Steam Systems (II)

Ir Dr. Sam C. M. Hui
Department of Mechanical Engineering
The University of Hong Kong
E-mail: cmhui@hku.hk

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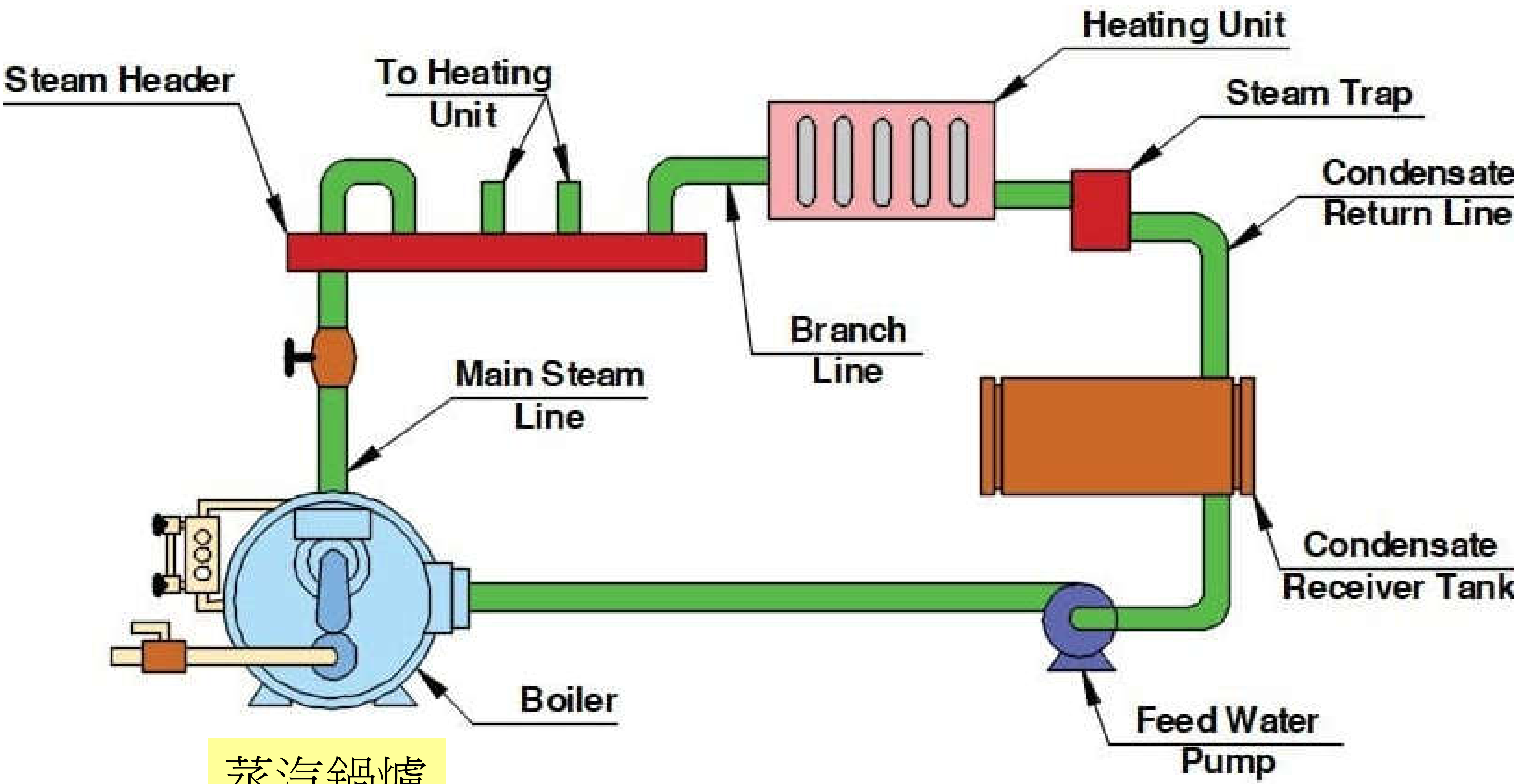
Contents

- Steam boilers
- Design considerations
- Steam pipeline
- Condensate recovery

Steam boilers

- 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

A steam boiler system and components



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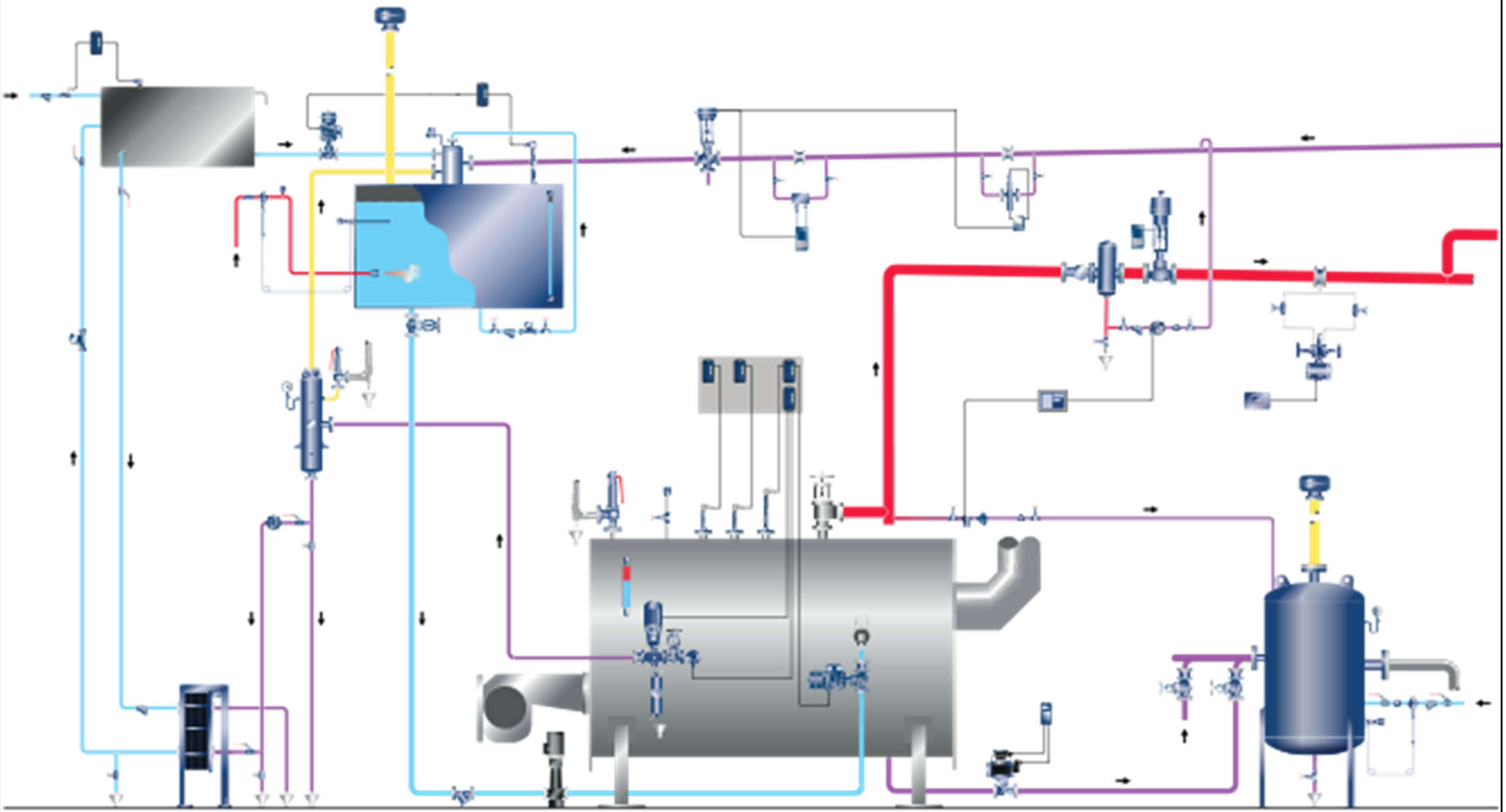
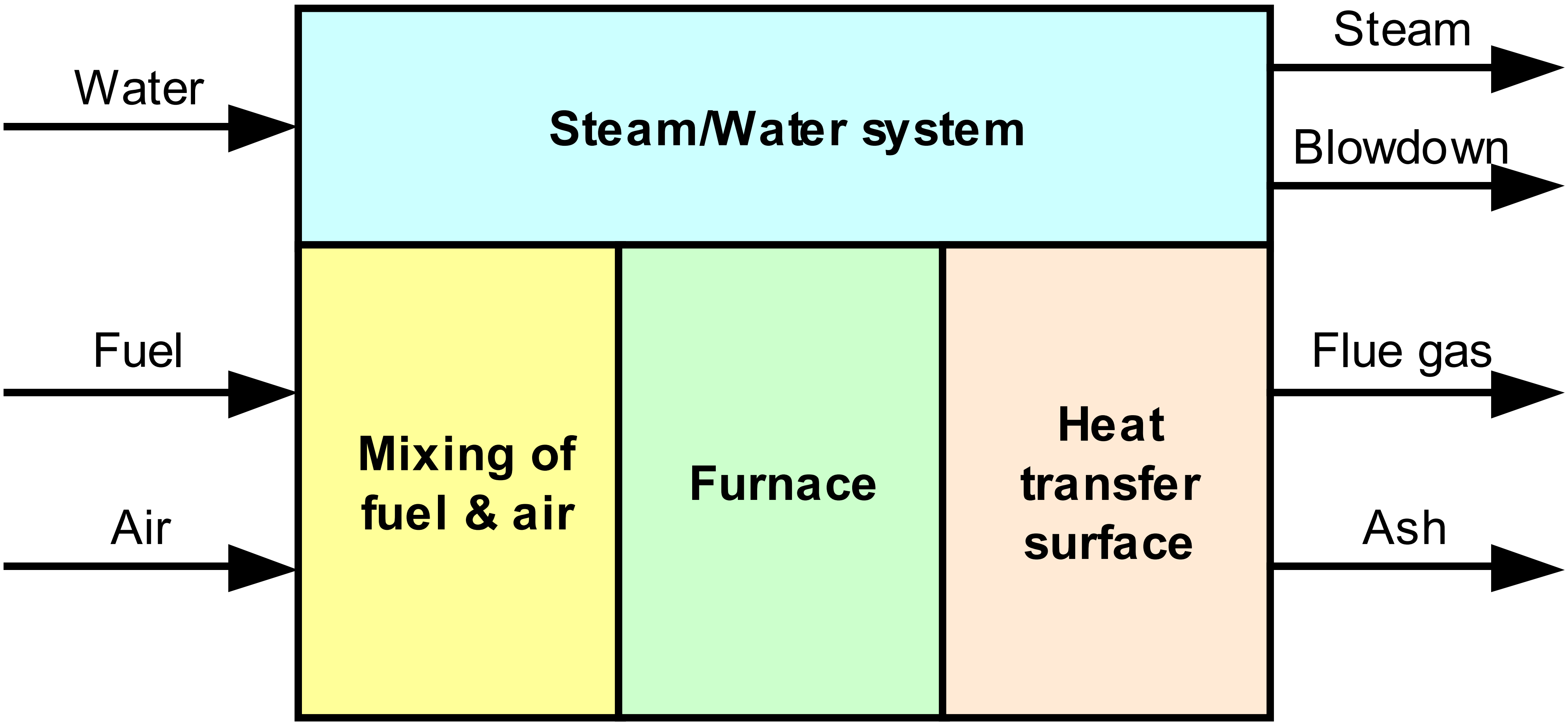
(Source: https://www.iqsdirectory.com/articles/boiler/steam-boilers.html)

A modern boiler house package



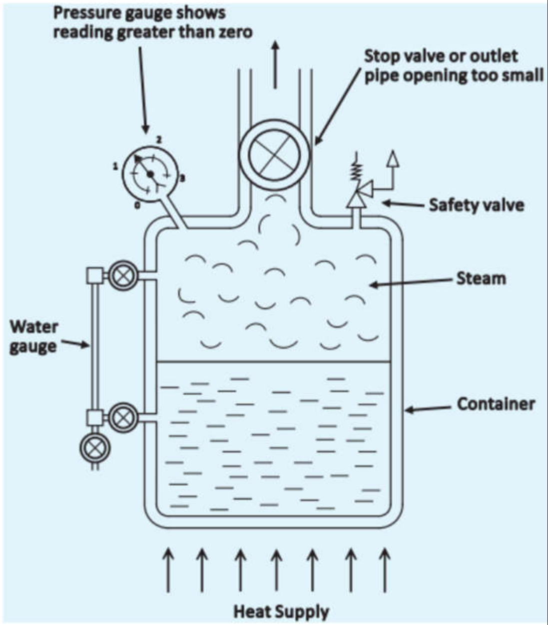
(Source: www.spiraxsarco.com)

Basic diagram of a boiler



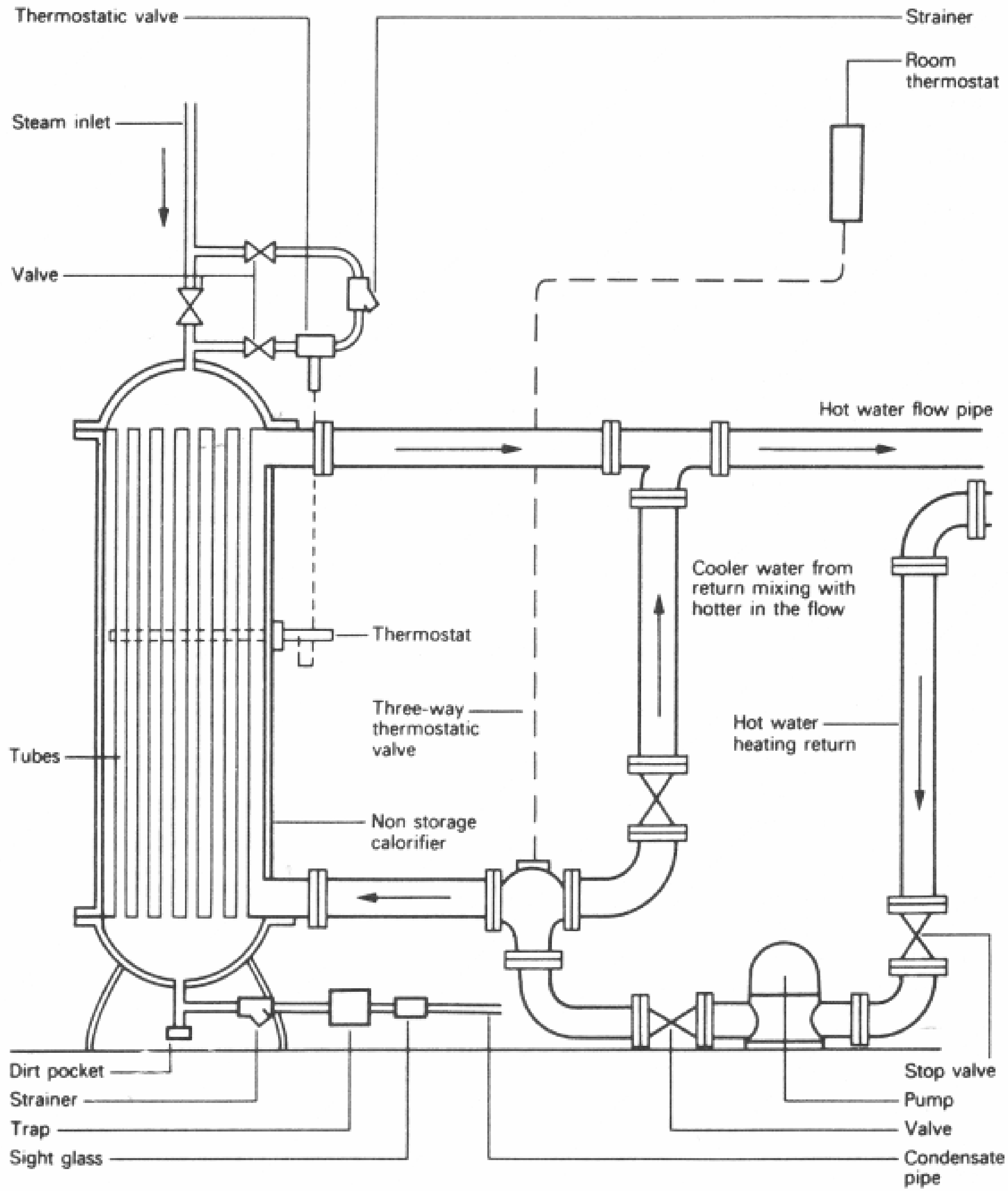
Steam boilers

- 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



Steam boilers

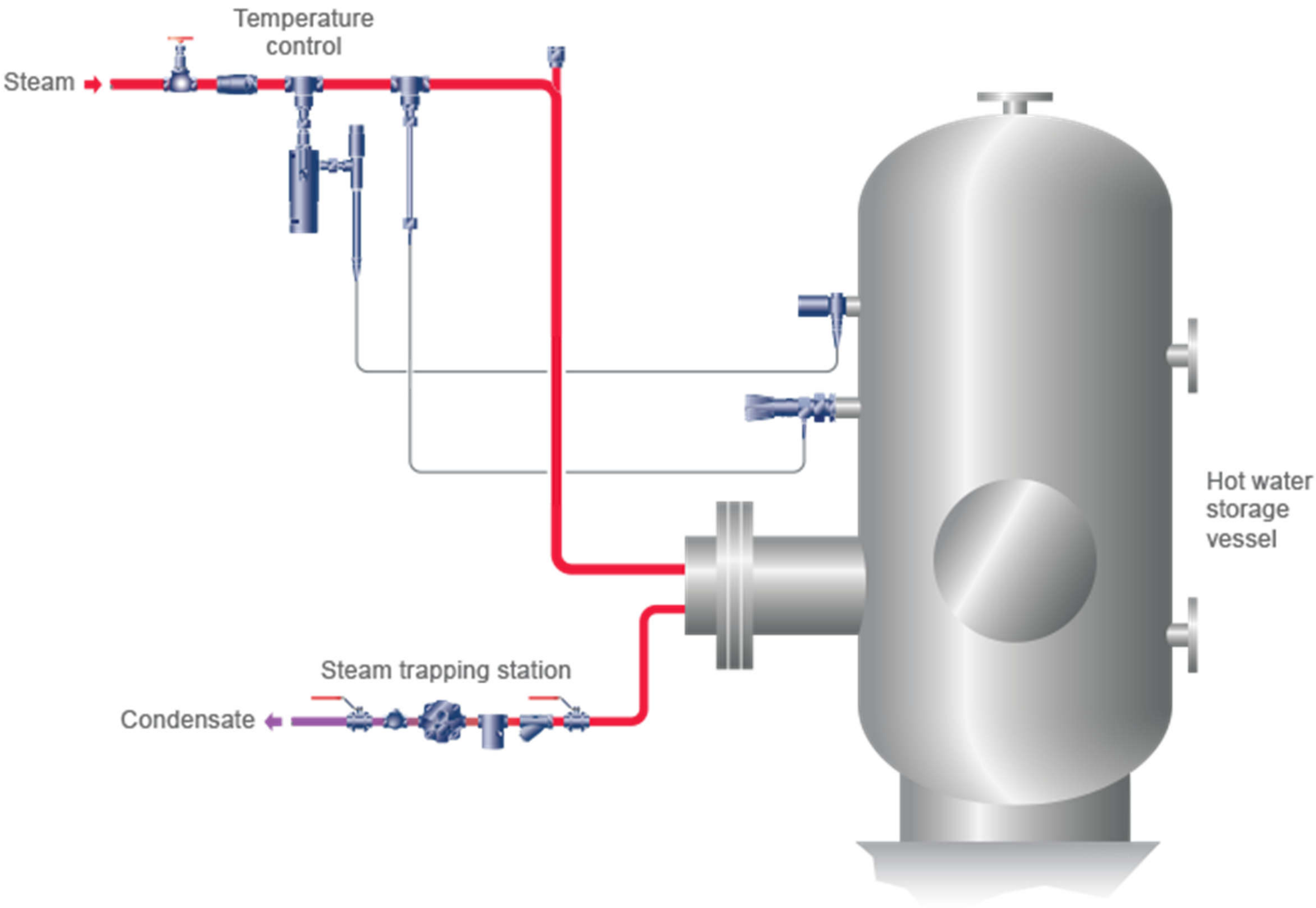
- Hot water boilers (high and low temperature)
  - High-temperature hot water (HTHW) boiler
    - Water at temp. > 121 ^{o}C or pressure > 1,100 kPa
    - Carry greater heat; reduce pumping & piping costs
  - Low-temperature hot water (LTHW) boiler
    - Water at temp. < 96 ^{o}C or pressure <= 1,100 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*)

A hot water storage calorifier installation

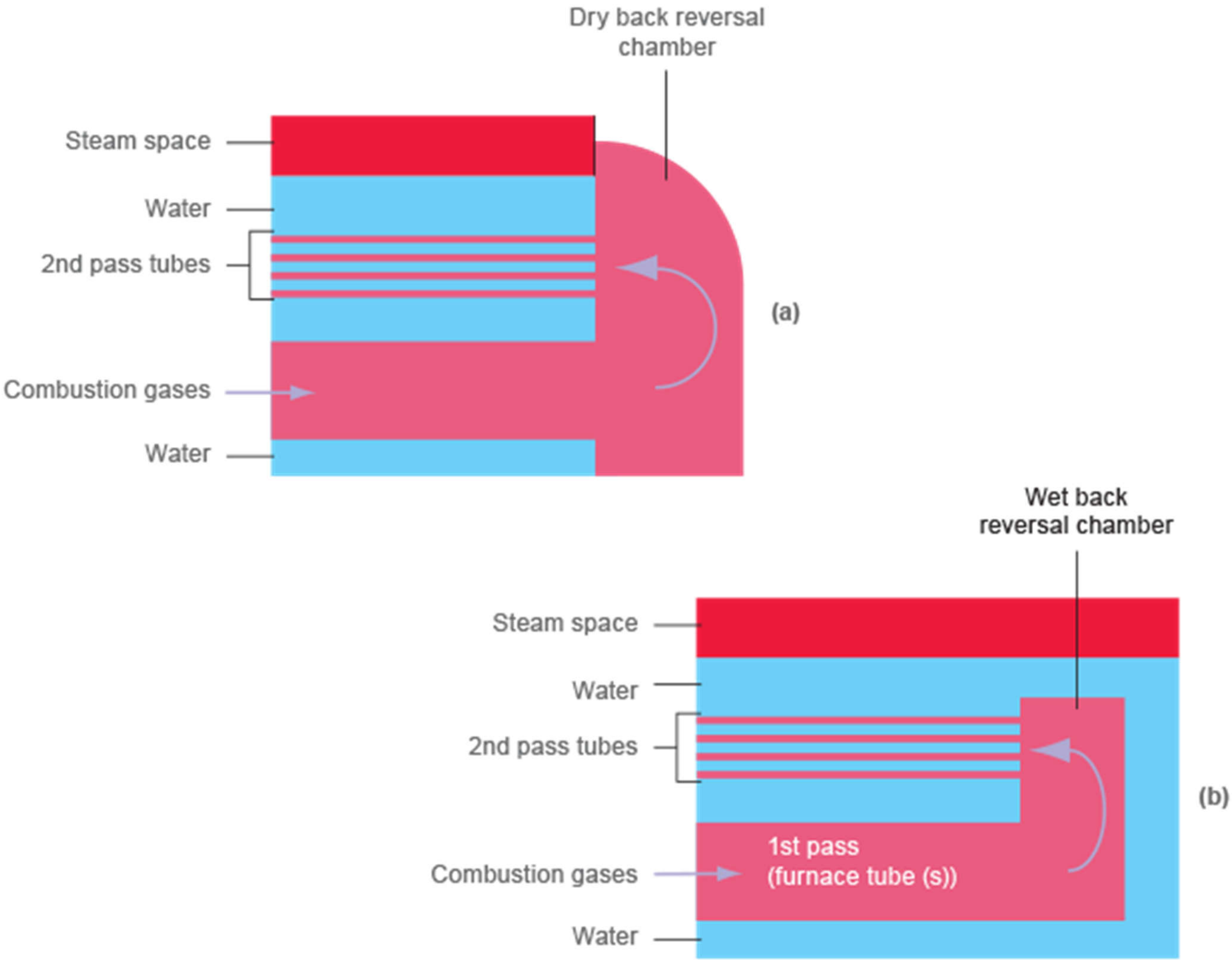


(Source: www.spiraxsarco.com)

Steam boilers

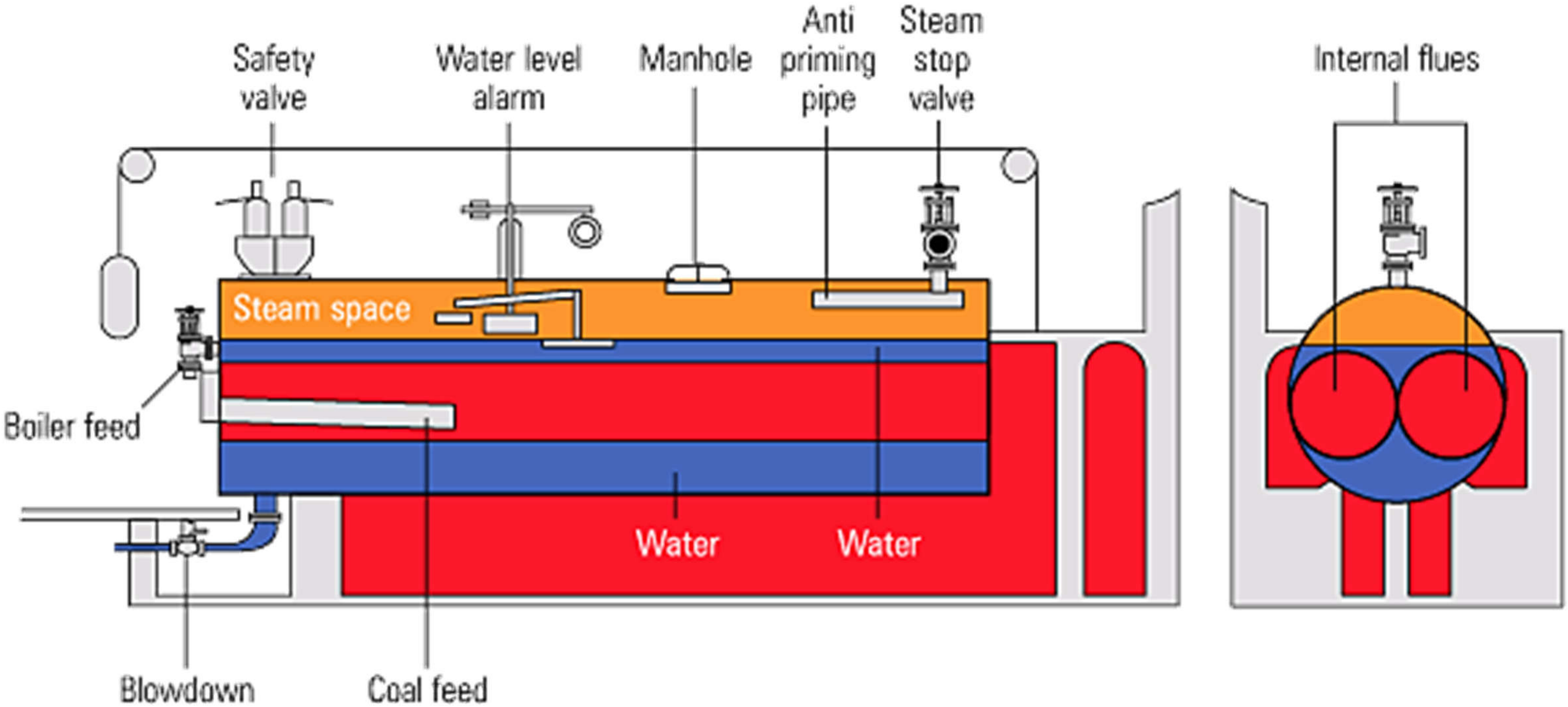
- Shell boilers
  - The heat transfer surfaces are all contained within a steel shell
  - Also known as 'fire tube' or 'smoke tube' boilers
    - Products of combustion pass through the boiler tubes, which in turn transfer heat to the boiler water
  - Typical types of shell boilers:
    - Lancashire boiler
    - Economic boiler (two-pass or three-pass)
    - Packaged boiler

Shell boiler – (a) dry back and (b) wet back configurations



(Source: www.spiraxsarco.com)

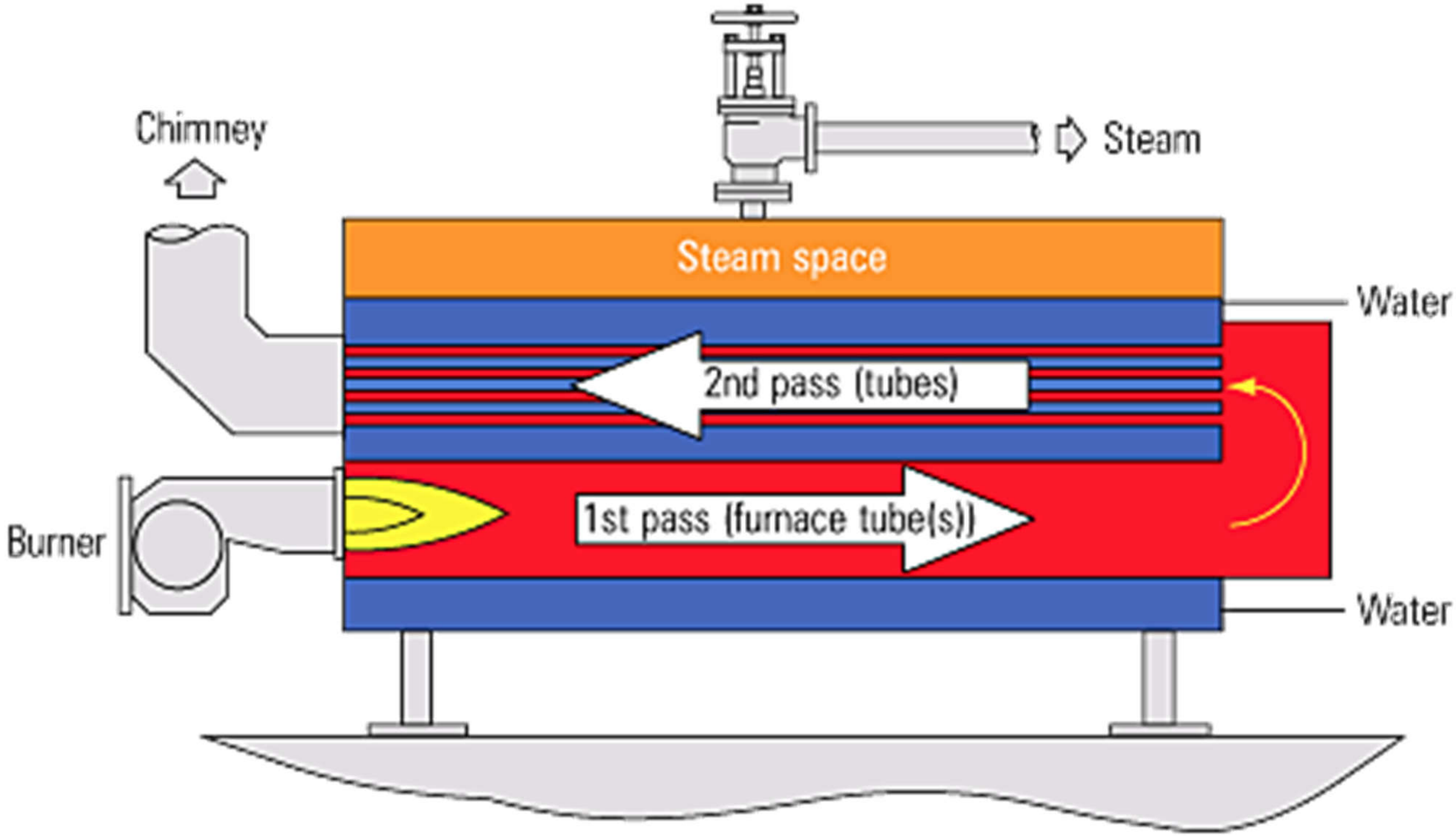
Lancashire boiler (first developed in 1844)



Capacity	Small	Large
Dimensions	5.5 m long x 2 m diameter	9 m long x 3 m diameter
Output	1 500 kg/h	6 500 kg/h
Pressure	Up to 12 bar g	up to 12 bar g

(Source: www.spiraxsarco.com)

Economic boiler (two-pass, dry back)

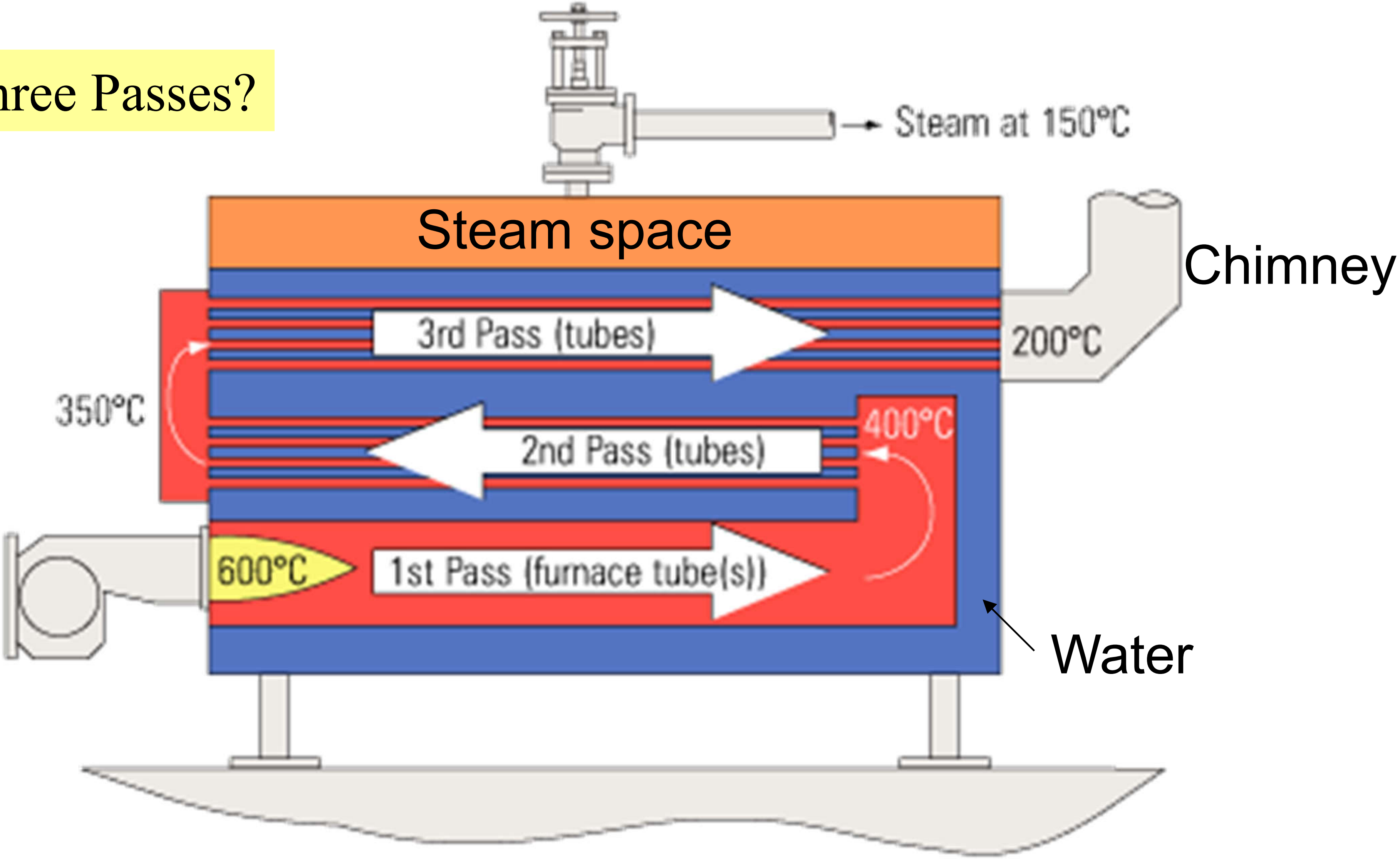


Capacity	Small	Large
Dimensions	3 m long x 1.7 m diameter	7 m long x 4 m diameter
Output	1 000 kg / h	15 000 kg / h
Pressure	Up to 17 bar g	up to 17 bar g

(Source: www.spiraxsarco.com)

Economic boiler (three-pass, wet back)

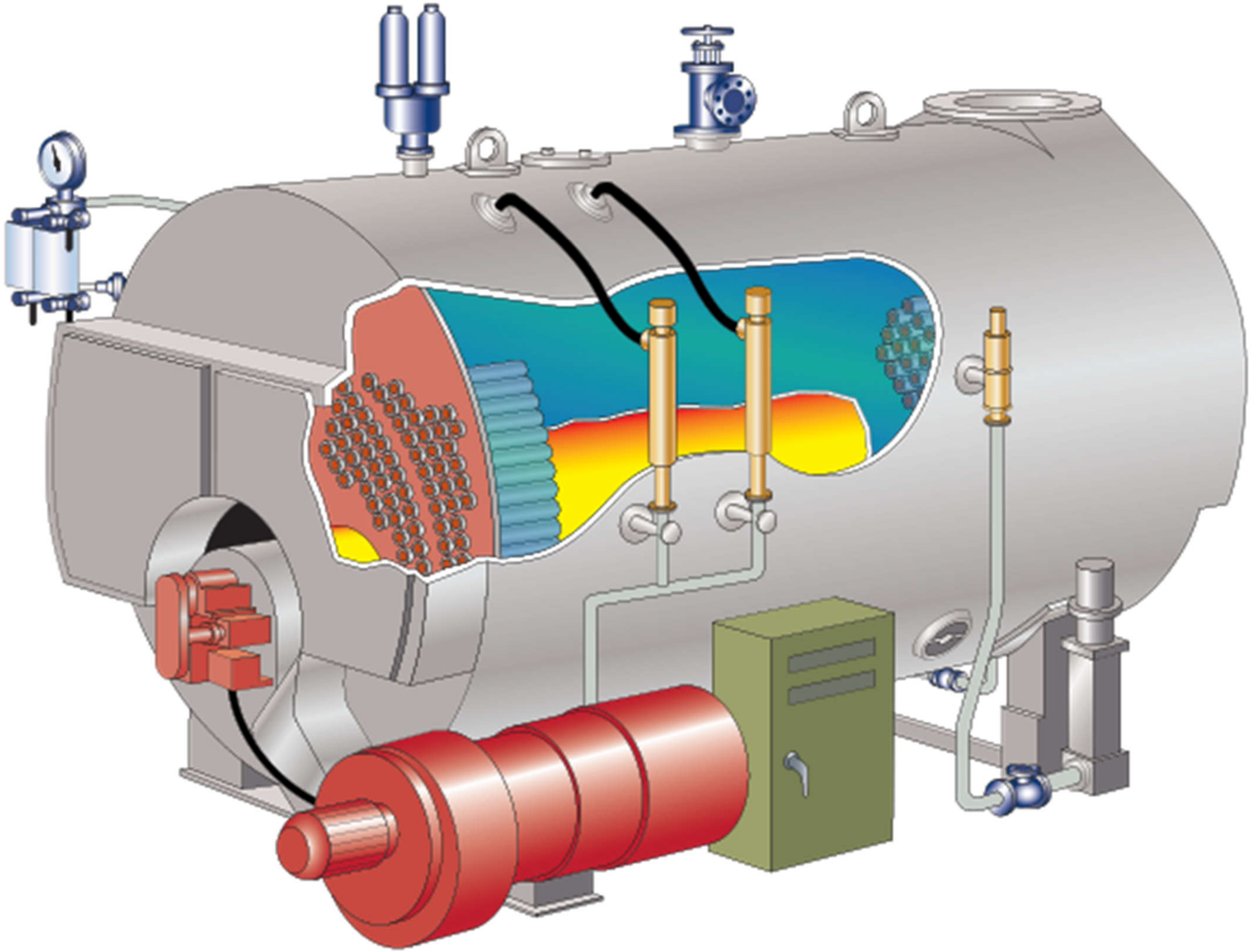
Why Three Passes?



	Area of tubes	Temperature	Proportion of total heat transfer
1st pass	11 m²	1 600°C	65%
2nd pass	43 m²	400°C	25%
3rd pass	46 m²	350°C	10%

(Source: www.spiraxsarco.com)

Modern package boiler



(Source: www.spiraxsarco.com)

Comparison of 5,000 kg/h boilers

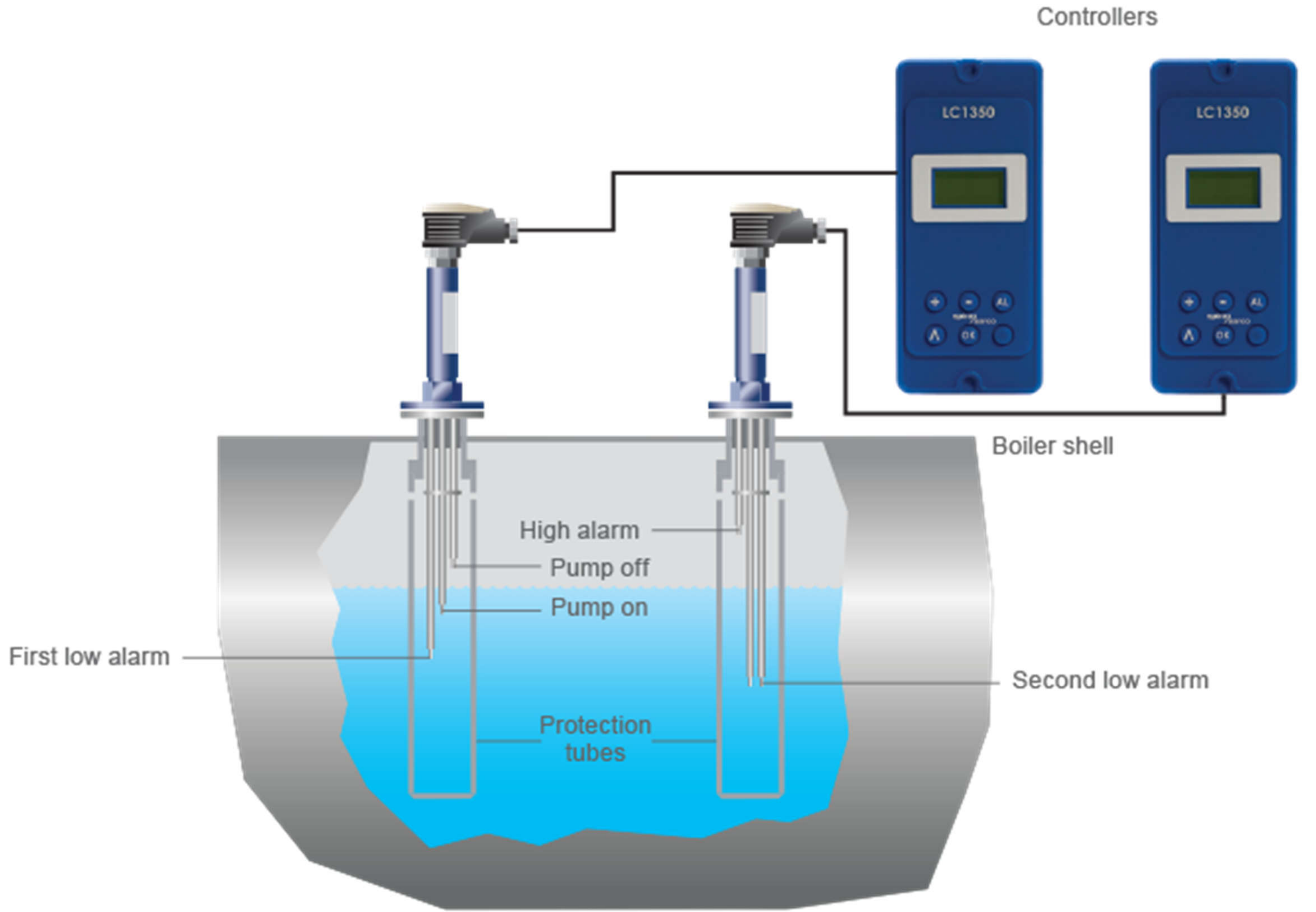
Boiler type	Fuel	Length (m)	Diameter (m)	Efficiency (%)	Volumetric heat release (kW/m^3)	Steam release rate from water Surface (kg/m^2 s)
Lancashire	Coal	9.0	2.75	74	340	0.07
Economic	Coal	6.0	3.00	76	730	0.12
Packaged	Oil	3.9	2.50	82	2 330	0.20
Packaged	Gas	3.9	2.50	80	2 600	0.20

Boiler related standards (UK)

BS 2790	Specification for design and manufacture of shell boilers of welded construction.
BS 1113	Specification for design and manufacture of water-tube steam generating plant.
EN ISO 4126	Specification for safety valves for steam and hot water.
BS 759 Part 1	Specification for valves, mountings and fittings for steam boilers above 1 bar g.

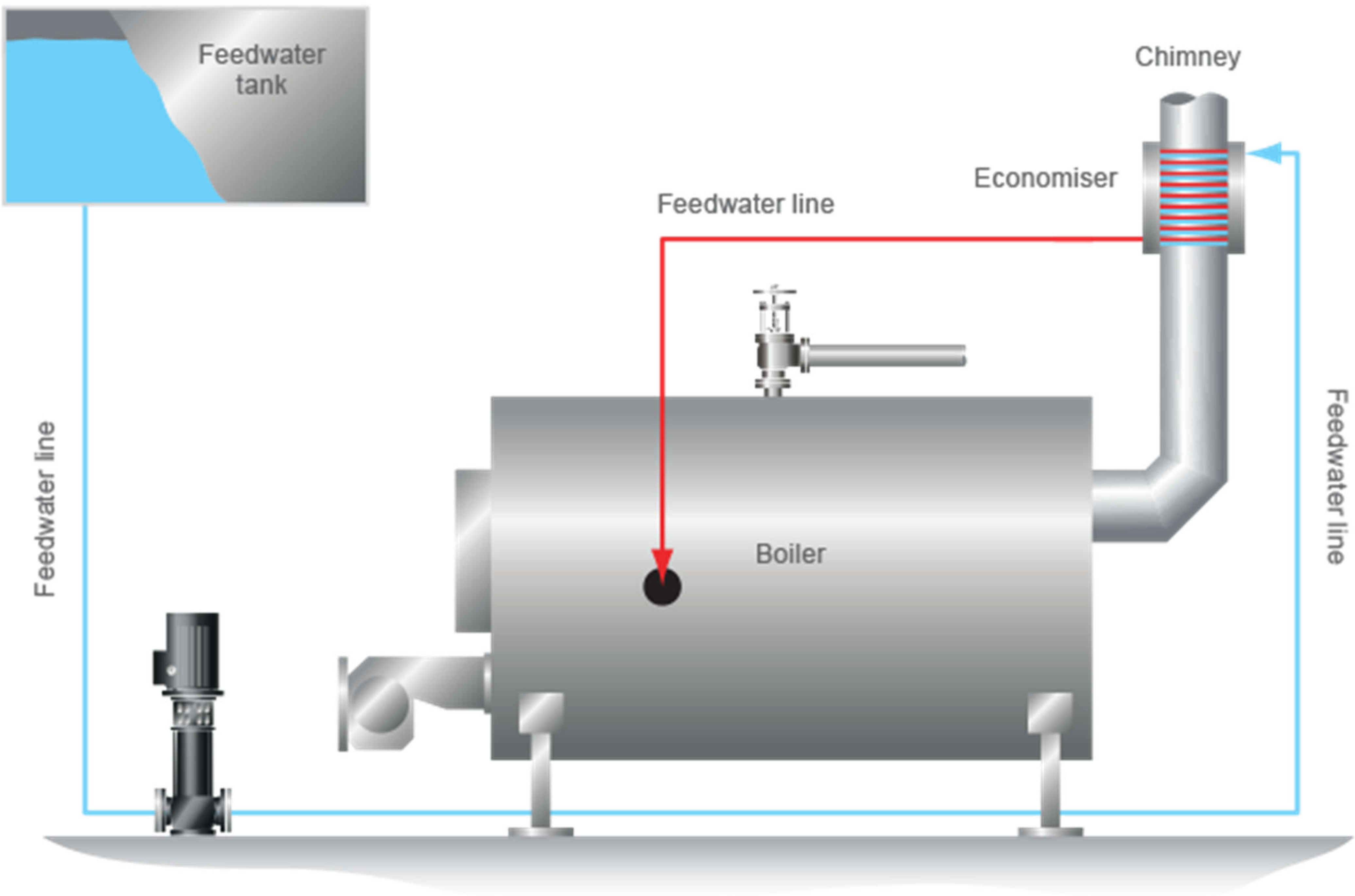
(Source: www.spiraxsarco.com)

Typical boiler level control/alarm configuration



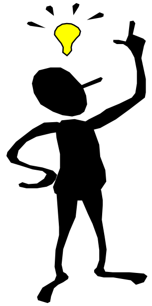
(Source: www.spiraxsarco.com)

A shell boiler with an economizer (for waste heat recovery)



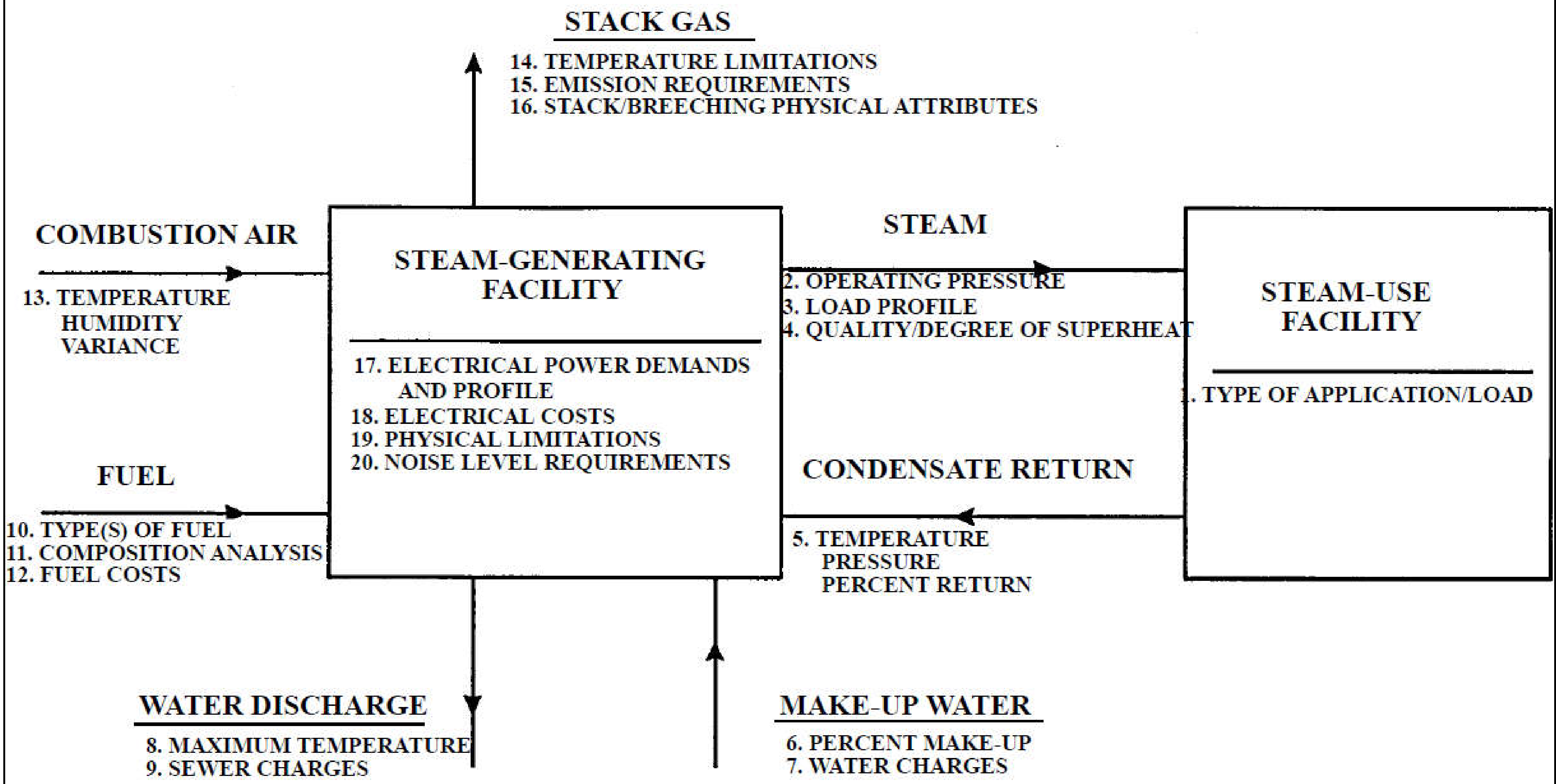
(Source: www.spiraxsarco.com)

Design Considerations



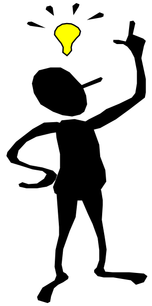
- Design issues of steam-generating facility:
  - Type of application/load
    - Such as heating/cooling, process or combination
  - Operating conditions, requirements and constraints
    - Pressure, load profile & characteristics, steam quality, degree of superheat, condensate conditions
  - Facility requirements and limitations
    - Fuel type, stack gas, boiler room space, noise control
  - Codes and standards
  - Other government and local requirements

Summary of application/energy-use audit items for steam systems



(Source: Cleaver-Brooks http://www.cleaverbrooks.com/)

Design Considerations



- Methods of estimating steam consumption
  - To determine steam demand of the plant:
    - Calculation - By analysing the heat output on an item of plant using heat transfer equations
    - Measurement - Steam consumption may be determined by direct measurement, using flowmetering equipment
    - Thermal rating or design rating - It is often displayed on the name-plate of an individual item of plant, as provided by the manufacturers
  - For flow and non-flow applications. Including warm-up, heat losses and running load

Typical heat exchanger manufacturer's name-plate

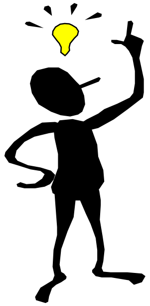
XYZ Heat Exchanger Company

Serial Number		HX12345	
Type and Size		AB12345	
Pressures		Design	Test
	Shell	10.0 bar g	15.0 bar g
	Tube	17.0 bar g	25.5 bar g
	NWP	14.0 bar g	
Main shell thickness		5 mm	
Date of hydraulic test		1985	
Design code - shell		BS 853	
Design code - tubes		BS 853	
Design rating		250 kW	

$$\text{Steam flowrate (kg/h)} = \frac{\text{Load in kW} \times 3\,600}{h_{fg} \text{ at operating pressure}}$$

(Source: www.spiraxsarco.com)

Design Considerations



- Steam Engineering Principles and Heat Transfer (Learn about steam)
  - https://www.spiraxsarco.com/Learn-about-steam
  - 6. Methods of Estimating Steam Consumption
  - 9. Energy consumption of tanks and vats
  - 10. Heating with coils and jackets
  - 11. Heating vats and tanks by steam injection
  - 12. Steam Consumption of Pipes and Air Heaters
  - 13. Steam Consumption of Heat Exchangers
  - 14. Steam Consumption of Plant Items

Design Considerations

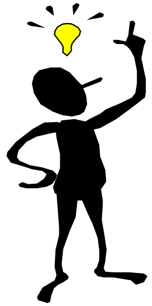
- Safety precautions [c.f. water heater at home]
  - 4 possible arrangements for burner safety control
    - Automatic recycling
    - Automatic non-recycling
    - Manual
    - Supervised manual
  - Purge and startup
  - Flame failure protection
  - Water level alarms and cut-off
  - Interlocks

Design Considerations

- Regulations in Hong Kong
  - Boilers and Pressure Vessels Ordinance (Cap 56)
    - Enforced by Boilers & Pressure Vessels Division, Labour Department
    - Fossil-fuel boilers, electric steam boilers
  - Relevant guide books and codes of practices
    - https://www.labour.gov.hk/eng/public/content2_10.htm
  - Accidents of boilers and pressure vessels in HK
    - See reference books from Labour Department

Accidents did happen in HK before !

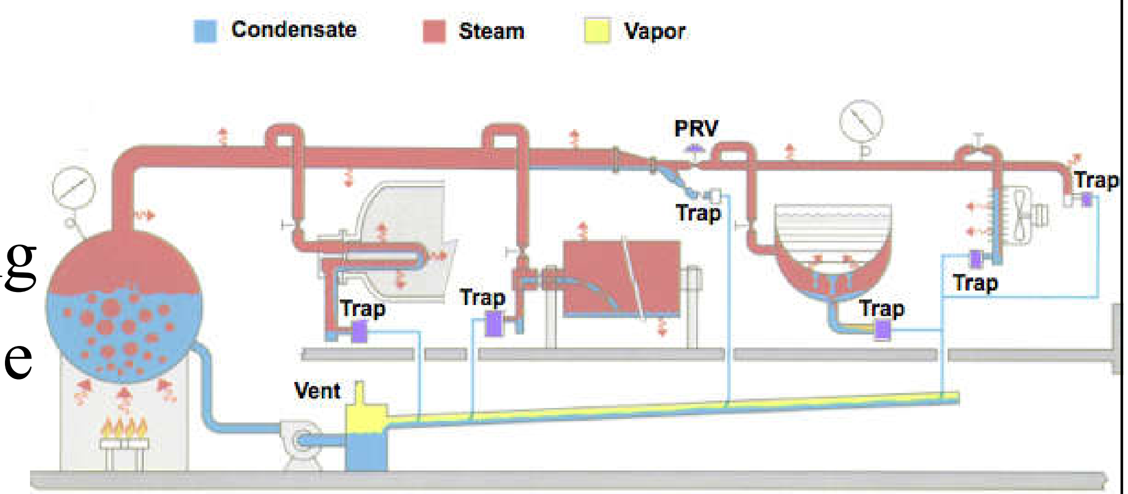
Design Considerations



- Regulations in Hong Kong (cont'd)
  - Basic requirements:
    - Registration of boilers/pressure vessels
    - Employ a qualified person with "Certificate of Competency" to operate the boiler / steam receiver
    - Engage an "Appointed Examiner"
    - Periodic examination & "Certificate of Fitness"
    - Notify the Authority of sale, hiring or removal of the boiler/pressure vessel
    - Notify the Authority of any accidents and defects
    - Examination after extensive repair

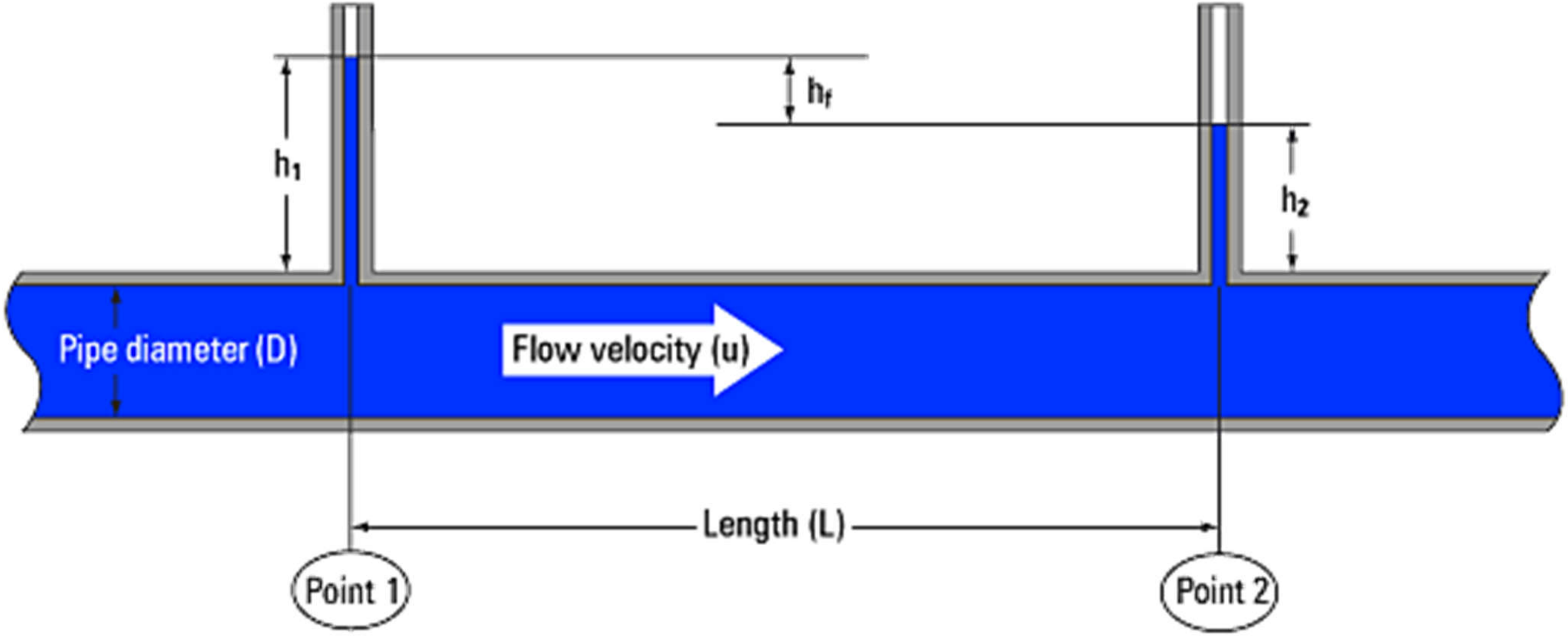
Steam pipeline

- 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



Steam pipeline

- 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
  - The pipe size may be selected on the basis of:
    - Velocity (usually pipes less than 50 m in length)
    - Pressure drop (should not normally exceed 0.1 bar/50 m)



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)

Steam pipeline

- 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)

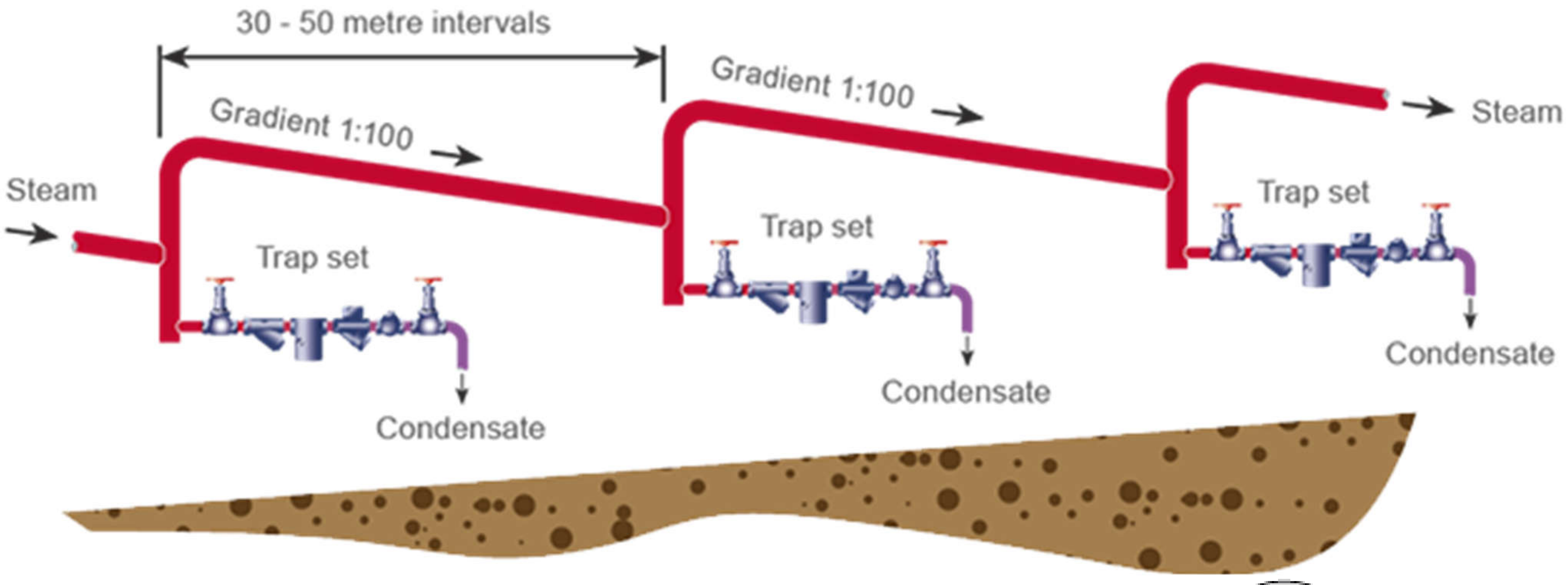
Steam pipeline

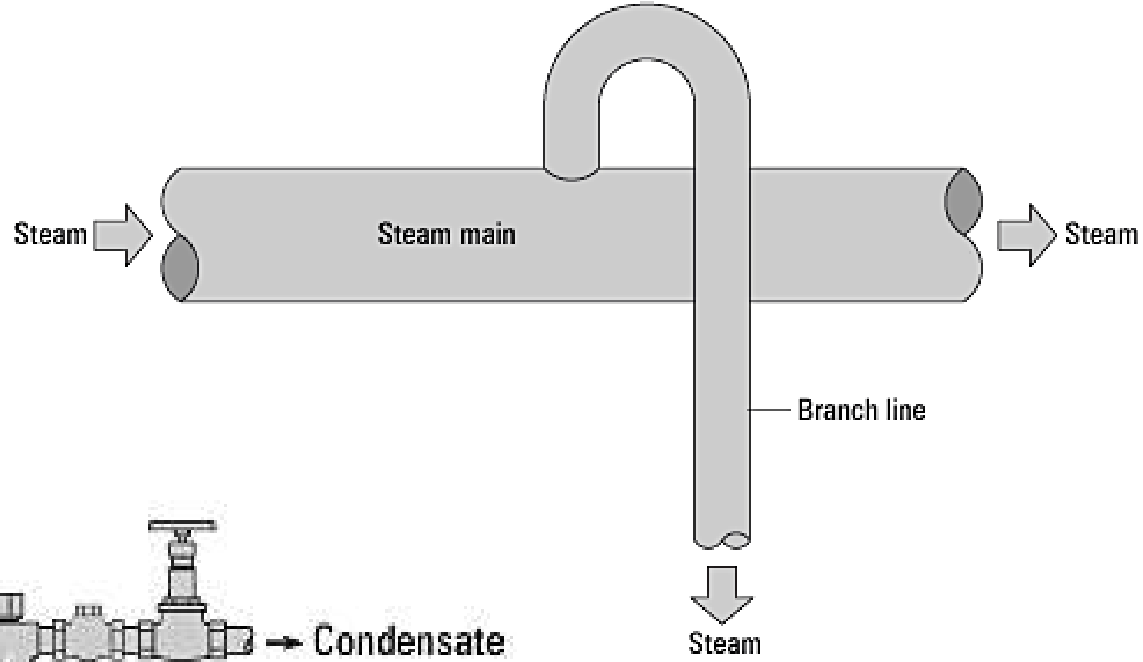
- Permissible pressure drop & flow velocity are affected by several factors:
  - Relative direction of steam & condensate flow within the same pipe
  - Whether the pipe is vertical, horizontal or sloping down in the direction of steam flow or against it
  - Steam quality & erosive action of wet steam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

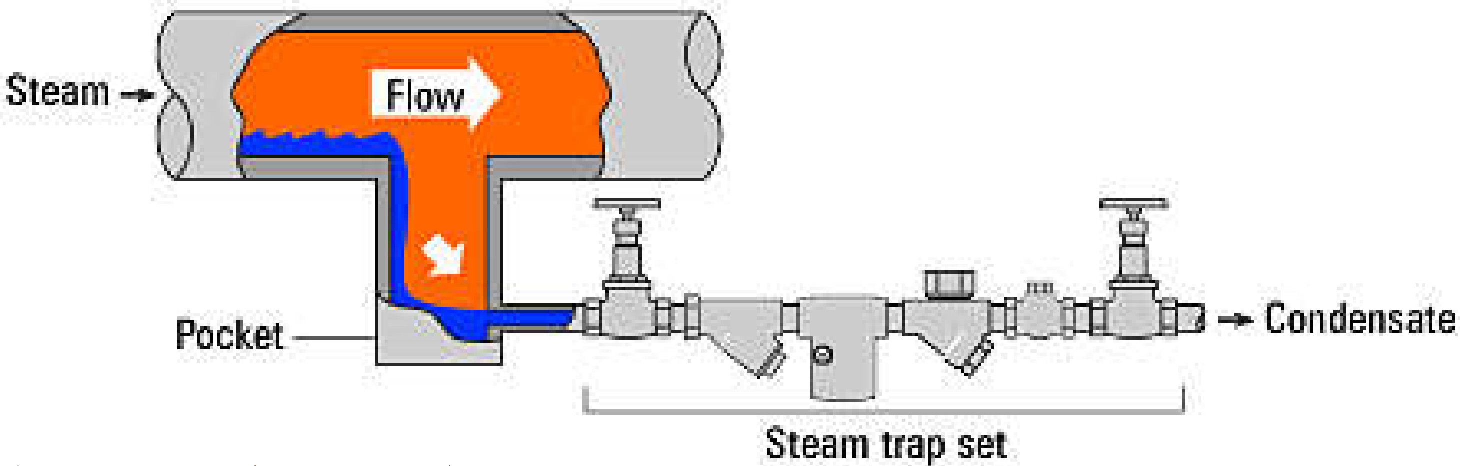
Steam pipeline

- Best practices for condensate removal on steam lines
  - 1. Choose trap locations carefully
  - 2. Provide proper support & inclined steam piping
  - 3. Pay attention to drip leg (drain pocket) configuration
  - 4. Properly remove air and condensate at end of steam line

Typical steam main & branch line installation

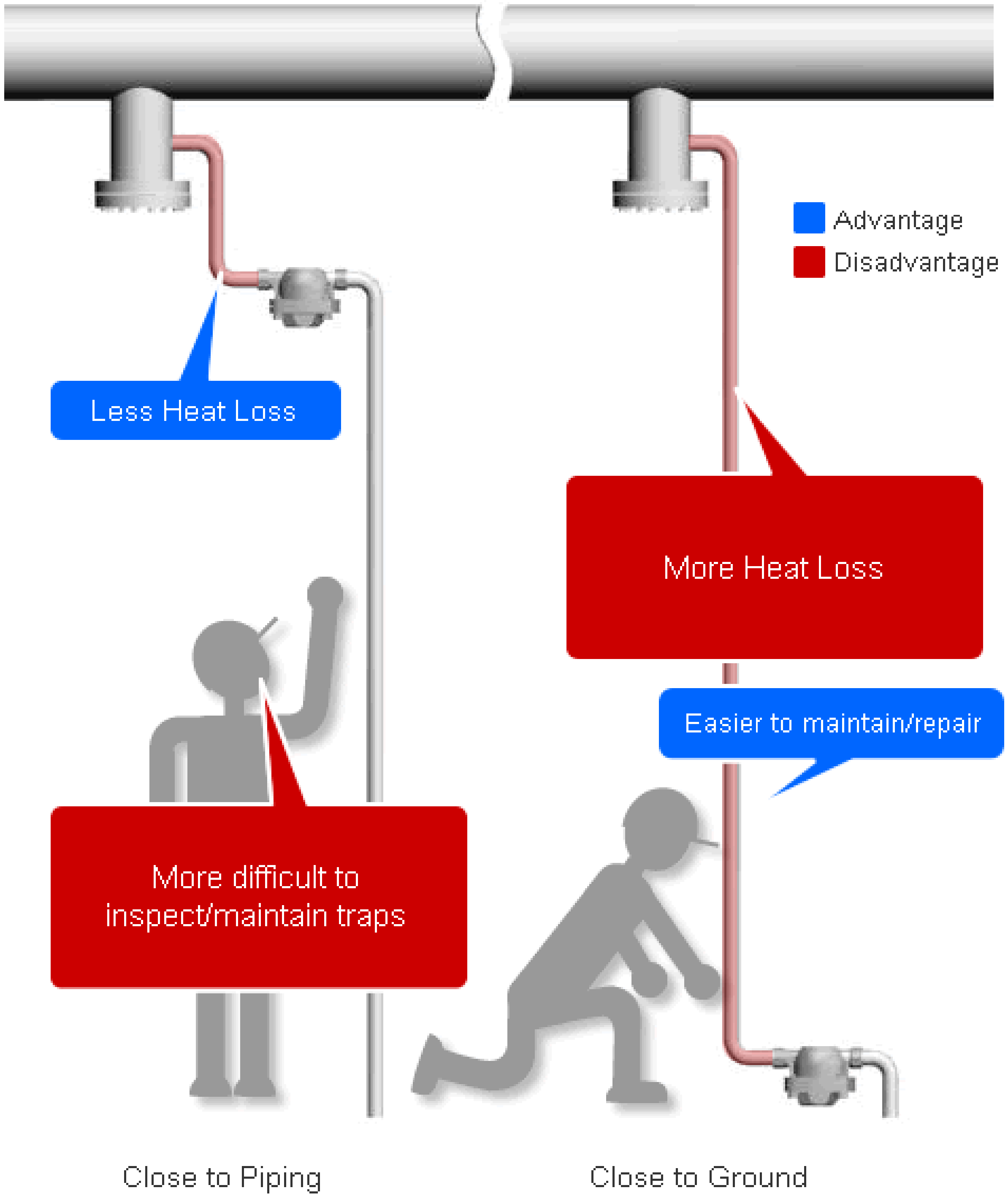






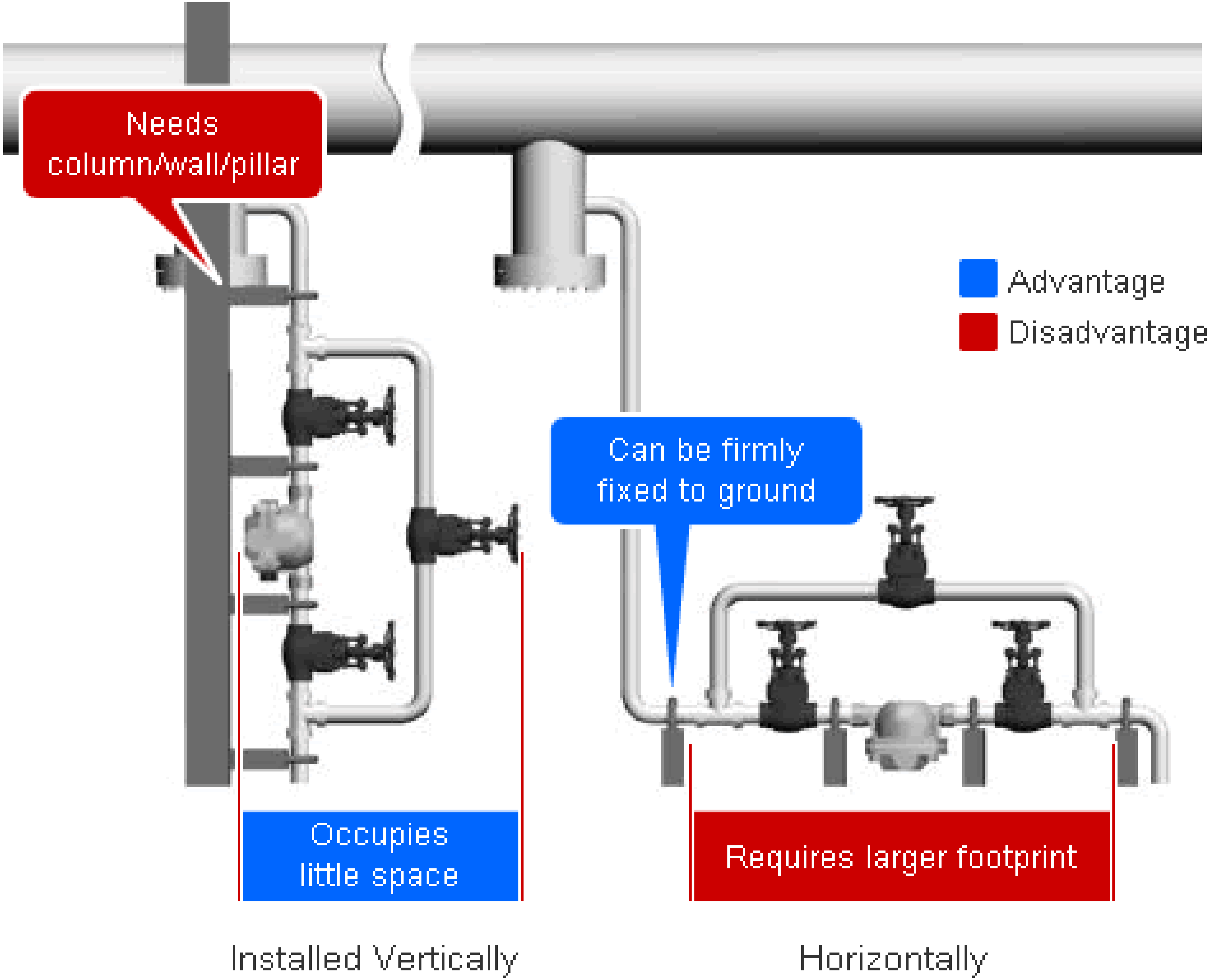
(Source: www.spiraxsarco.com)

Installation tips for steam traps on steam mains



(Source: https://www2.tlv.com/en-au/steam-info/steam-theory/distribution/trap-steam-mains)

Installation tips for steam traps on steam mains (cont'd)

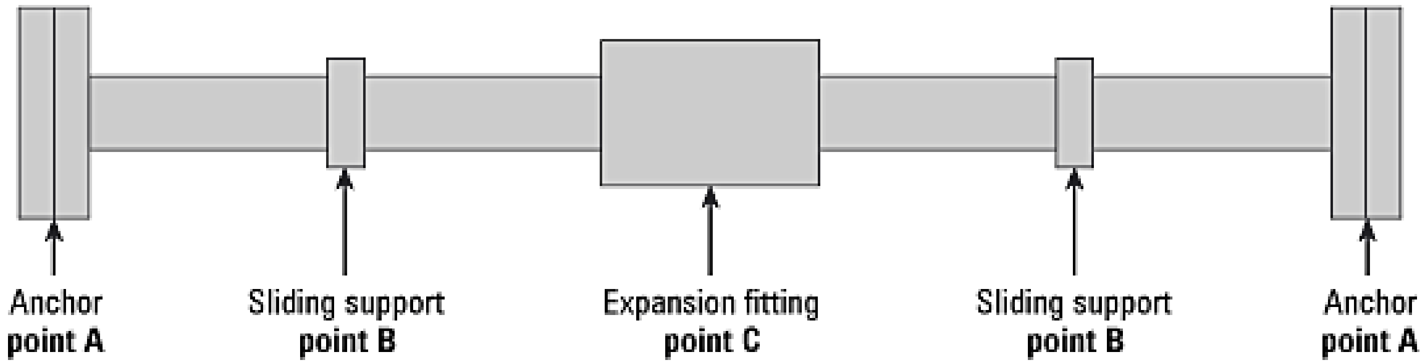


(Source: https://www2.tlv.com/en-au/steam-info/steam-theory/distribution/trap-steam-mains)

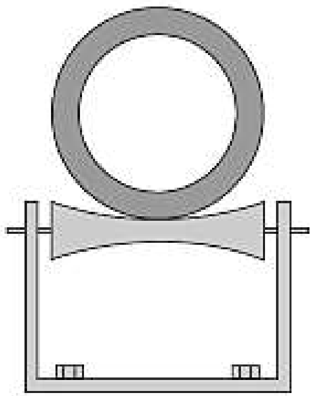
Steam pipeline

- Installation of 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
  - Suitable pipe support spacing, bracket and method

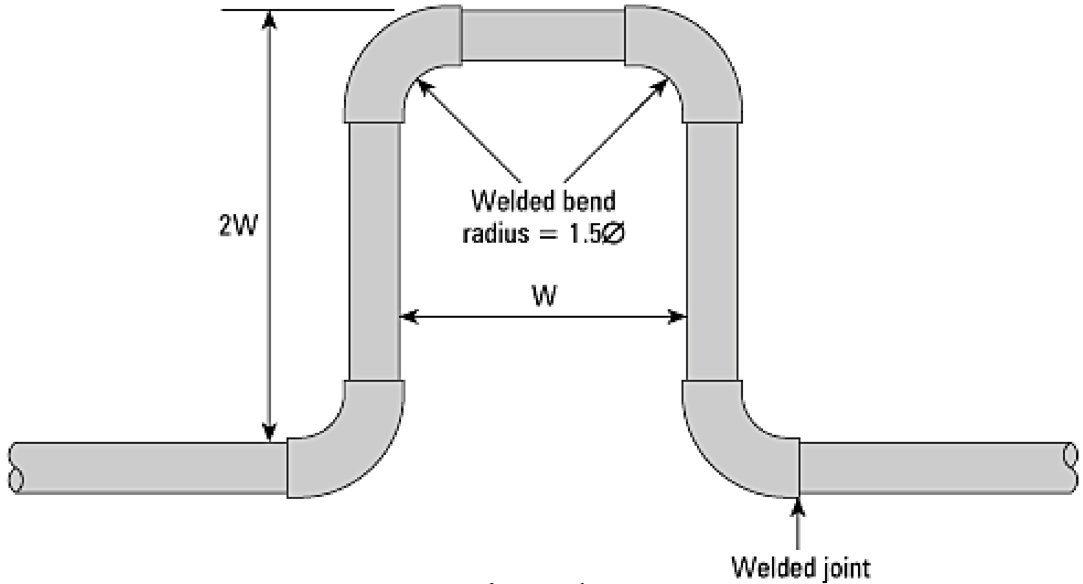
Pipe expansion and support



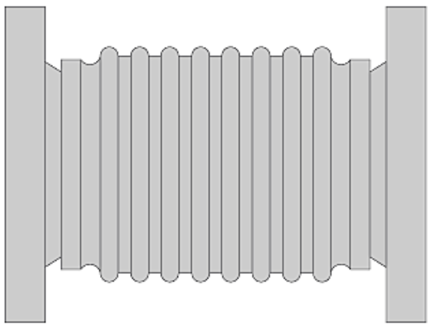
Pipeline with fixed point, variable anchor point and expansion fitting



Chair and roller



Expansion loop



Expansion bellow

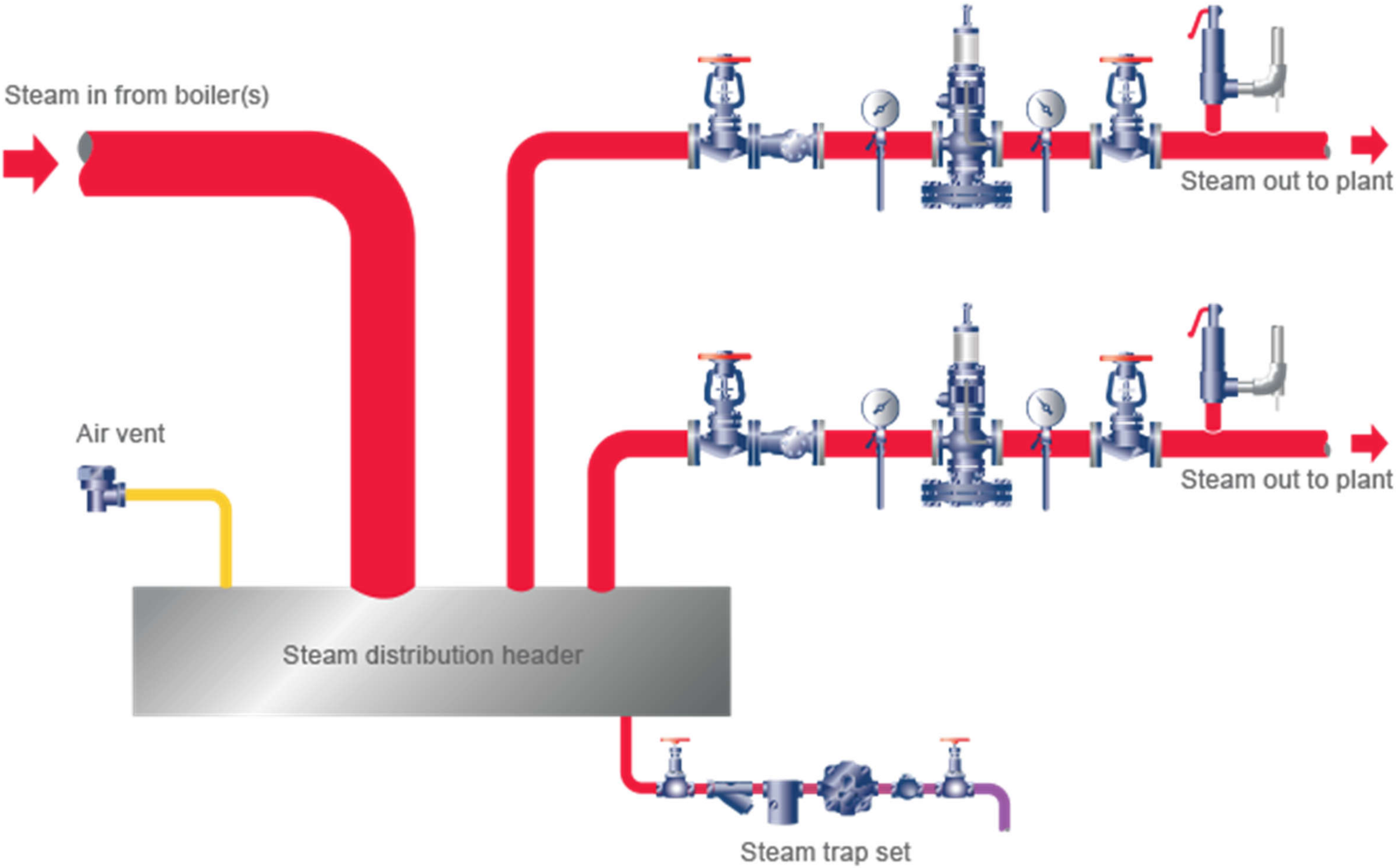
(Source: www.spiraxsarco.com)

Recommended support spacing for steam pipework

Nominal pipe size (mm)		Interval of horizontal run (metre)		Interval of vertical run (metre)	
Steel bore	Copper outside diameter	Mild steel	Copper	Mild steel	Copper
	15		1.2	2.4	1.8
15		1.8		3.0	
20	22	2.4	1.2	3.0	1.8
25	28	2.4	0.5	3.0	2.4
32	35	2.4	1.8	3.7	3.0
40	42	2.4	1.8	3.7	3.0
50	54	2.4	1.8	4.6	3.0
65	67	3.0	2.4	4.6	3.7
80	76	3.0	2.4	4.6	3.7
100	108	3.0	2.4	5.5	3.7
125	133	3.7	3.0	5.5	3.7
150	159	4.5	3.7	5.5	
200		6.0		8.5	
250		6.5		9.0	
300		7.0		10.0	

(Source: www.spiraxsarco.com)

Steam distribution manifold



(Source: www.spiraxsarco.com)

Steam pipeline

- Erosion and corrosion in the piping
  - Erosion -- gradual wearing away of a solid through abrasion
    - Physical degradation of a material due to the flow of water, wind, or debris; e.g. caused by liquid droplet impingement or high velocity dis-entrained condensate
    - https://www2.tlv.com/en-au/steam-info/steam-theory/problems/piping-erosion
  - Corrosion -- degradation of a material caused by chemical reactions
    - https://www2.tlv.com/en-au/steam-info/steam-theory/problems/corrosion

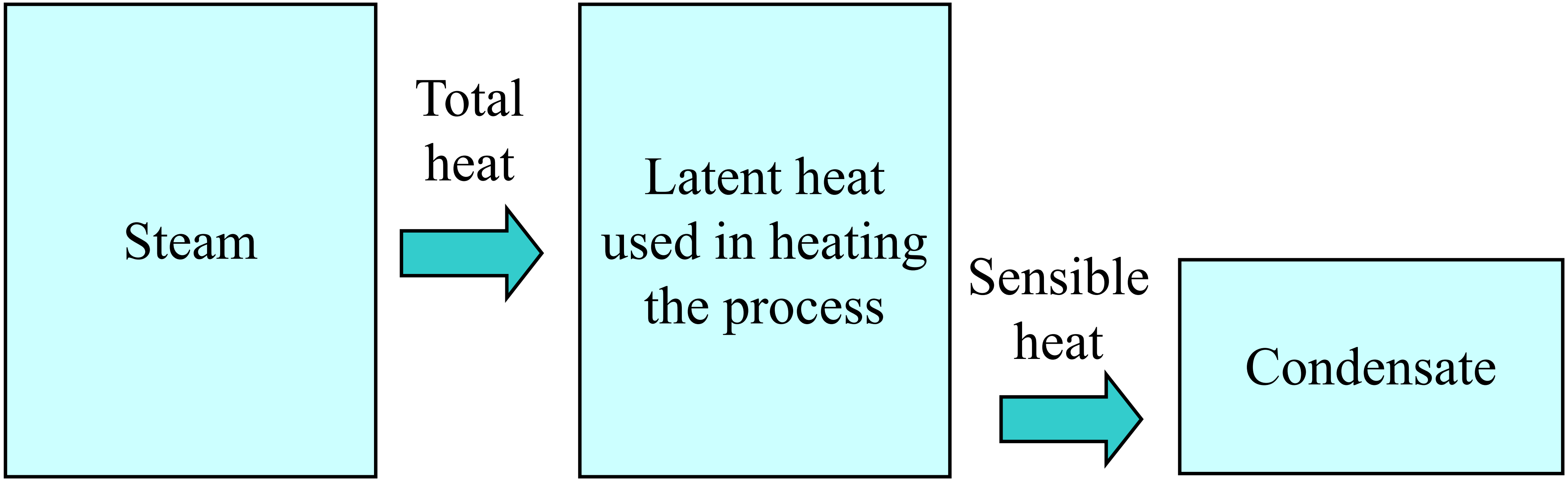
Examples of corroded pipes

(Source: https://www2.tlv.com/en-au/steam-info/steam-theory/problems/corrosion)

Condensate recovery

- Importance of 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

Condensate Recovery

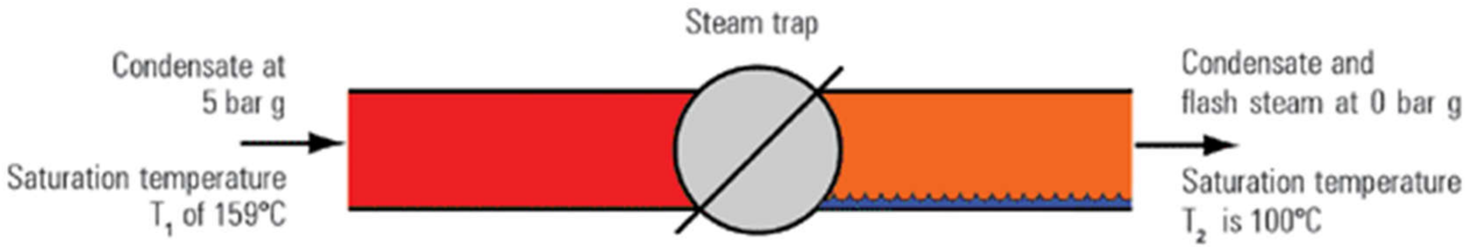


After giving up its latent heat to heat the process, steam turns to water containing only sensible heat

(Source: www.spiraxsarco.com)

Condensate recovery

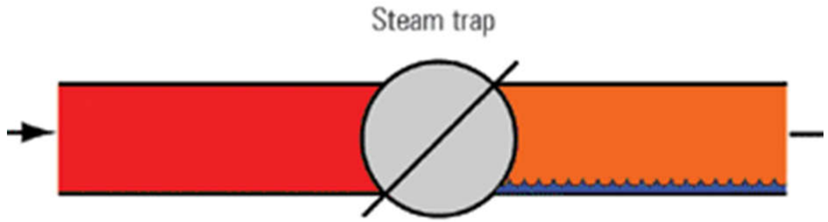
- Flash steam



  - Formed when high pressure condensate is discharged to a lower pressure ("flash evaporation") (same as live steam)
  - Should be collected and led to a flash vessel (for reuse)
- 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

(See also: https://www2.tlv.com/en-au/steam-info/steam-theory/steam-basics/flash-steam)

Example: Calculate the amount of flash steam from condensate.



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%**
(can be reused by flash steam recovery systems)

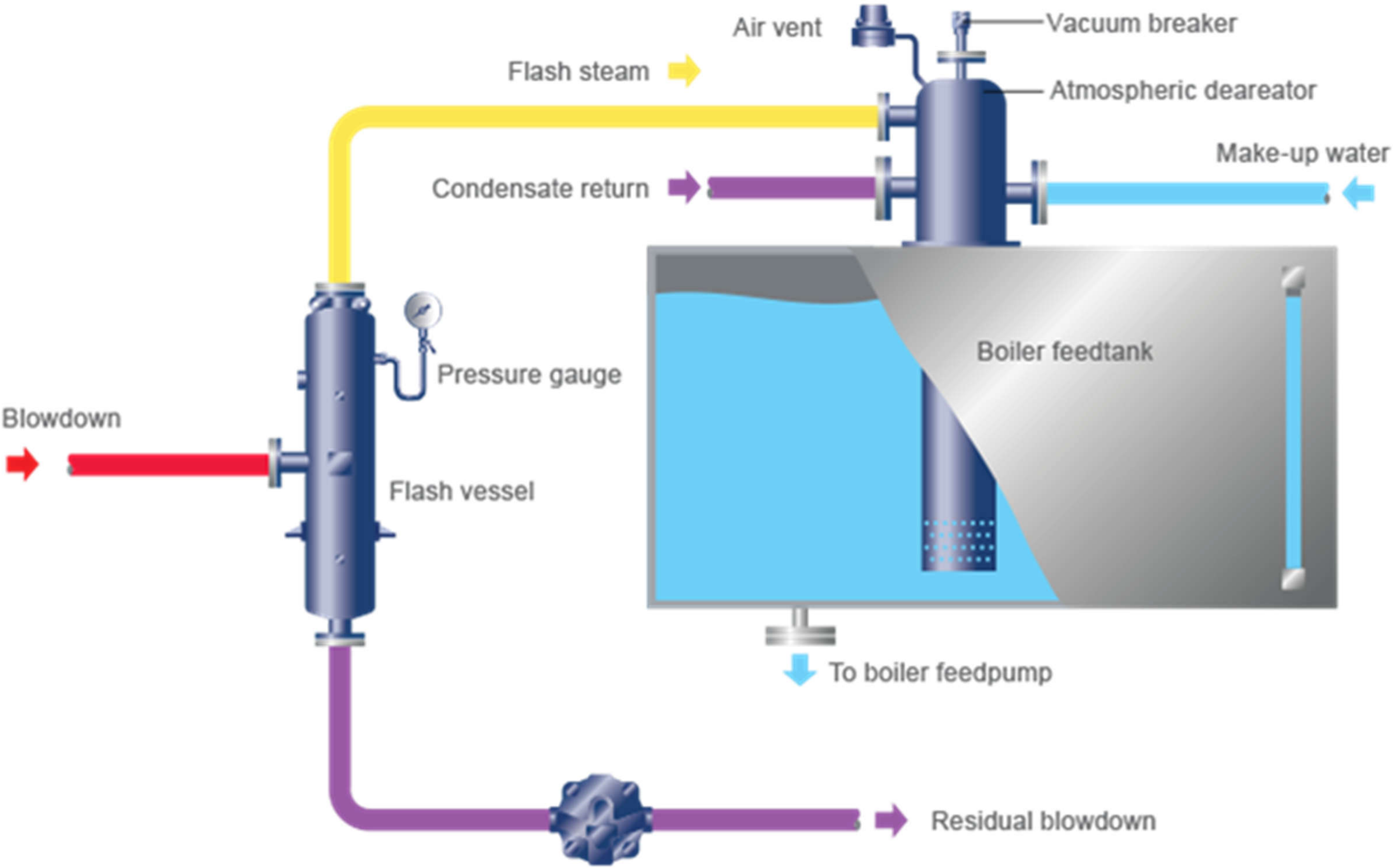
(See also: Engineering Calculator -- Flash Steam Generated by Hot Condensate
http://www.tlv.com/global/AU/calculator/flash-steam-generation.html)

Condensate recovery

- Condensate can be reused in many different ways, for example:
  - As heated feedwater, by sending hot condensate back to the boiler's deaerator
  - As pre-heat, for any applicable heating system
  - As steam, by reusing flash steam
  - As hot water, for cleaning equipment or other cleaning applications
- Condensate Recovery vs. No Recovery

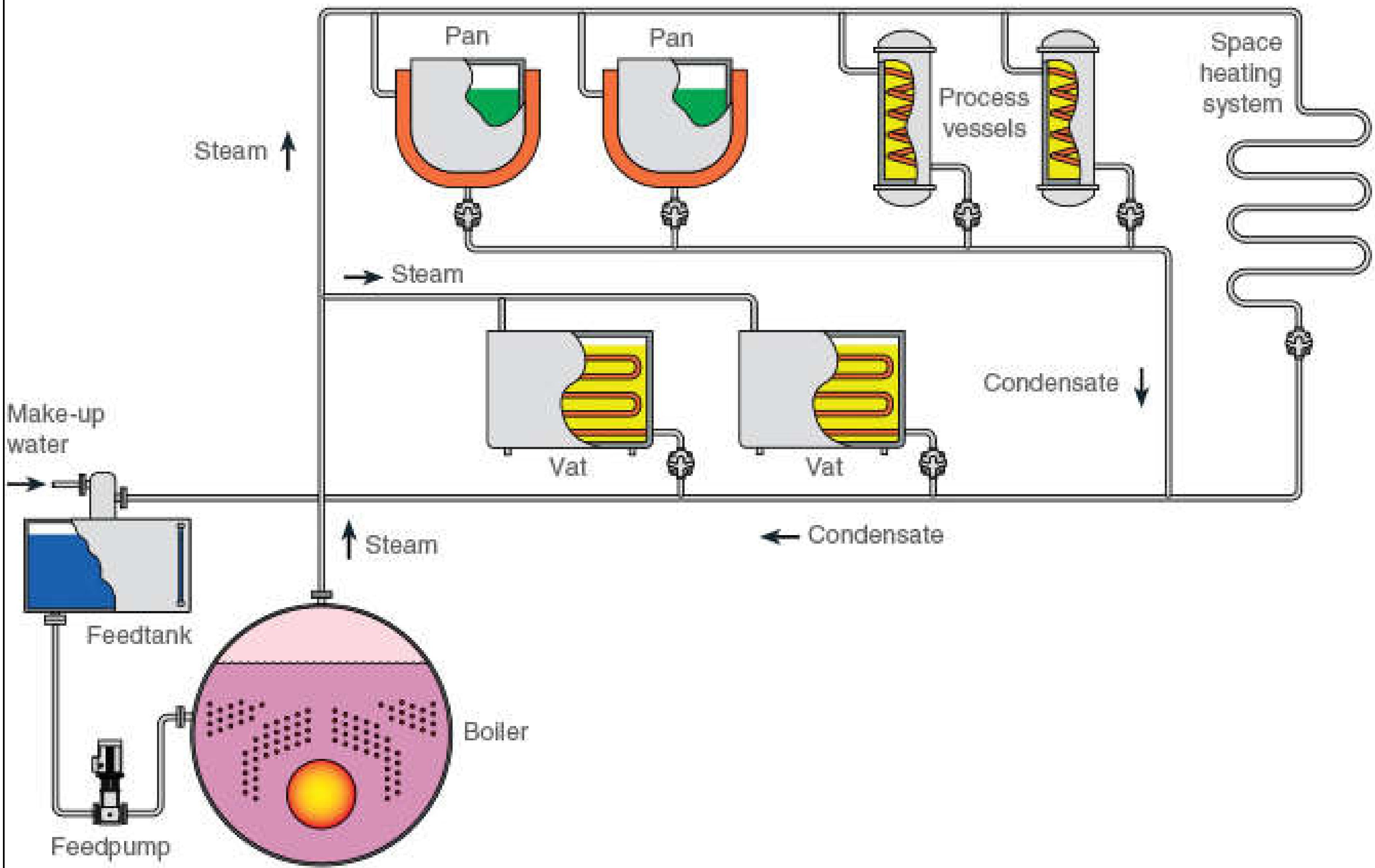
(See also: https://www2.tlv.com/en-au/steam-info/steam-theory/condensate-recovery/introduction-to-condensate-recovery)

Using a flash vessel to return energy to the boiler feedtank



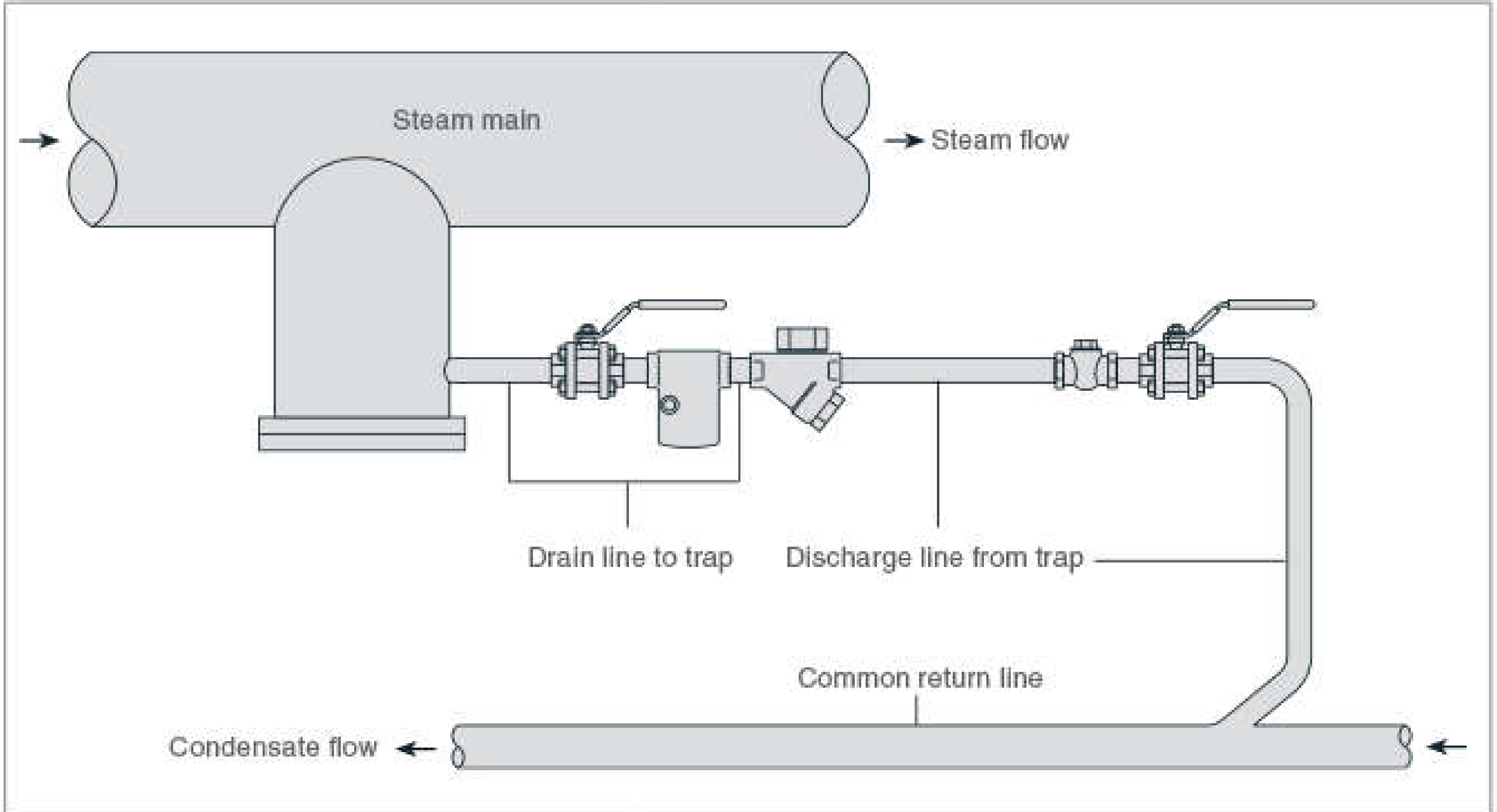
(Source: www.spiraxsarco.com)

A simple steam system with condensate returning to the boiler feedtank



(Source: www.spiraxsarco.com)

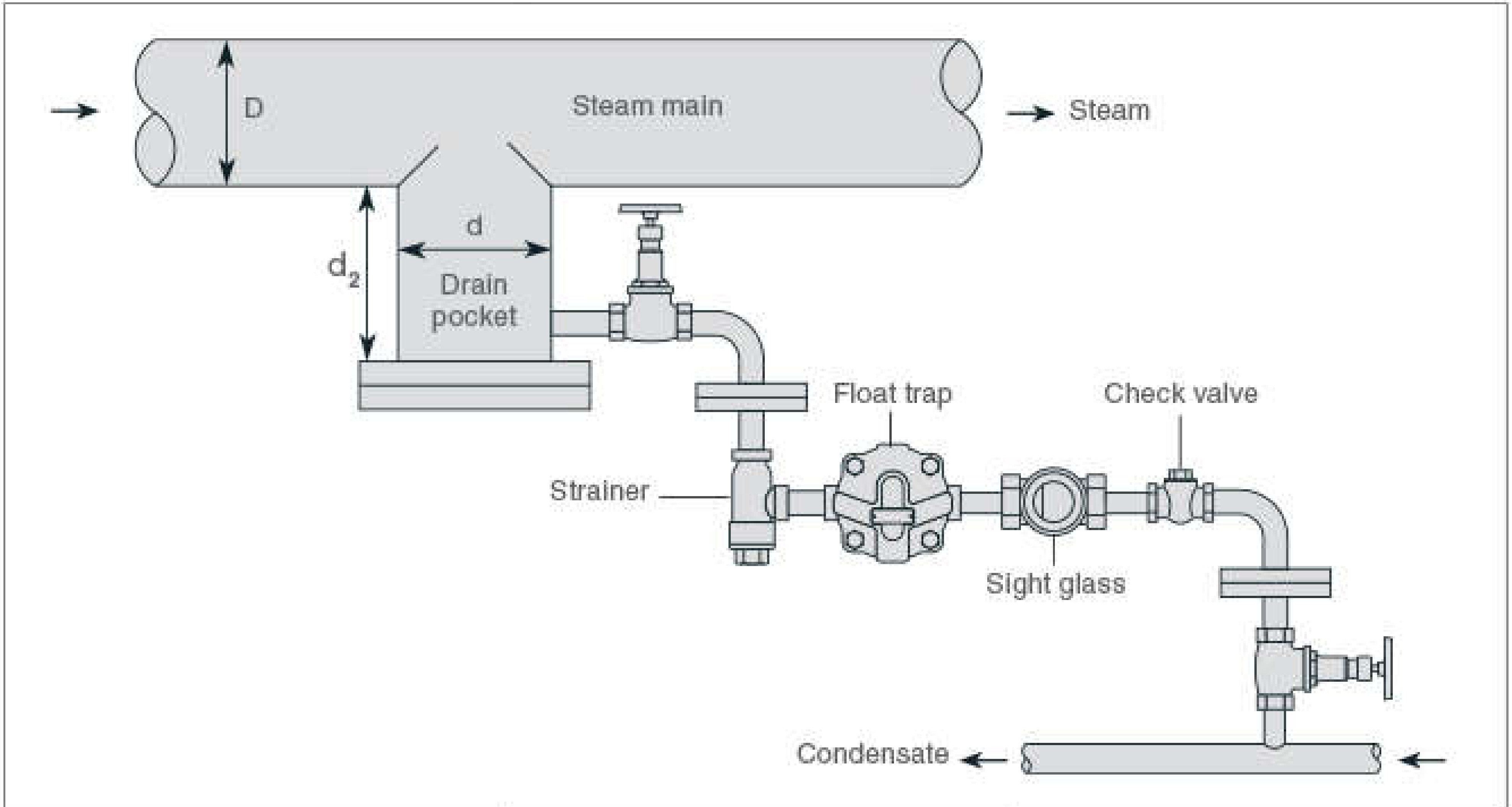
Four basic types of condensate piping and their considerations



Type of condensate line	Condensate line is sized to carry the folllowing:
Drain line to trap	Condensate
Discharge line from trap	Flash steam
Common return line	Flash steam
Pumped return line (not shown)	Condensate

(Source: www.spiraxsarco.com)

Ideal arrangement when draining a steam main



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 $d_2 = D$

(Source: www.spiraxsarco.com)

Condensate recovery

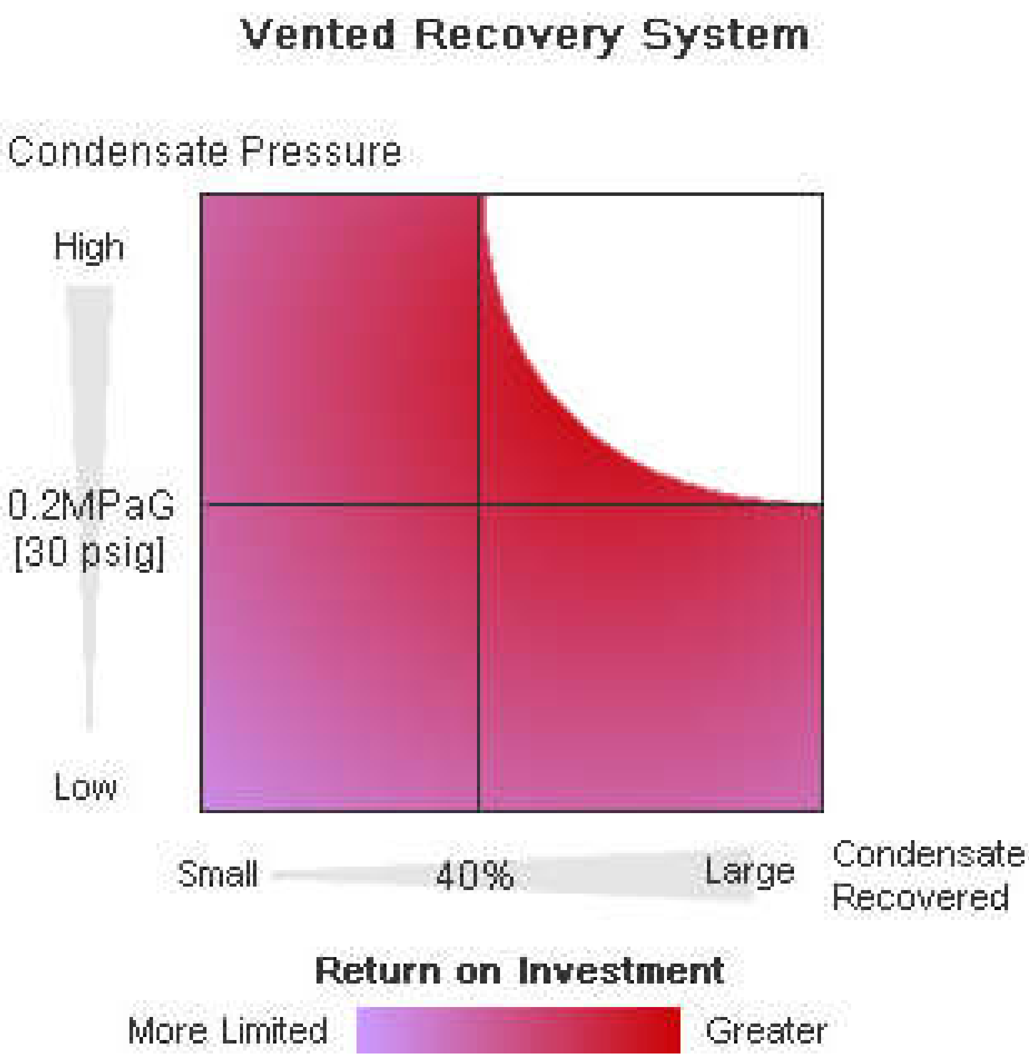
- Returning condensate and condensate pumps
  - Use trap inlet pressure
    - Gravity return
    - Elevated return
  - Use a pump to overcome return line backpressure
    - Electric centrifugal or turbine condensate pumps
    - Non-electric steam or air-powered mechanical condensate pumps
    - Using a specialized centrifugal pump for condensate recovery pumps

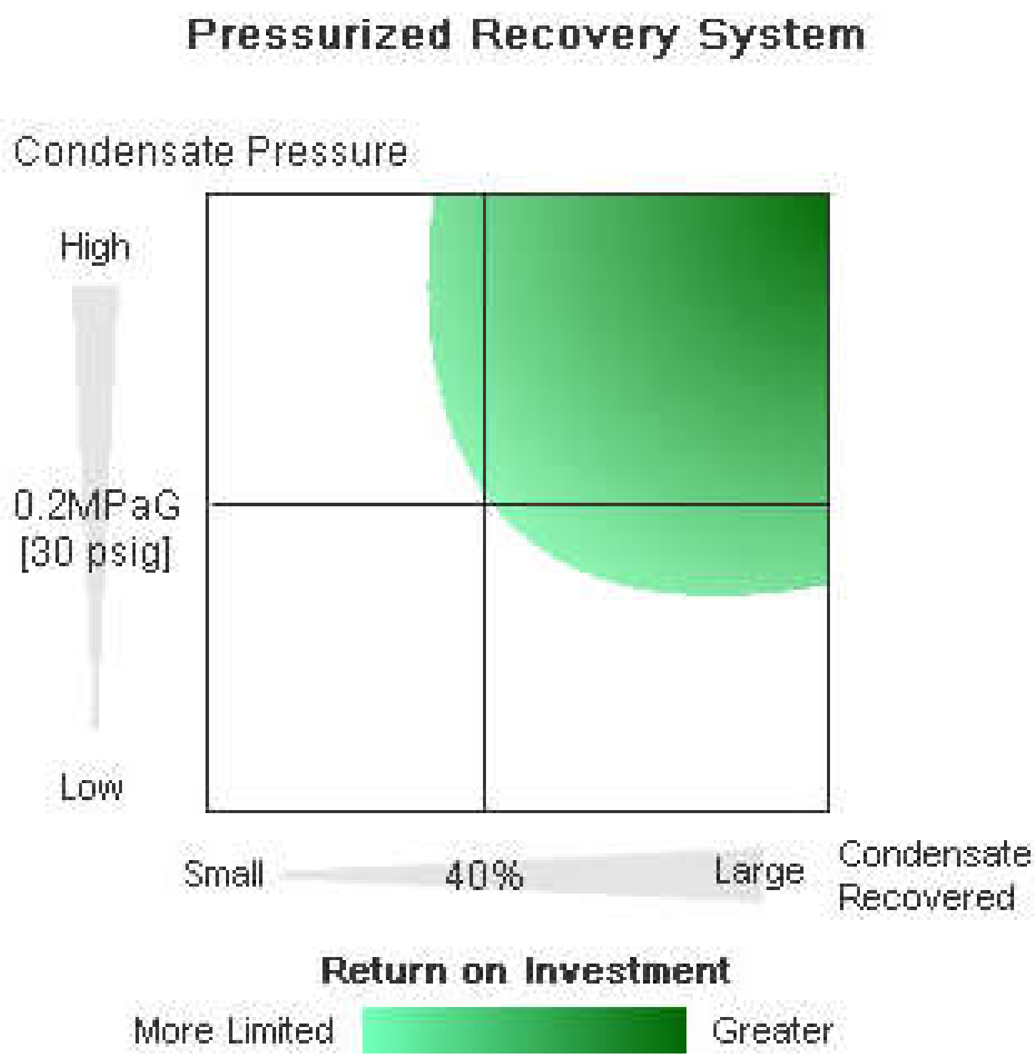
(See also: https://www2.tlv.com/en-au/steam-info/steam-theory/condensate-recovery/types-of-condensate-recovery)

Condensate recovery

- Condensate recovery: vented vs. pressurized
  - Vented
    - Return condensate to an open-to-atmosphere collection tank for use as boiler make-up water, pre-heat or other hot water applications
  - Pressurized
    - In a pressurized vessel/directly to the boiler
    - Recovered condensate is maintained above atmospheric pressure throughout the recovery process
    - It is generally used as boiler make-up water
    - Can also recover the associated flash or live steam

Typical range for vented / pressurized systems





(Source: https://www2.tlv.com/en-au/steam-info/steam-theory/condensate-recovery/vented-pressurized-condensate-recovery)

Condensate recovery: vented vs. pressurized systems

	Vented Recovery	Pressurized Recovery
Recovered Condensate Temperature	Up to 100 ºC [212 ˚F]	Up to 180 ºC [356 ˚F]*
System Configuration	Simple	Advanced
Initial Costs	Lower	Higher
Running Costs	Varies	Varies
Piping Corrosion	Significant (condensate comes into contact with air)	Slight (no contact with air)
Vapor Clouds	Large amount (if condensate temp. is high)	Minimal amount
Recovery Applications	Boiler make-up water Pre-heat Water for cleaning, etc.	Mainly for direct feed to boiler, and Flash Steam Recovery Applications

* May be higher. Limited by max operating temperature of pump and peripheral equipment.

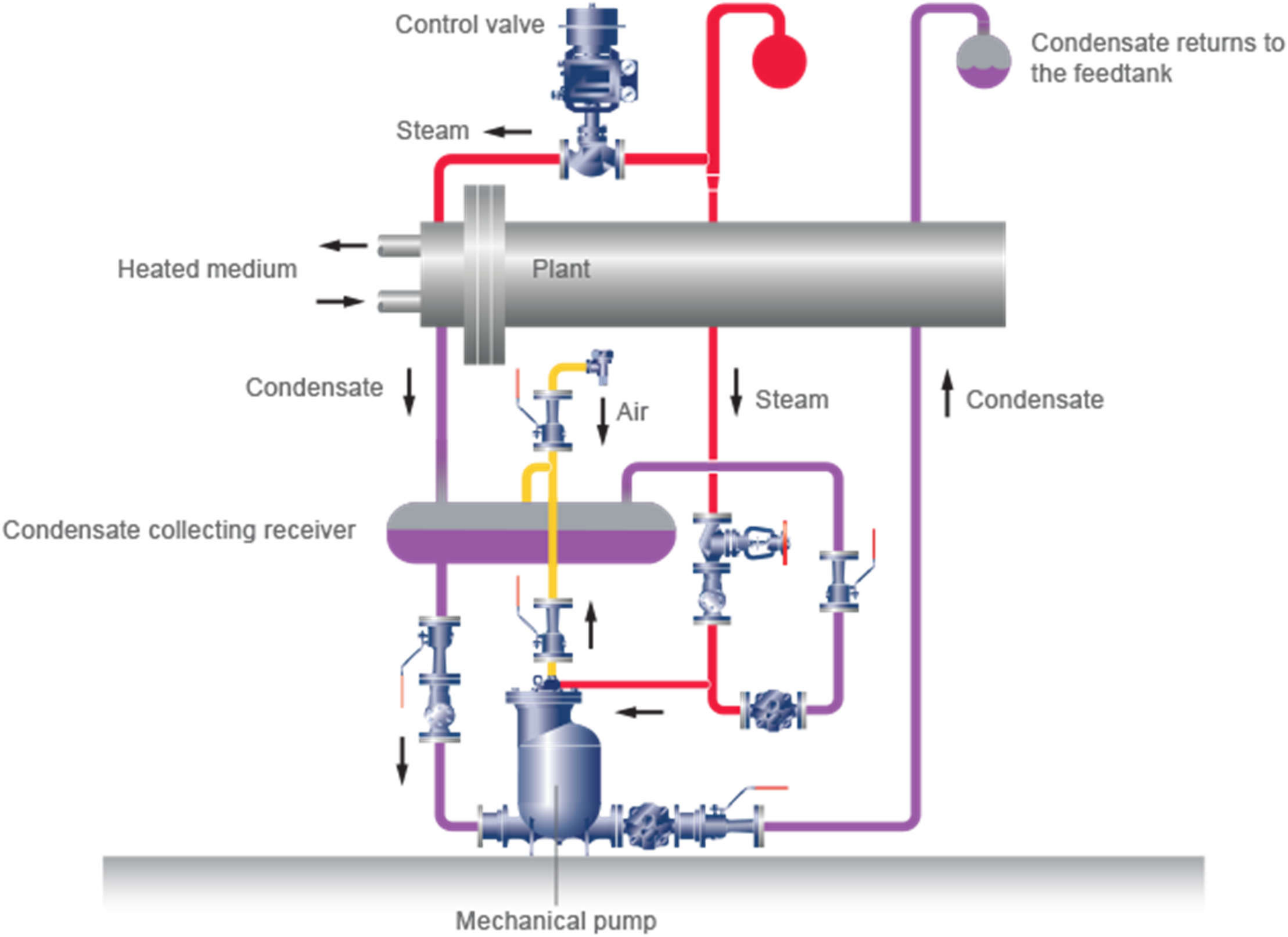
(Source: https://www2.tlv.com/en-au/steam-info/steam-theory/condensate-recovery/vented-pressurized-condensate-recovery)

Condensate recovery

- Condensate recovery/return piping
  - Must be designed for “two-phase flow”
    - Vapour such as steam (either flash steam, live steam, or a mix of both) flows through piping together with liquid condensate
  - The design requires calculating the amount of flash steam and then sizing the pipe to accommodate both water and steam flow for the required velocity and pressure drop design parameters

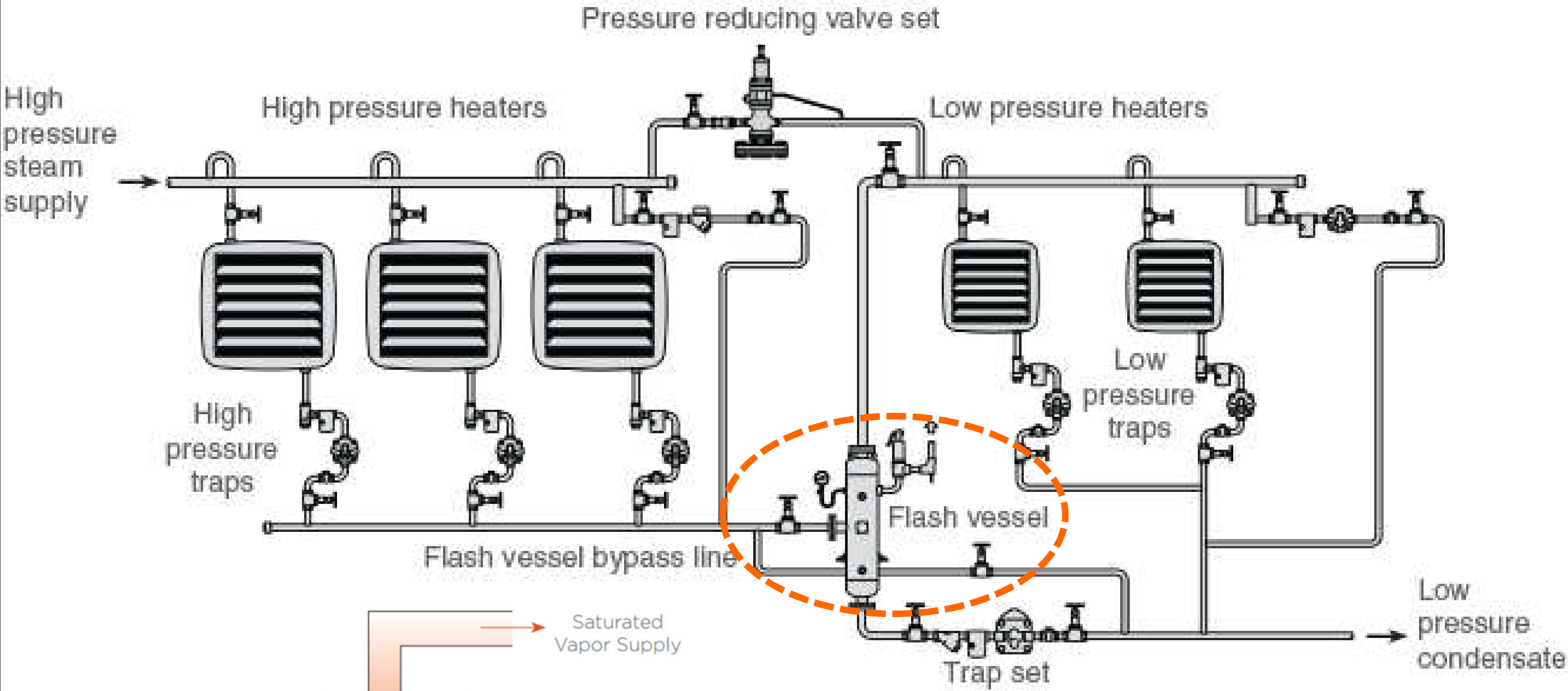
(See also: https://www2.tlv.com/en-au/steam-info/steam-theory/condensate-recovery/condensate-recovery-piping)

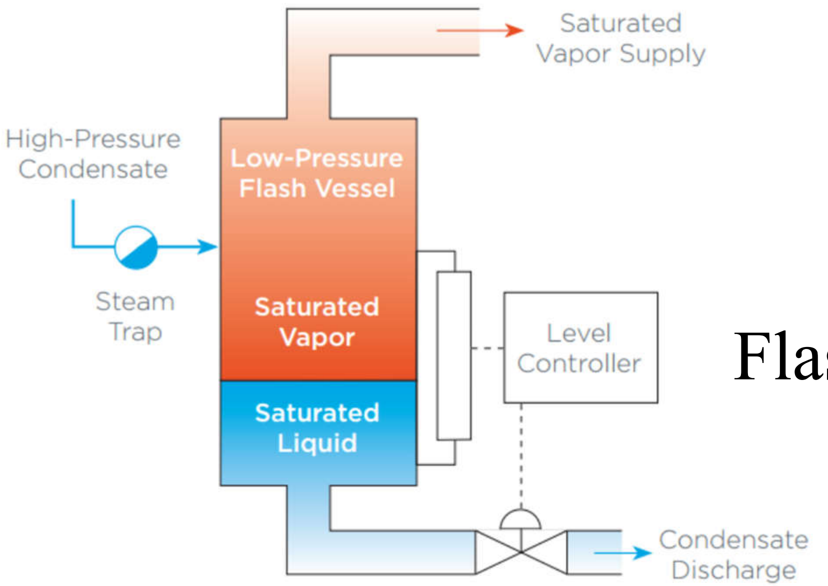
Condensate recovery and return



(Source: www.spiraxsarco.com)

Flash steam supply and demand in step (recover flash steam energy)

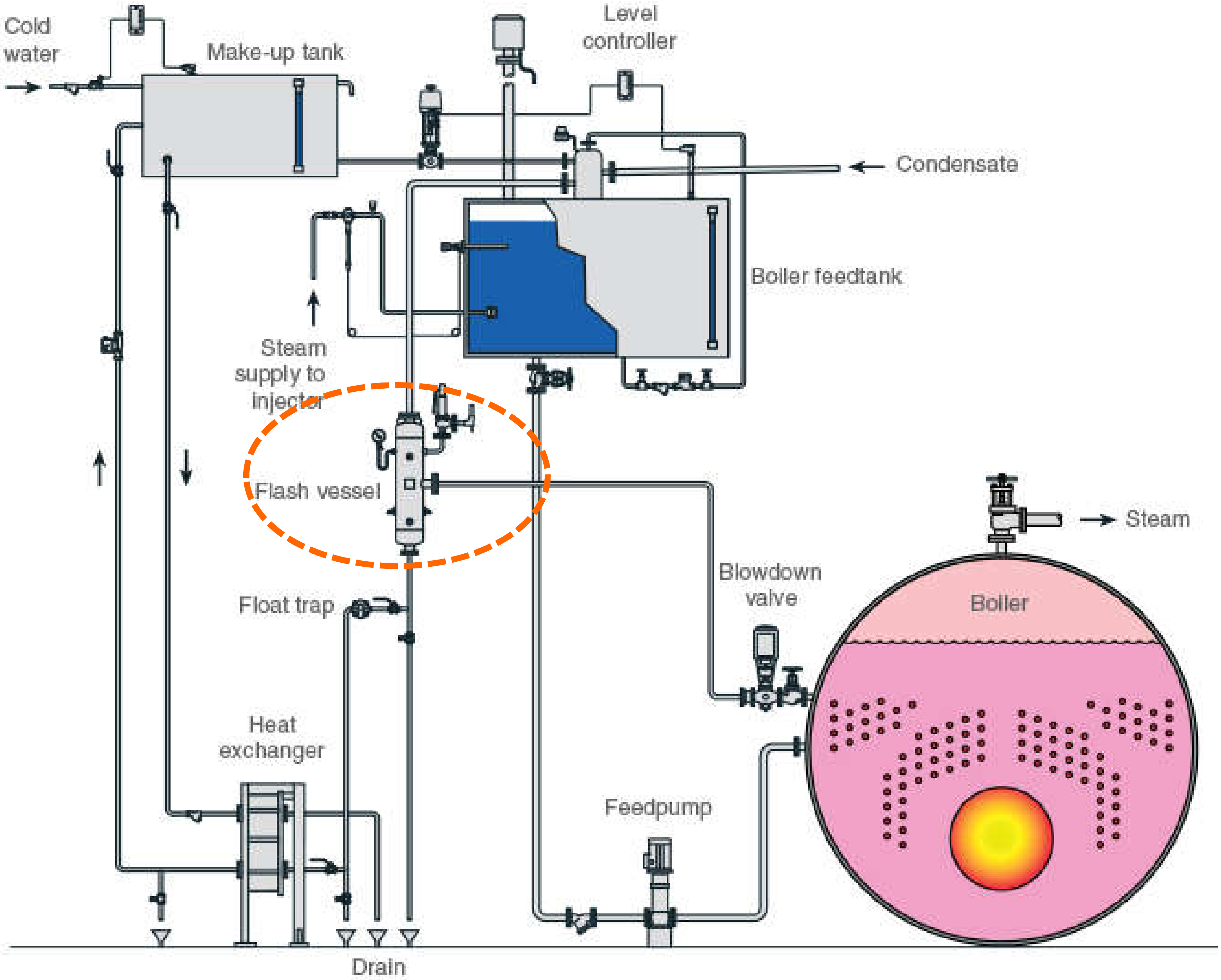




Flash steam recovery vessel

(Source: www.spiraxsarco.com)

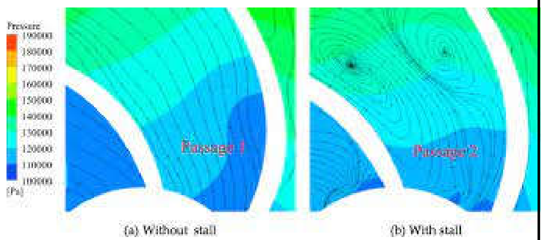
Typical heat recovery from boiler blowdown



(Source: www.spiraxsarco.com)

Condensate recovery

- What is Stall?
  - A condition which occurs when the necessary pressure differential across a drainage device such as a trap becomes negative, causing condensate to no longer be discharged from the drainage device and instead to pool inside a heat exchanger
  - Stall can occur because:
    - Vacuum always present inside equipment
    - Constant negative pressure differential
    - Varying positive to negative pressure differential



(See also: https://www2.tlv.com/en-au/steam-info/steam-theory/problems/stall-phenomenon-pt1)

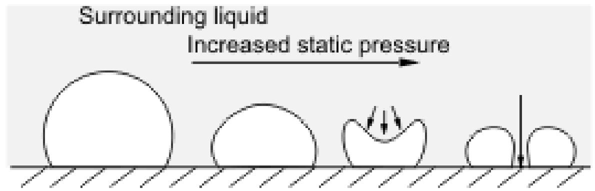
Condensate recovery

- Stall is often linked to the following problems:
  - Degraded or ruptured heaters
    - Can foul or damage equipment
  - Water hammer
    - Can damage tubes and channel head gaskets
  - Uneven heating temperatures
    - Can affect product quantity and quality
- Two ways to prevent stall:
  - Increase trap inlet (primary) pressure
  - Reduce trap outlet (secondary) pressure

Condensate recovery

- Practical methods of preventing stall
  - 1. Ensure the steam pressure in the steam space can never drop below atmospheric pressure, and that the condensate can drain by gravity to and from a ball float steam trap
  - 2. Accept that the pressure in the steam space may be less than the backpressure, and provide an alternative means of removing condensate, by installing a pump-trap
  - 3. Ensure the pressure in the steam space is stable and higher than the backpressure. This will entail having the temperature control system on the secondary side of the system

Condensate recovery

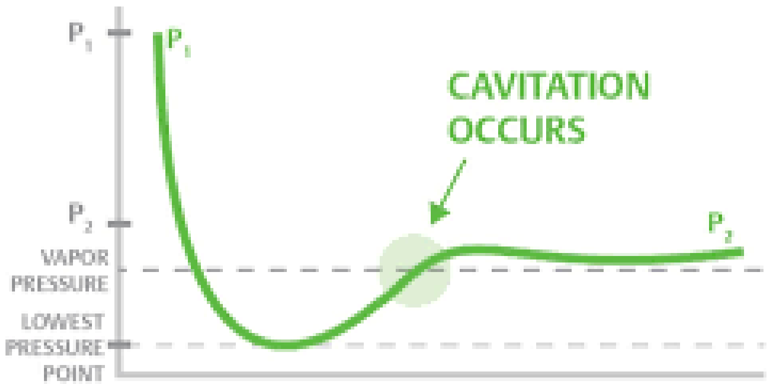


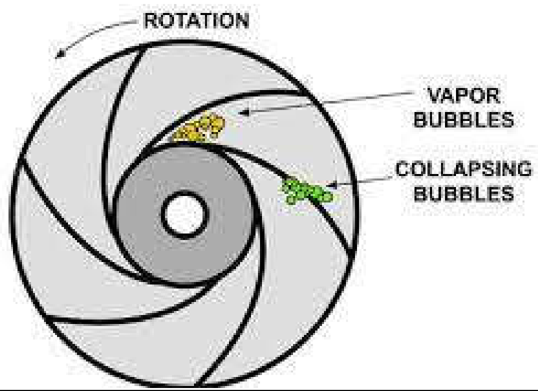
- Cavitation in condensate pumps
  - Flash steam cavities (like bubbles) formed within the liquid collapse, imploding rapidly with considerable force. The rapid implosions create shockwaves
  - The rapid formation and implosion of vapour cavities that form via cavitation damage the inner surfaces of pumps and piping, causing the erosion and thinning of impellers and pump casing

(See also: https://www2.tlv.com/en-au/steam-info/steam-theory/problems/cavitation-in-condensate-pumps)

Condensate recovery

- Cavitation coping methods
  - Calculate the Net Positive Suction Head Available (NPSHA) and careful select pumps with a compatible Net Positive Suction Head Required (NPSHR)
  - Use of a steam or air-powered mechanical pump as opposed to an electric-powered pump



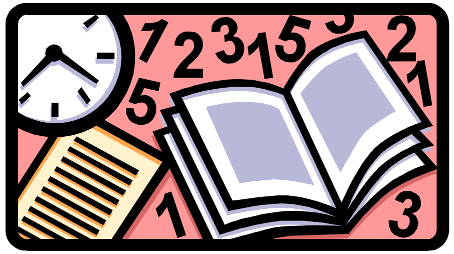


Further Reading

- Training videos:

  - What is a Boiler and How does It Work? (8:55) https://youtu.be/fk3DjD9gSsk
- Steam Boilers
  - https://www.iqsdirectory.com/articles/boiler/steam-boilers.html
- Learn about steam (Spirax Sarco)
  - https://www.spiraxsarco.com/Learn-about-steam
    - 3. The Boiler House
    - 13. Condensate Removal
    - 14. Condensate Recovery

References



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