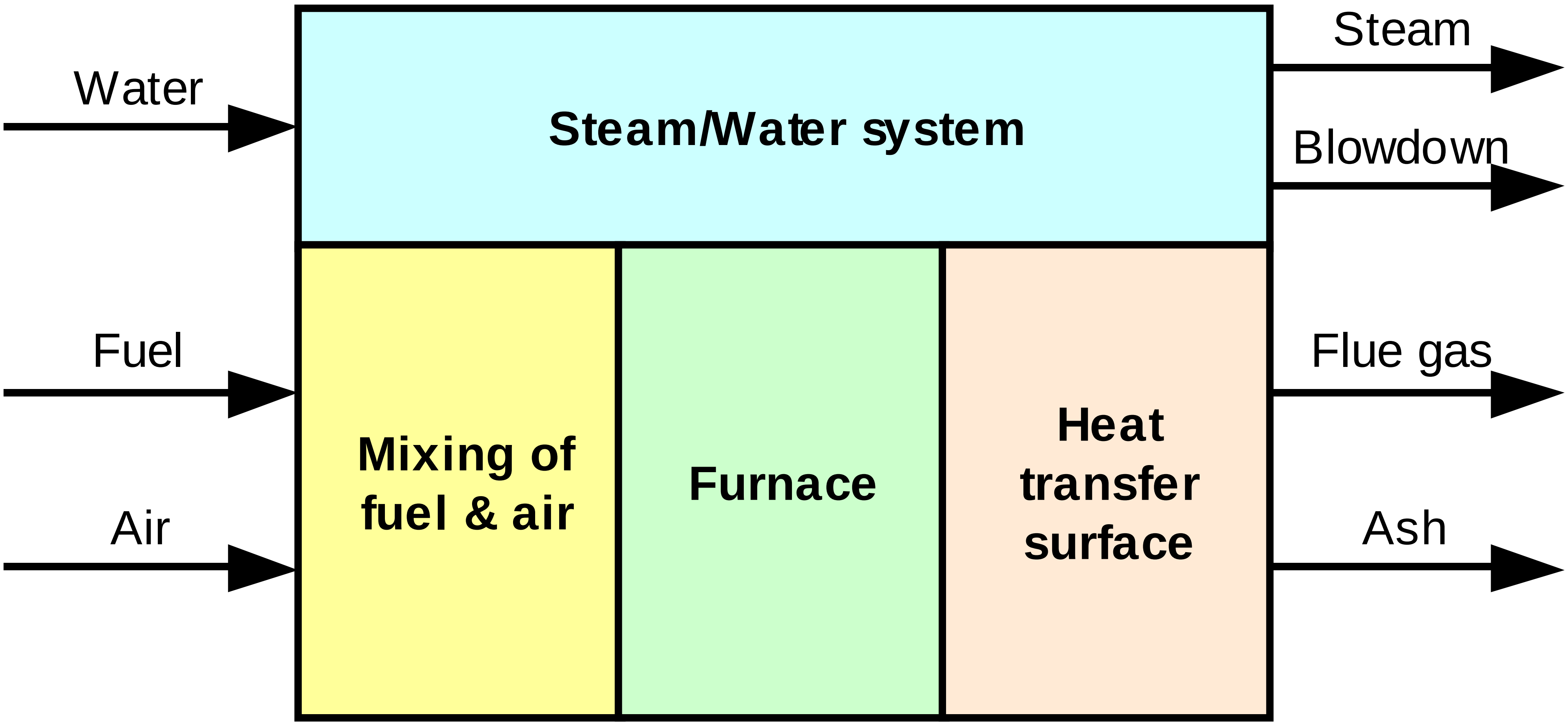
- Other components
  - Steam separators
  - Strainers
  - Automatic air vent
  - Check valves
  - Isolation valves
  - Gauges, sight glasses
- Typical steam equipment:
  - Steam heated cooking vessel



System components

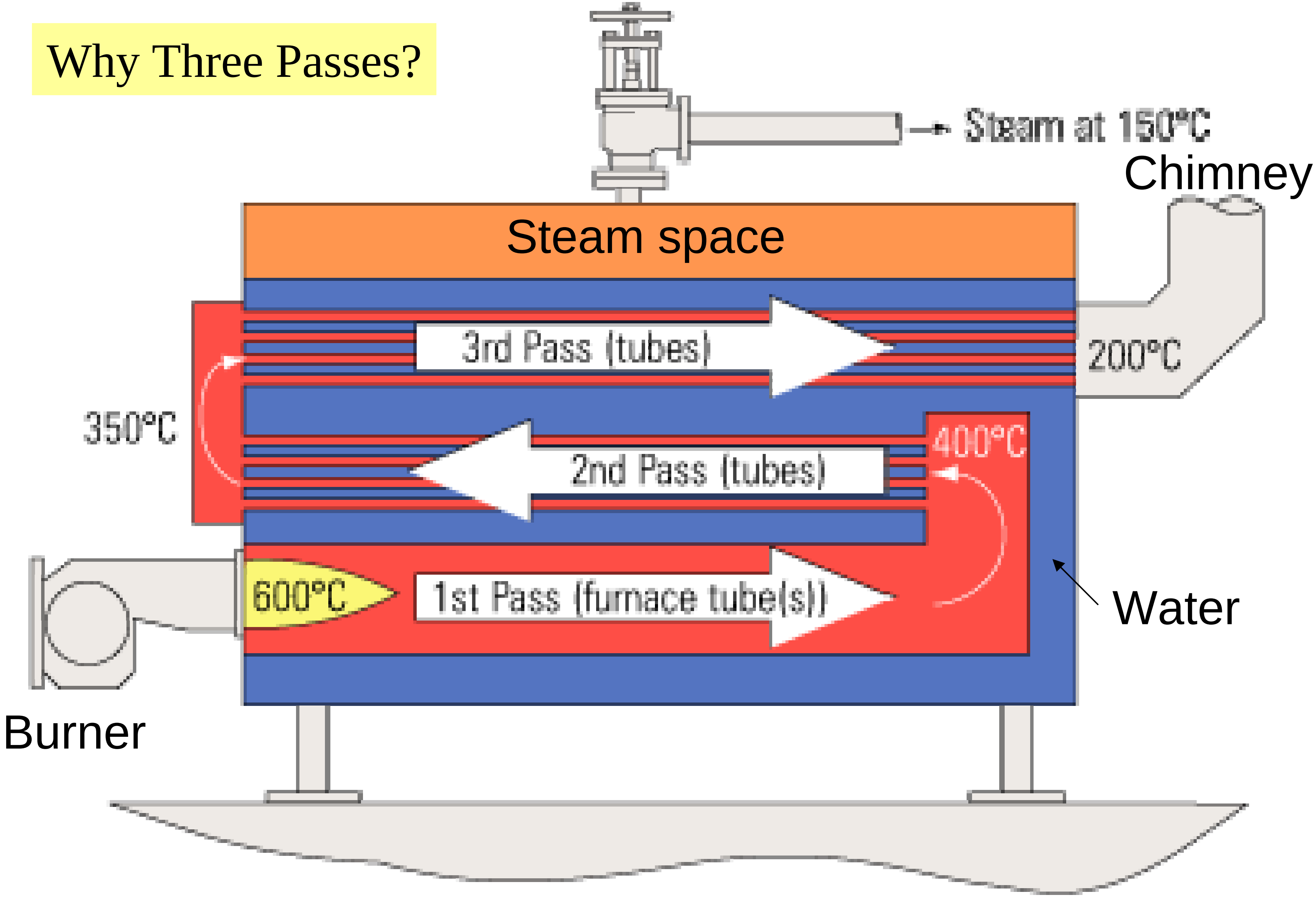


- Boilers – classified according to:
  - Type of working fluid or heat carrier used
    - Such as steam and hot water
  - Physical arrangement of the working fluid
    - Fire tube: flue gas products flow through boiler tubes
    - Water tube: water circulates within boiler tubes
  - Combustion gases/fuels
    - Natural gas, town gas, diesel, etc.
    - Gas & oil replace coal for fuel of boiler/furnace
      - Easier to handle & less pollution product



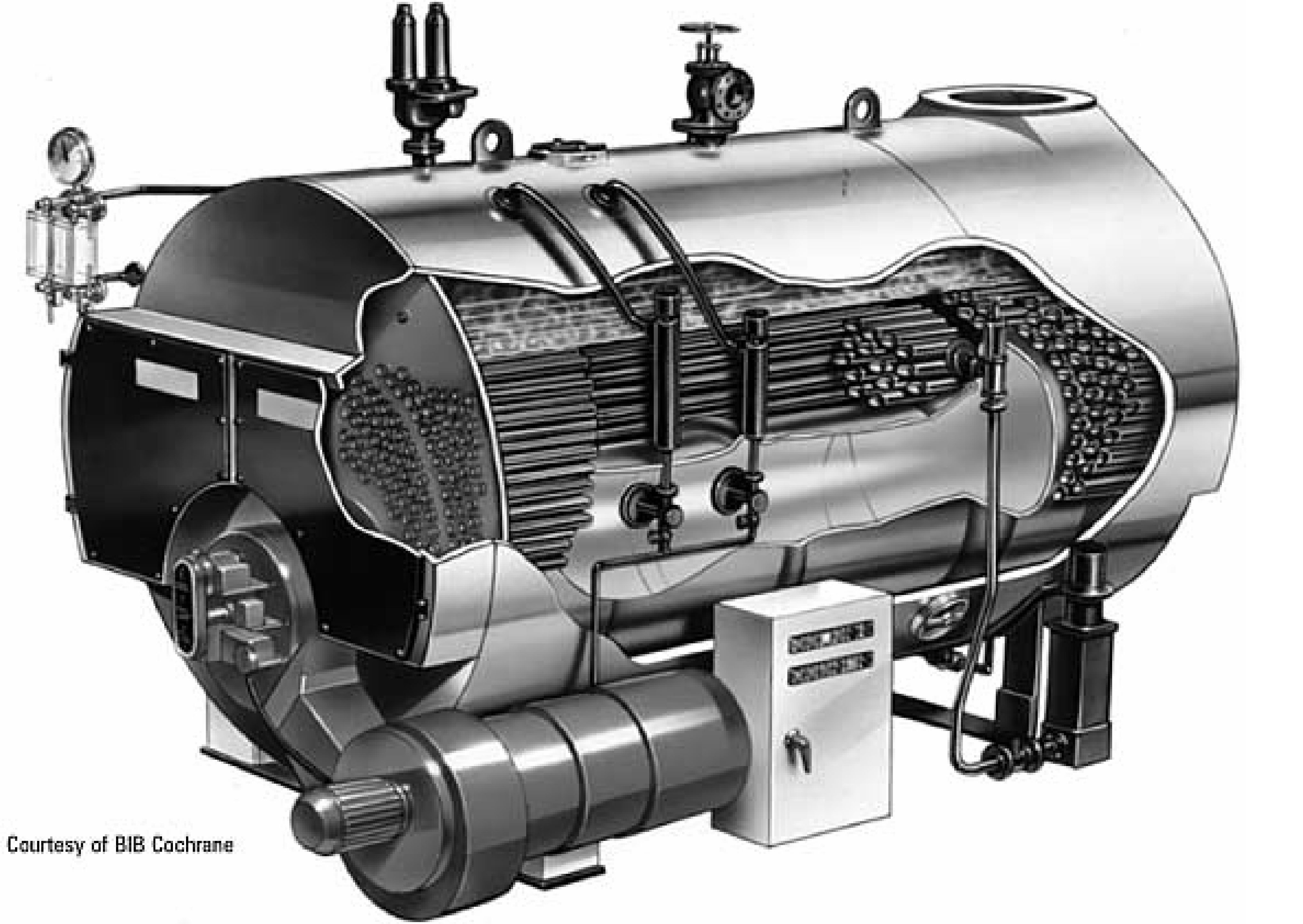
Basic diagram of a boiler

Why Three Passes?



Typical heat path through a smoke tube shell boiler

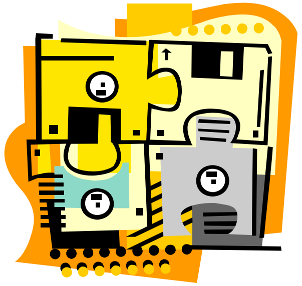
(Source: www.spiraxsarco.com/learn)



Modern packaged boiler

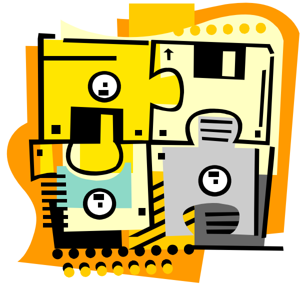
(Source: www.spiraxsarco.com/learn)

System components

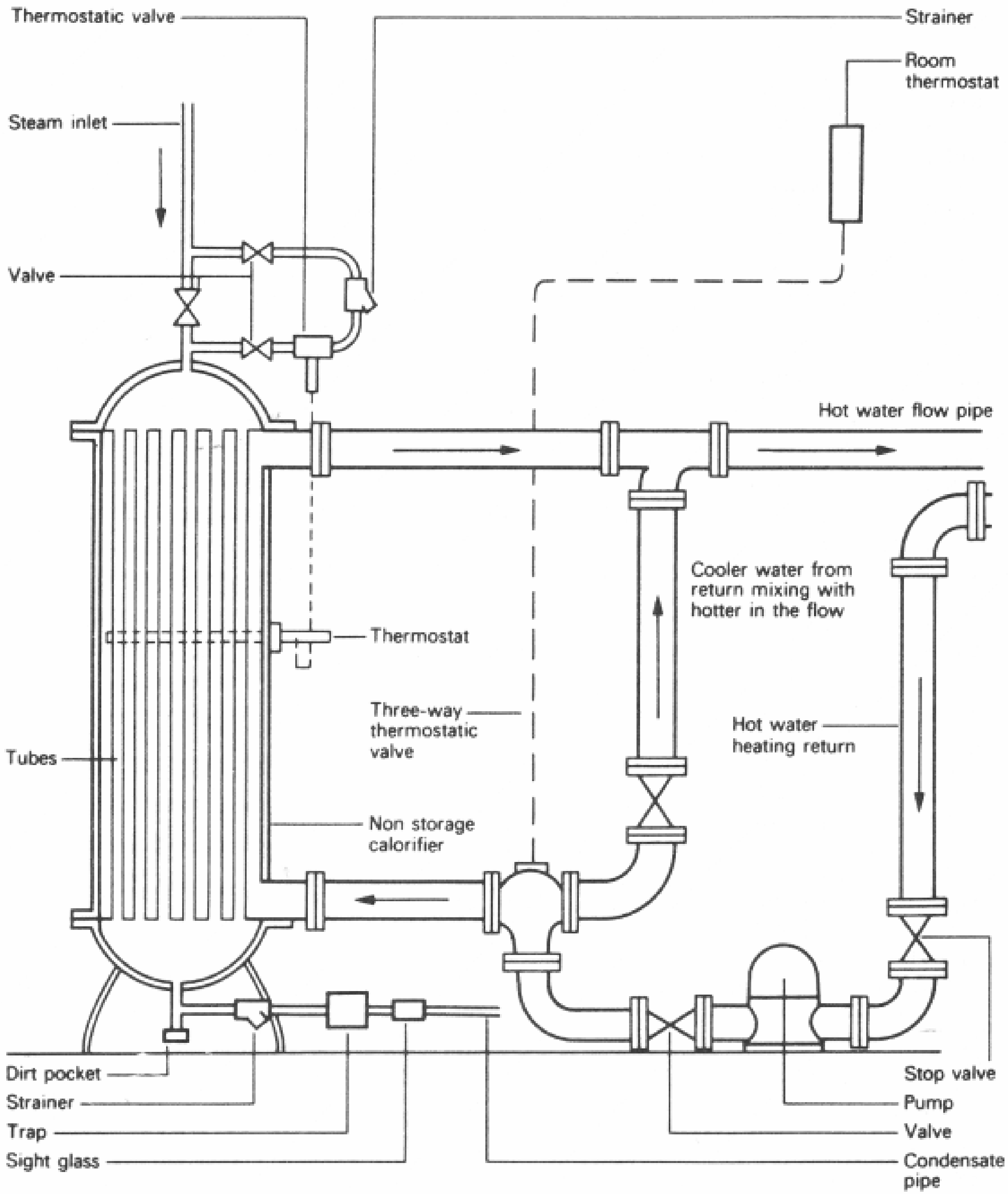


- Steam boilers (high and low pressure)
  - High-pressure >100 kPa
    - Reduce size of boiler & steam piping (due to density)
    - But decrease boiler efficiency
    - Good for heat load at long distance
  - Low-pressure <=100 kPa
    - Simpler in both design & operation
    - No pressure-reducing valves are required
    - Water chemical treatment less costly & complex

System components



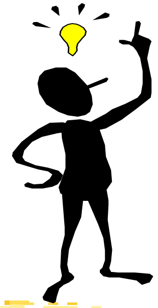
- Hot water boilers (high and low temperature)
  - High-temperature hot water (HTHW) boiler
    - Water at temp. > 121 ^{o}C or pressure > 1,100 kPa
    - Carry greater heat; reduce pumping & piping costs
  - Low-temperature hot water (LTHW) boiler
    - Water at temp. < 96 ^{o}C or pressure <= 1,100 kPa
- Calorifiers
  - Provide storage & allow heat exchange
  - Non-storage calorifiers can also be used for providing hot water for space heating



Non-storage type calorifier

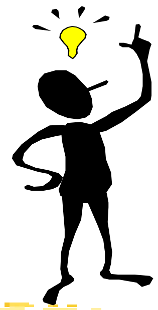
(Source: Hall, F. and Greeno, R., 2008. *Building Services Handbook*)

Design considerations

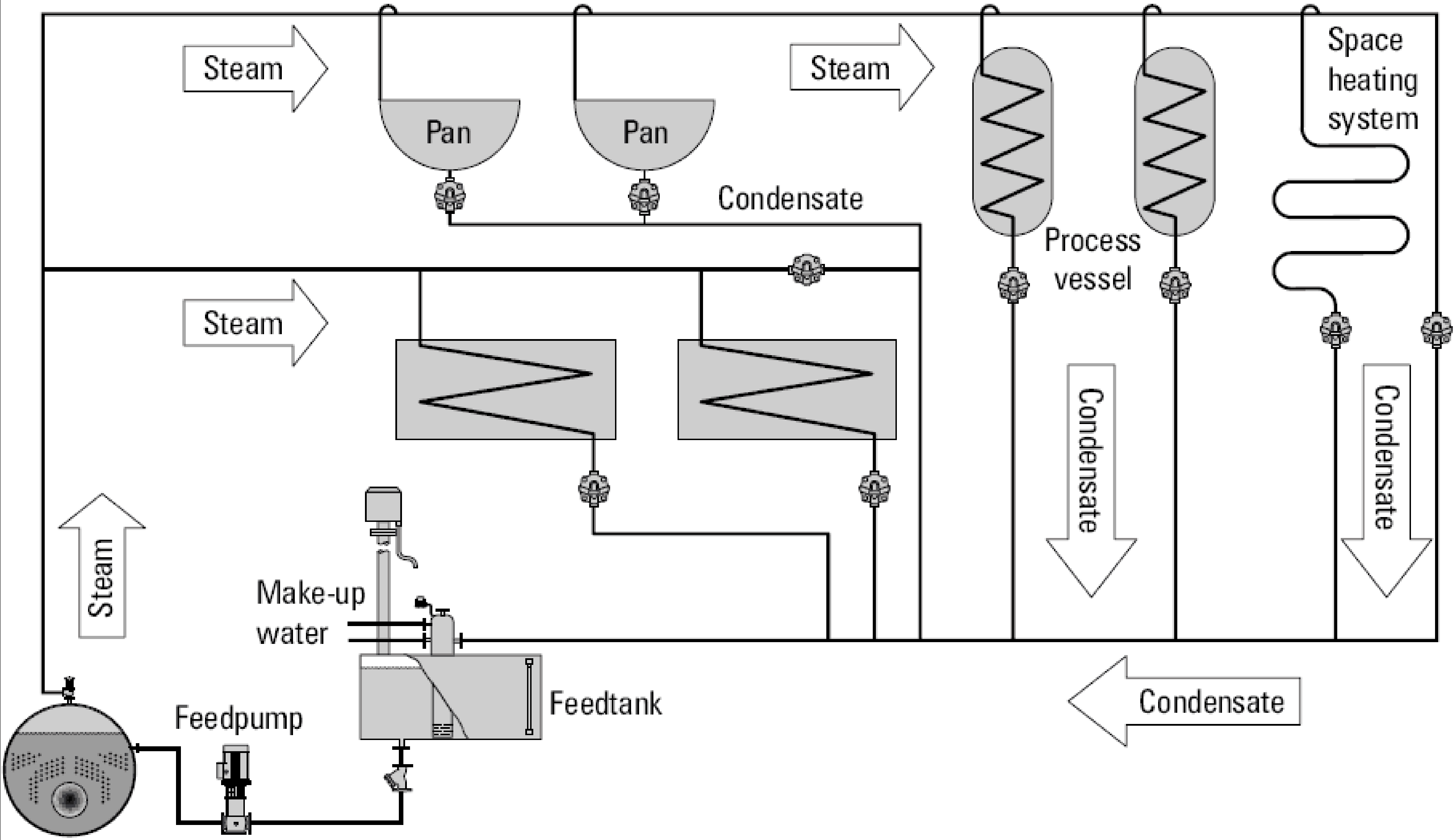


- Methods of estimating steam consumption
  - Calculation - By analysing the heat output on an item of plant using heat transfer equations
  - Measurement - By direct measurement, using flowmetering equipment (for an existing plant)
  - Thermal rating - design rating displayed on the equipment name-plate (in kW). The steam consumption required in kg/h will depend on the recommended steam pressure
    - Steam flow rate (kg/h) = (Load in kW x 3600) / h_{fg}

Design considerations



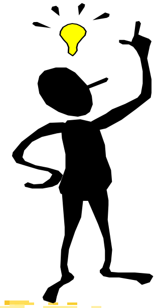
- Efficient steam distribution system:
  - Steam of the right quality and pressure is to be supplied, in the right quantity, to the steam using equipment
- Major issues of steam system design
  - Sufficient pressure difference
  - Pipeline velocity
  - Condensate return
  - Safety issues
  - Testing & commissioning
  - Operation & maintenance



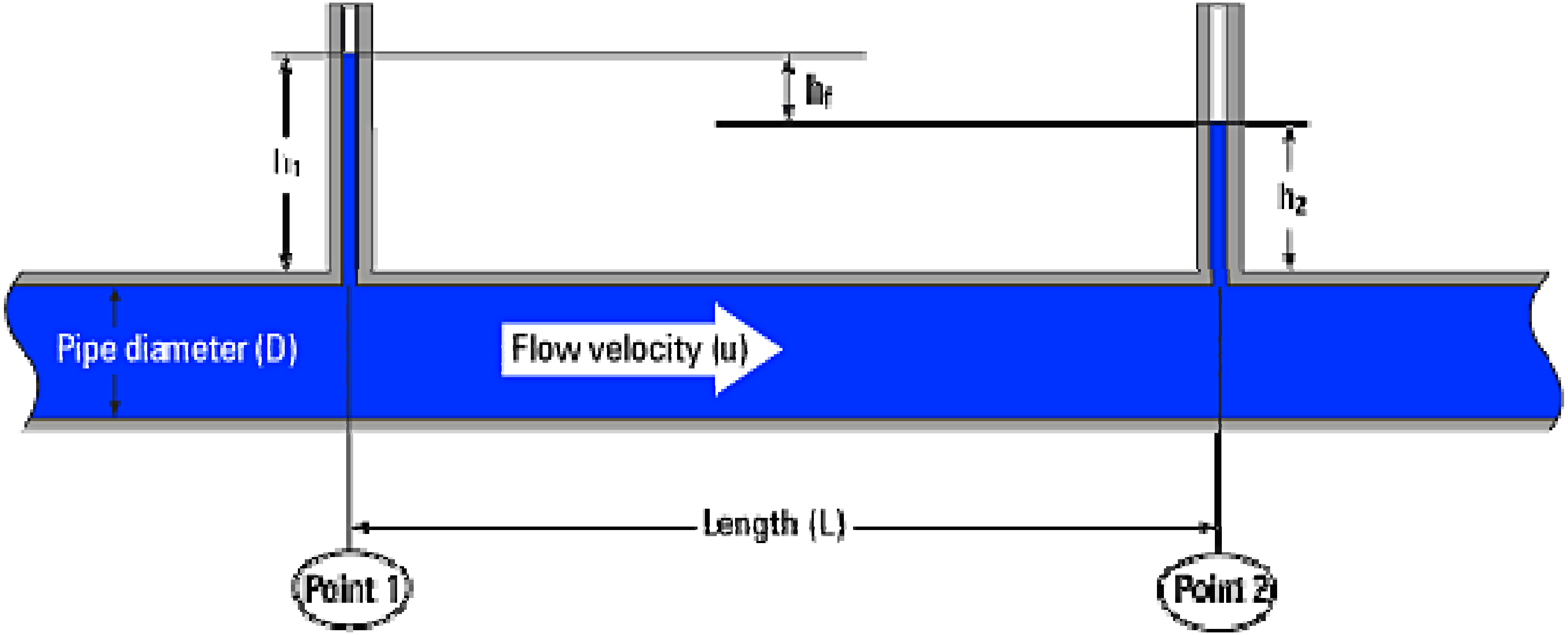
A typical basic steam circuit

(Source: www.spiraxsarco.com/learn)

Design considerations



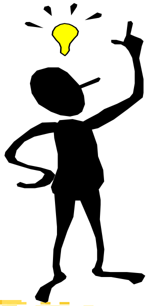
- Steam pipe sizing
  - Info. required:
    - Initial or final steam pressure, temperature & quality
    - Steam flow rate
    - Length of the pipe
    - Permissible pressure drop
    - Permissible velocity of flow
  - Detailed pipe sizing procedure & data can be found in the further reading materials



D'Arcy equation: $$h_f = \frac{f \cdot L \cdot u^2}{2 \cdot g \cdot D}$$

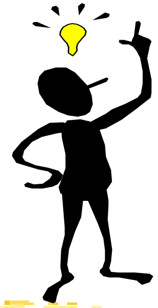
where h_f = head loss to friction (m)
f = friction factor (dimensionless)
L = length (m)
u = flow velocity (m/s)
g = gravitational constant (9.81 m/s^2)
D = pipe diameter (m)

Design considerations

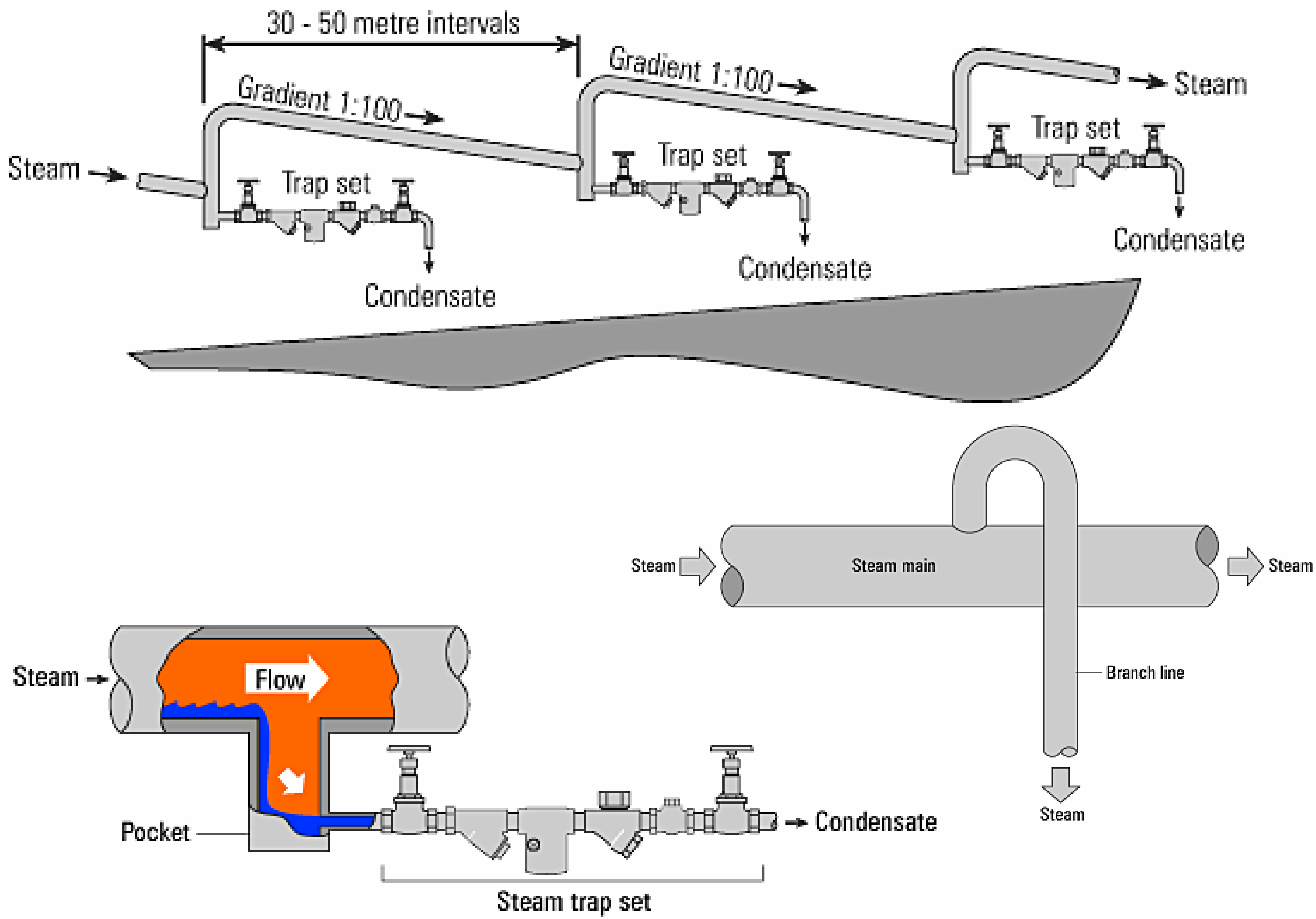


- Steam pipe sizing (cont'd)
  - Friction factor can be difficult to determine, especially for turbulent steam flow. As a result, some graphs, tables and slide rules are produced to relate steam pipe sizes to flowrates and pressure drops, e.g. the "pressure factor" method:
    - $F = (P_1 - P_2) / L$
      - F = pressure factor
      - P_1 = factor based on the inlet pressure
      - P_2 = factor based on the pressure at a distance of L metres
      - L = equivalent length of pipe (m)

Design considerations



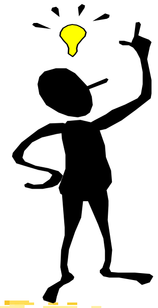
- Permissible pressure drop & flow velocity are affected by several factors:
  - Relative direction of steam & condensate flow within the same pipe
  - Whether the pipe is vertical, horizontal or sloping down in the direction of steam flow or against it
  - Steam quality & erosive action of wet steam on valve seats
  - Possibility of carry-over of water droplets from boiler steam spaces & flash steam vessels
  - Permissible noise level



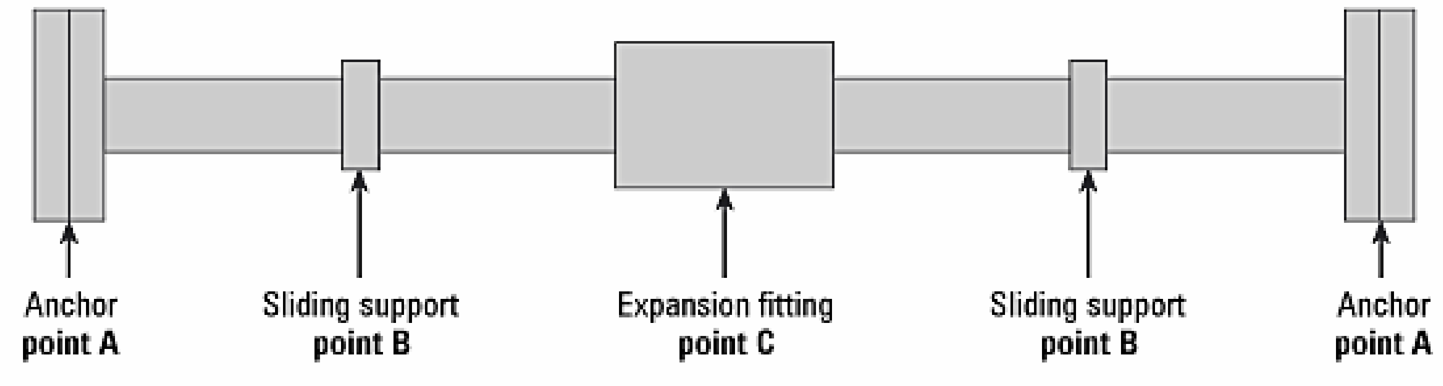
Typical steam main & branch line installation

(Source: www.spiraxsarco.com/learn)

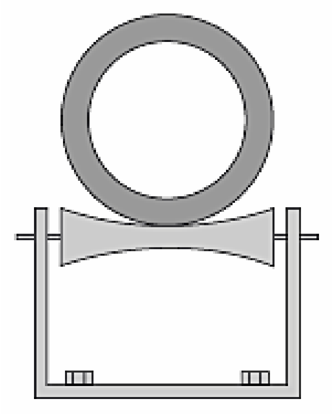
Design considerations



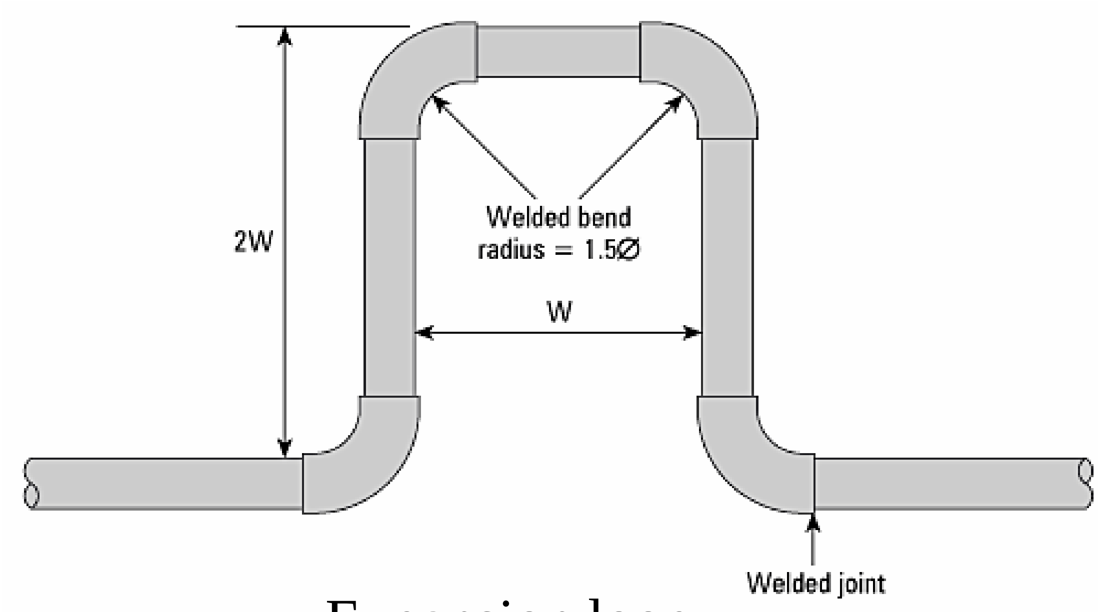
- Steam and condensate pipes
  - Analyse most economic thickness for pipe thermal insulation
  - Expansion joints or loops to relieve stresses due to expansion and contraction
  - Provided with a fall of about 1 in 300
  - Provided with drainage outlet at low points

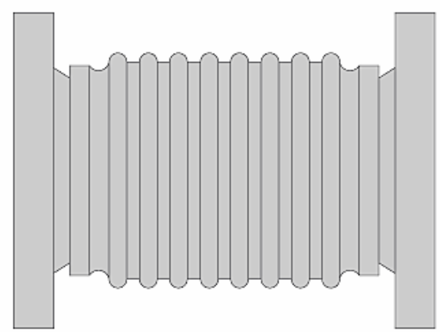


Pipeline with fixed point, variable anchor point and expansion fitting



Chair and roller



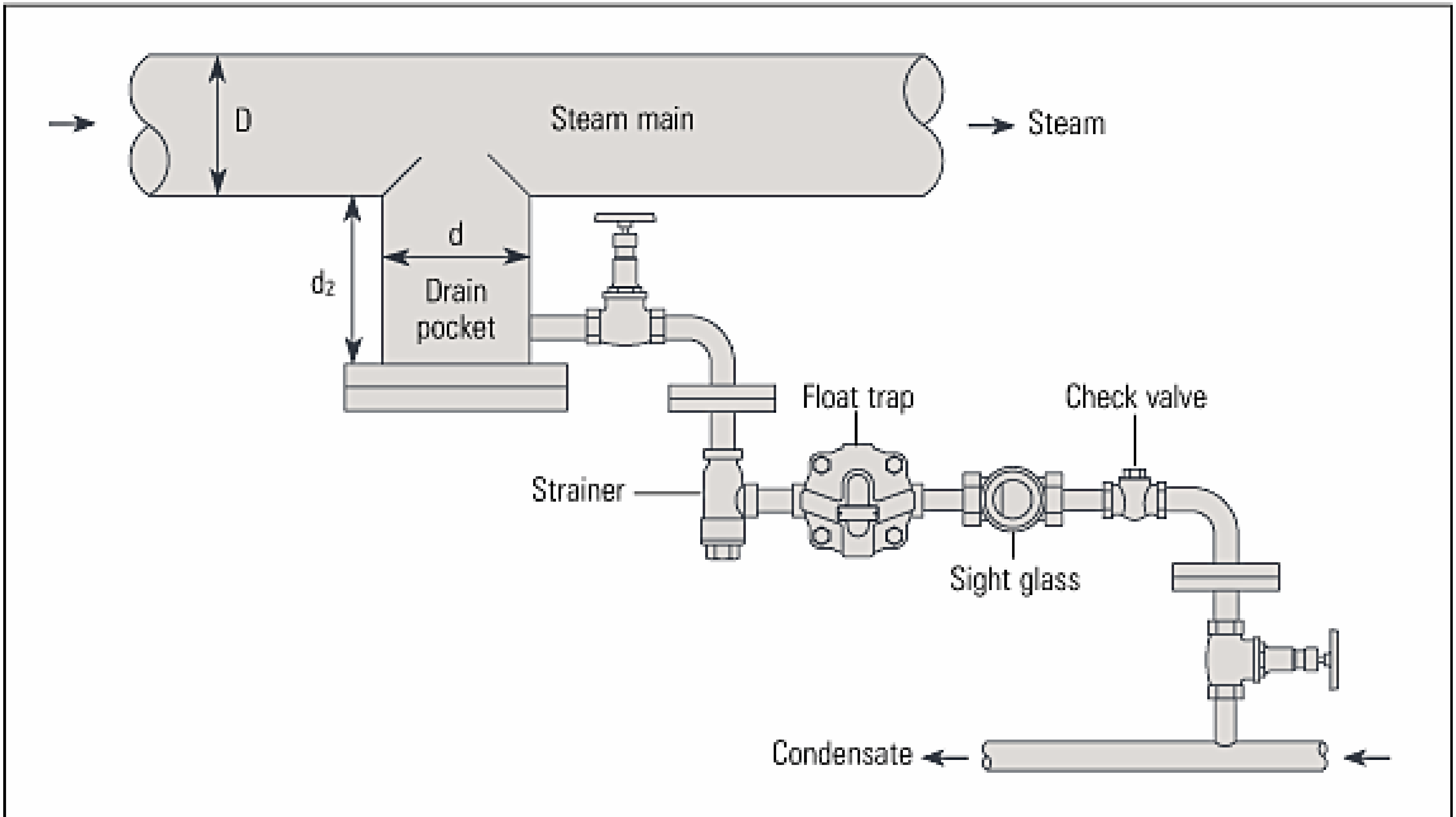


Expansion bellow

Expansion loop

Pipe expansion and support

(Source: www.spiraxsarco.com/learn)

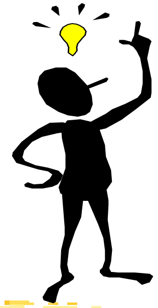


Main diameter D	Pocket diameter d_1	Pocket depth d_2
Up to 100 mm	$d_1 = D$	Minimum d_2 = 100 mm
125 mm - 200 mm	d_1 = 100 mm	Minimum d_2 = 150 mm
250 mm and above	$d_1 = D/2$	Minimum $d_2 = D$

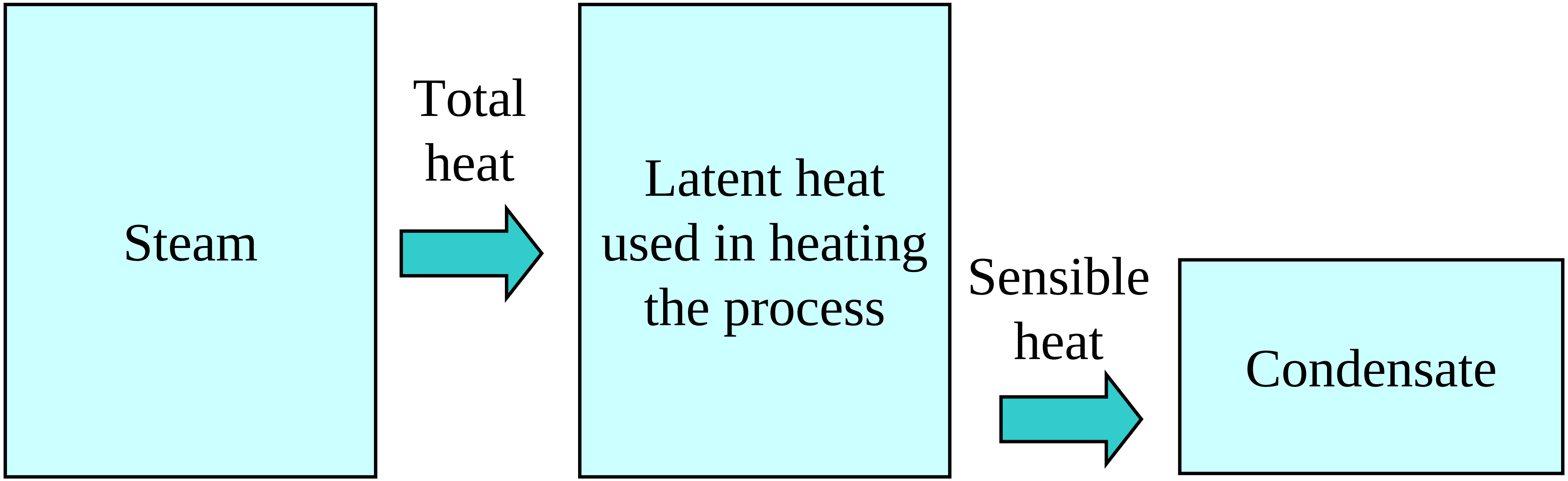
Ideal arrangement when draining a steam main

(Source: www.spiraxsarco.com/learn)

Design considerations



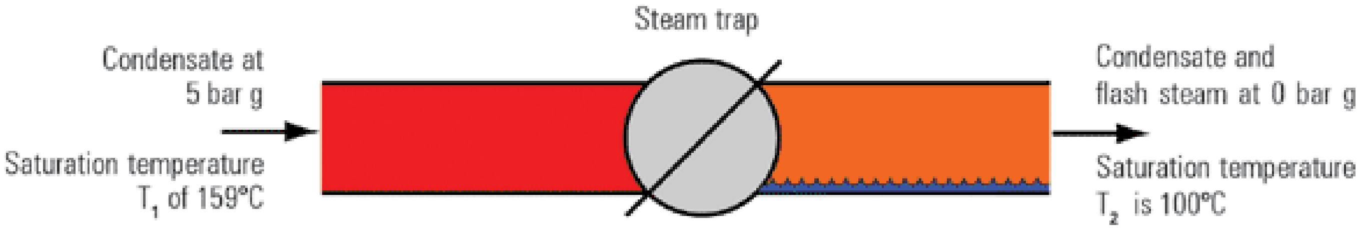
- Condensate recovery
  - Returned to the boiler for reuse as feed-water
    - Can increase heat efficiency of the cycle
    - Can reduce make-up water charges
    - Can reduce effluent charges and possible cooling costs
    - Can keep water-treatment problems to a minimum
    - Can reduce boiler blowdown (less energy is lost)
  - Start-up load: initial warm up of components
    - Highest steam consumption
  - Running load: fairly stable condition



After giving up its latent heat to heat the process, steam turns to water containing only sensible heat

(Source: www.spiraxsarco.com/learn)

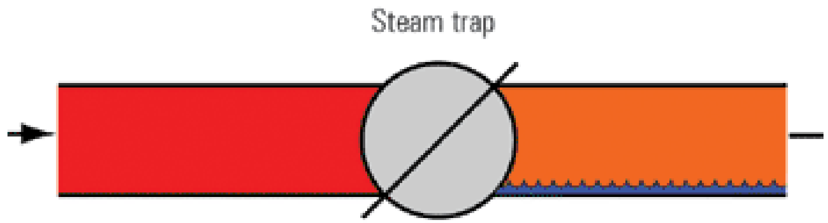
Design considerations



- Flash steam
  - Formed when high pressure condensate is discharged to a lower pressure
  - Should be collected and led to a flash vessel
- Other important issues:
  - Suitable collecting legs or reservoirs for condensate
  - Minimum pressure differential across the steam trap
  - Choice of steam trap type and size
  - Proper trap installation

Example: Calculate the amount of flash steam from condensate.

Condensate
at 7 bar g



Condensate
& flash steam
at 0 bar g

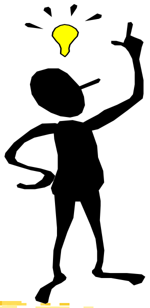
Hot condensate at 7 bar g has a heat content of 721 kJ/kg. When it is released to atmospheric pressure (0 bar g), each kilogram of water can only retain 419 kJ of heat.

The excess energy in each kg of the condensate is 721 - 419 = 302 kJ
This excess energy is available to evaporate some of the condensate into steam.

If the enthalpy of evaporation at atmospheric pressure is 2258 kJ/kg, then the percentage of flash steam evaporated is = 302 / 2258 x 100%

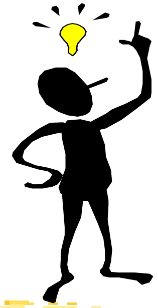
Thus, flash steam evaporated = **13.4%**

Design considerations



- Safety precautions [c.f. water heater at home]
  - 4 possible arrangements for burner safety control
    - Automatic recycling
    - Automatic non-recycling
    - Manual
    - Supervised manual
  - Purge and startup
  - Flame failure protection
  - Water level alarms and cut-off
  - Interlocks

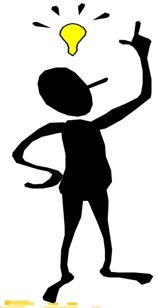
Design considerations



- Regulations in Hong Kong
  - Boilers and Pressure Vessels Ordinance (Cap 56)
    - Enforced by Boilers & Pressure Vessels Division, Labour Department
  - Relevant guide books and codes of practices
    - See Web Links
  - Accident cases of boilers and pressure vessels in Hong Kong
    - See reference book from Labour Department

Accidents did happen in HK before !

Design considerations



- Regulations in Hong Kong (cont'd)
  - Basic requirements
    - Engage an "Appointed Examiner"
    - Engrave registration number on boiler/pressure vessel
    - Acquire a "Certificate of Fitness"
    - Employ a qualified person with "Certificate of Competency" to operate the boiler / steam receiver
    - Notify the Authority of any accidents and defects
    - Notify the Authority of sale or hiring of boiler/pressure vessel

Further reading

- Spirax Sarco Learning Centre
  - www.spiraxsarco.com/learn/
  - Steam Engineering Tutorials
    - 1. Introduction
    - 2. Steam Engineering Principles and Heat Transfer
    - 3. The Boiler House
    - 10. Steam Distribution
    - 11. Steam Traps and Steam Trapping
    - 14. Condensate Recovery

Further reading

- Steam and Condensate [Engineering ToolBox] (web sites)
- www.engineeringtoolbox.com/steam-condensate-properties-t_28.html
  - Classification of Steam Heating Systems
  - Design of Steam Heating Systems
  - Entropy of Superheated Steam
  - Flash Steam
  - Properties of Saturated Steam - SI Units
  - Sizing Steam and Condensate Pipes
  - Steam Pipes – Sizing
  - Steam Thermodynamics
  - Steam Trap Selection Guide