Sustainable Power Generation
MJ2405

Steam Boilers & Industrial Furnaces

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Reading material on boilers

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Many books can be used –

Any chapter on combustors, boilers, furnaces, steam generators, etc., might be good to look through!

The main suggested sources:

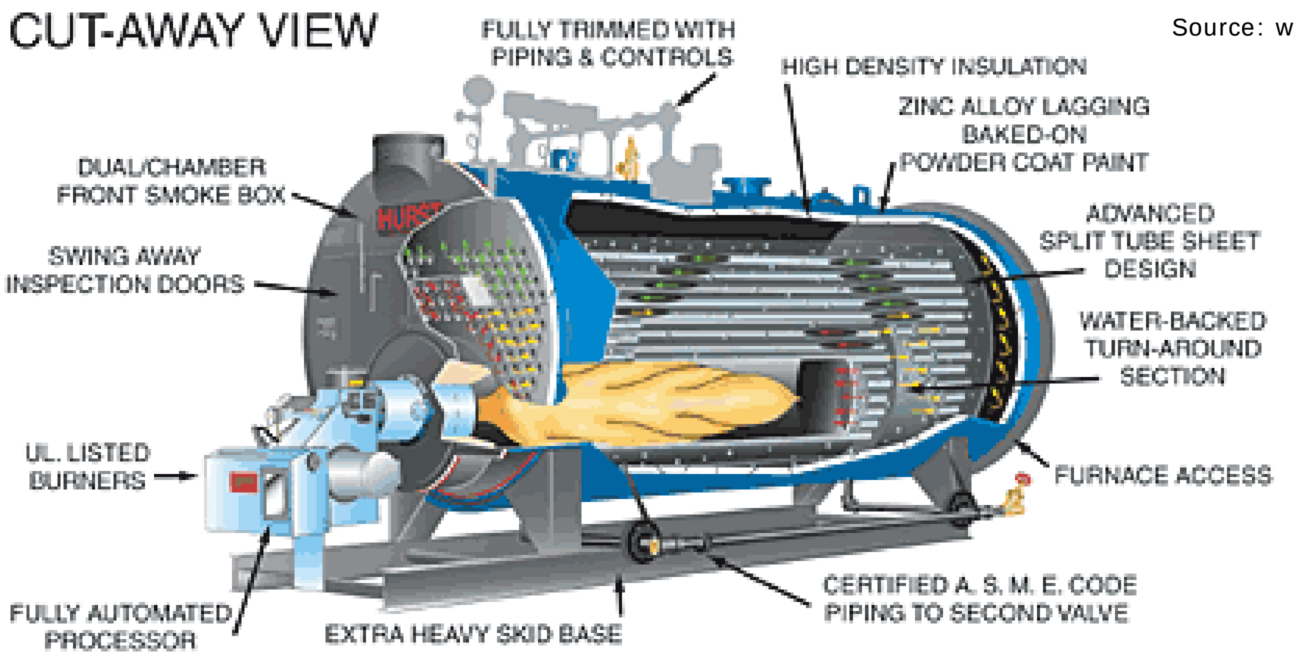
Advanced Energy Systems (Khartchenko&Kharchenko), *CRC Press 2014* – section 3.7 and parts of chapters 6 & 7.

Energy Conversion – *free e-book by courtesy of the University of Tulsa*, Kenneth C. Weston, 2000 – parts of chapters 4 and 9
http://www.personal.utulsa.edu/~kenneth-weston/

På svenska:

Energiteknik - Del 2; Henrik Alvarez, *Studentlitteratur 2006* – delar av kapitel 9 & kapitel 10.

Horizontal fire-tube water heater



Source: www.steamshowersauna.org

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Simplest boiler type. Used typically to produce hot water or saturated steam. The combustion zone (the flame) is inside a tube immersed in a water tank.

Fired with liquid or gas fuels. Mostly at small- to mid-scale district heating or industrial applications. Not suitable for large sizes or for solid fuels.

Purpose and parts of a large steam boiler

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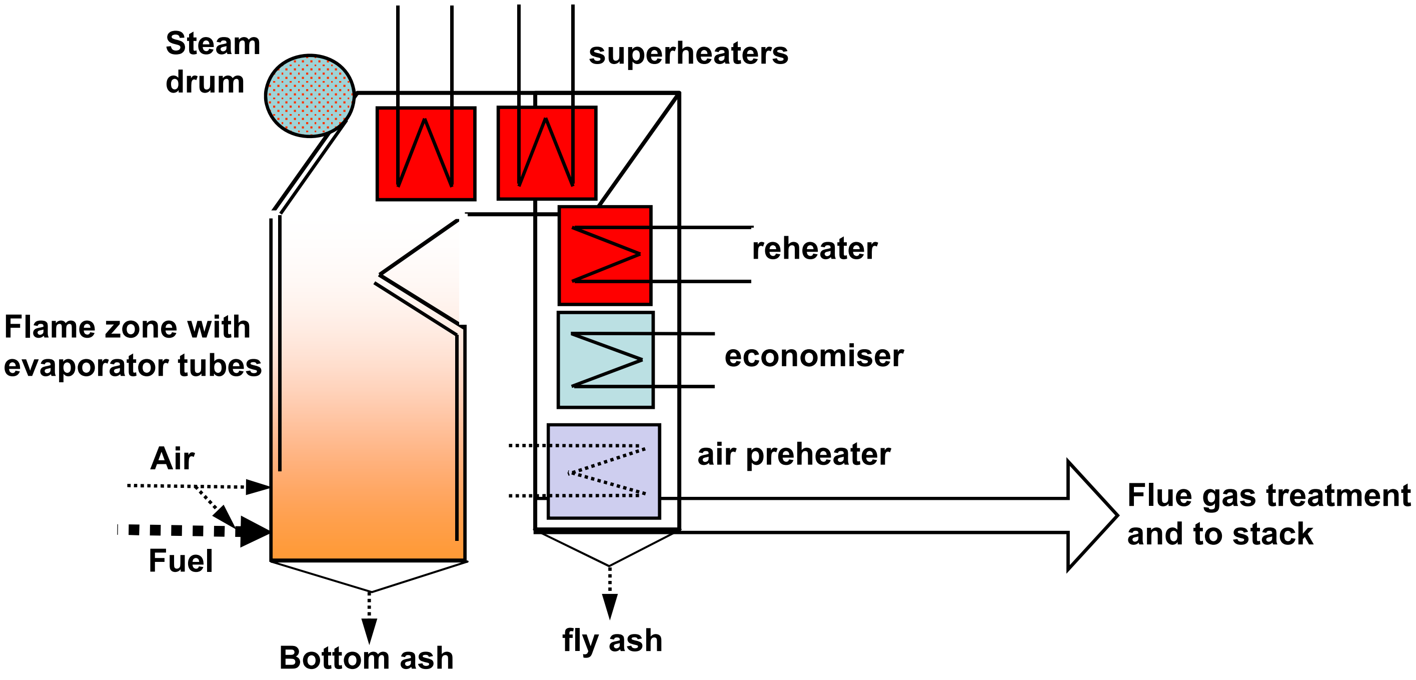
- Should properly be called a "**steam generator**"!
- Burns fuel to produce hot gases in the combustion zone (furnace) which then transfer heat to the water/steam side in the steam generation zone. Alternatively, some available waste hot gases from another process can be used, instead of burning a fuel.
- The steam generation zone consists of **economizer** (water heater), **evaporator** (boiling section), and **superheater/reheater** situated along the flue gas path.
- Remaining heat from the flue gas is transferred back to the fresh air supplied to the combustion zone, via an **air preheater**.
- The common subcritical steam boiler would have a **steam drum** situated usually high up at the top of the evaporator section.

Conceptual setup of a modern steam boiler

Water-tube design! The combustion zone is surrounded by tubes filled with boiling water. All other heat exchangers are hidden from the flame in the horizontal and downward flue gas ducts.



Main boiler components

Steam generator schematic for a large power plant, with its major auxiliaries

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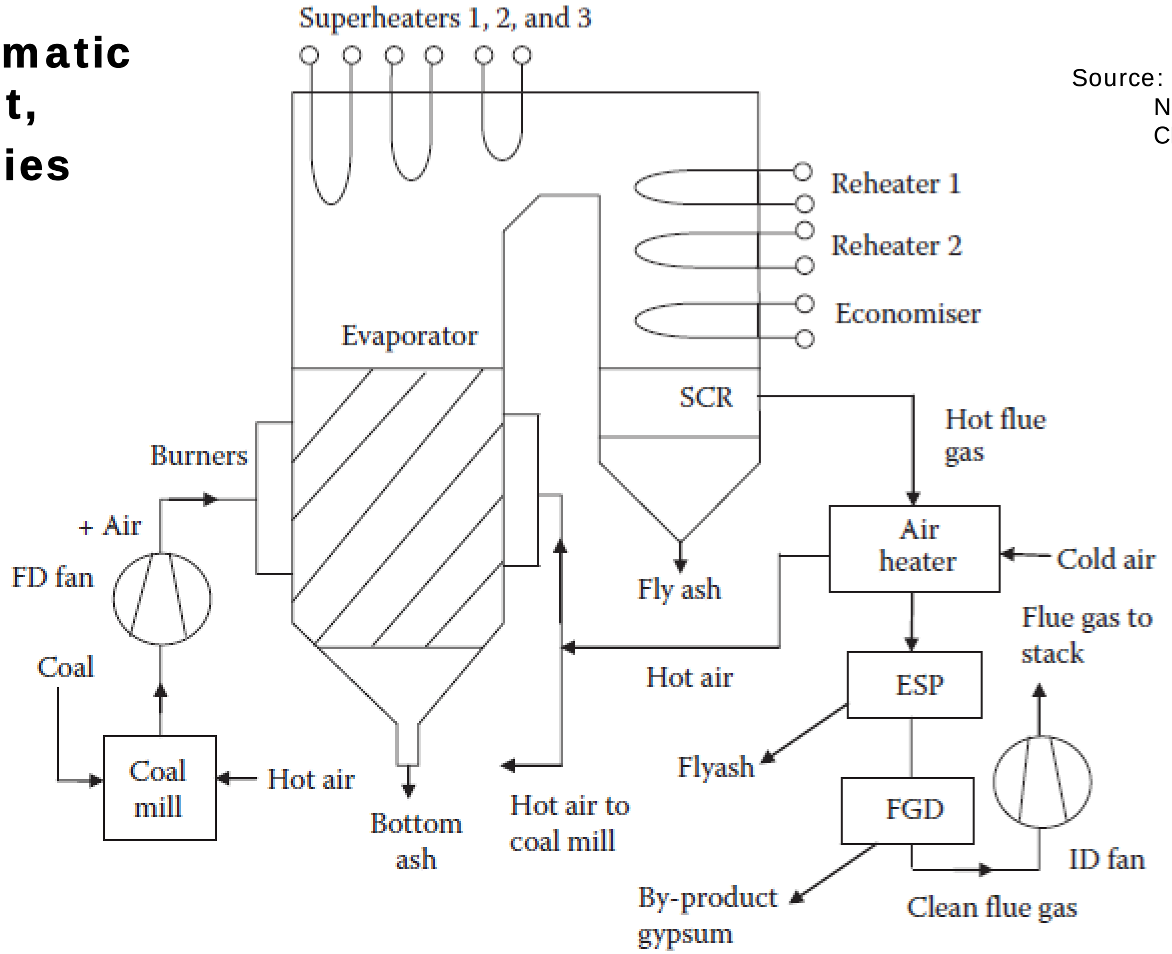
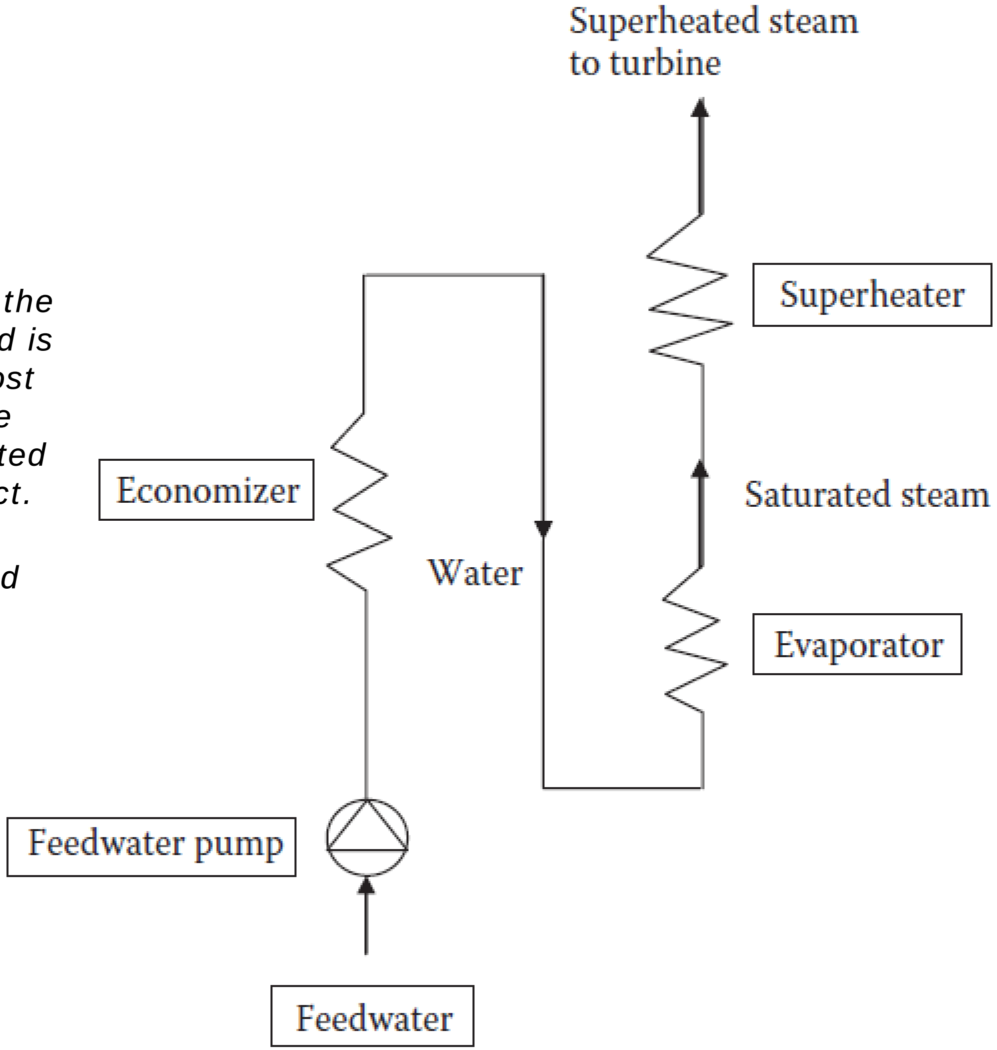


Source: Advanced Energy Systems,
N.V.Khartchenko & V.M.Kharchenko,
CRC Press 2014.

Water / steam path through the boiler

Feedwater enters the boiler as liquid and is heated up to almost boiling point in the economizer, situated in the flue gas duct.

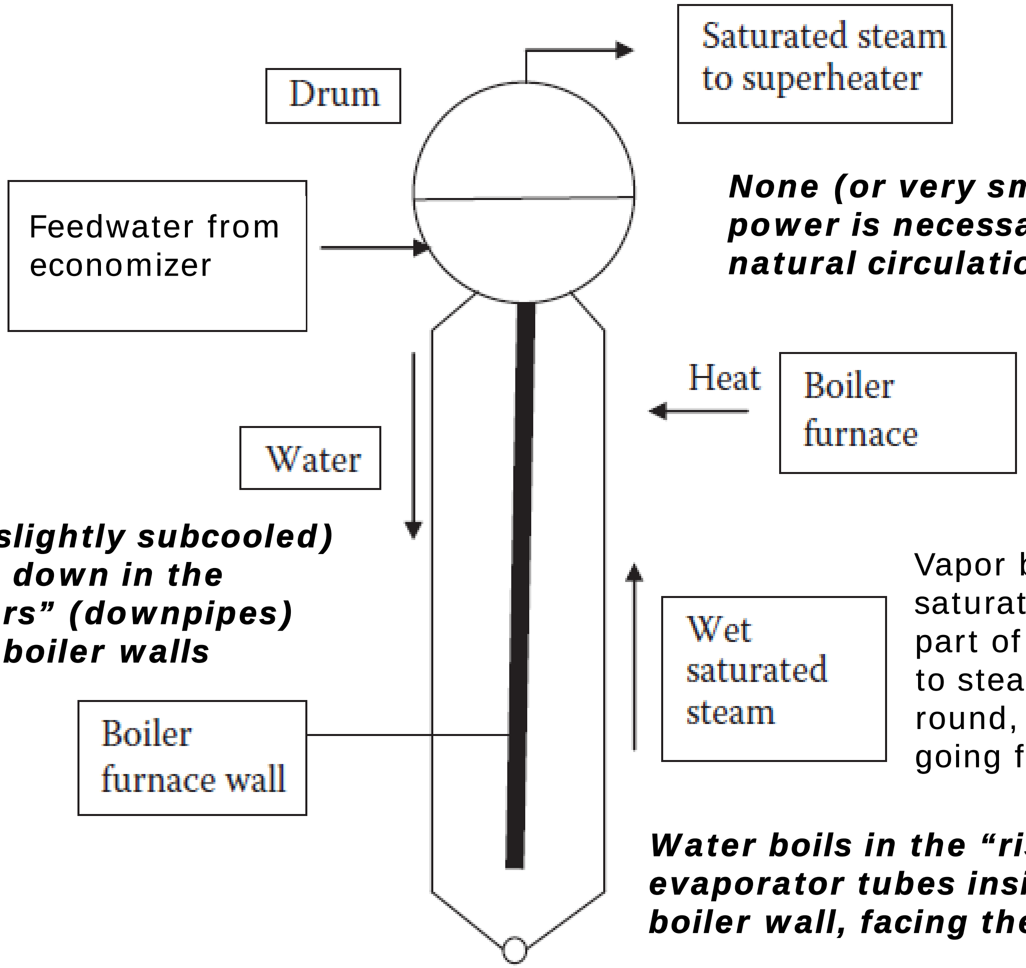
Evaporation should not happen in the economizer.



Saturated steam is drawn from the steam drum and flows to the superheater tubes, after which it is directly sent to the turbine or to other users.

The evaporator section is situated around the combustion zone. Water boils in vertical pipes around the furnace. Saturated steam is collected in the steam drum.

Natural circulation in a subcritical boiler



Drum

Saturated steam to superheater

Feedwater from economizer

Heat

Boiler furnace

Water

Wet saturated steam

Boiler furnace wall

None (or very small) pumping power is necessary for the natural circulation!

Heat from the combustion zone

Saturated (slightly subcooled) water flows down in the "downcomers" (downpipes) outside the boiler walls

Vapor bubbles mixed with saturated water. Only a small part of the feedwater boils off to steam in one circulation round, the rest of the water going for another round.

Water boils in the "risers" - evaporator tubes inside the boiler wall, facing the furnace

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Source: Modified from:

Advanced Energy Systems,
N.V.Khartchenko & V.M.Kharchenko,
CRC Press 2014.

Steam Boiler with natural circulation

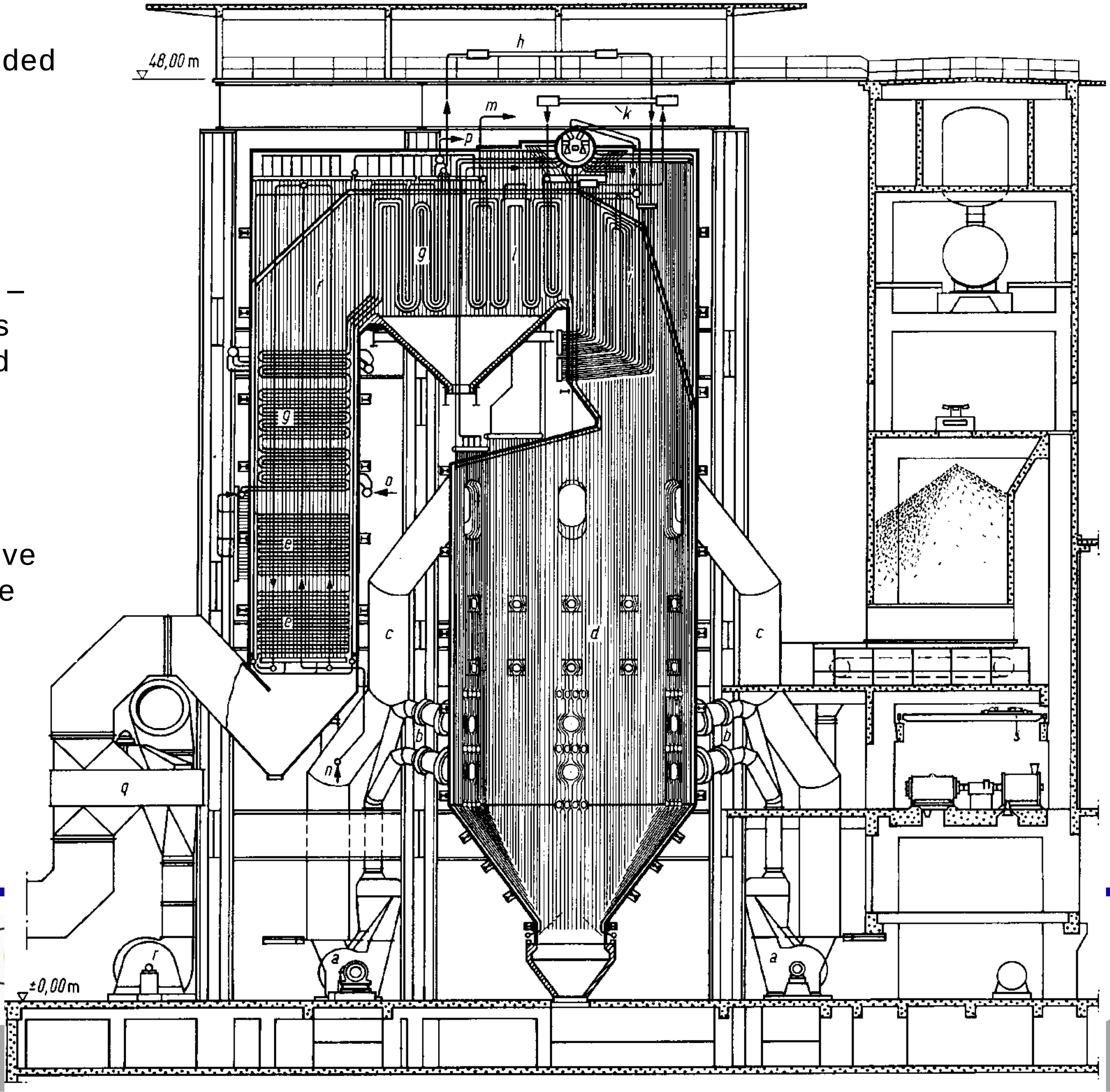
Combustion zone (d) surrounded by tube walls where water is partially evaporated under continuous recirculation.

Superheater & reheater (*g, l*) situated in the gas ducts.

Steam drum & steam header – highest up on top – separates the evaporated steam (*k*) and sends liquid water down for another evaporation round.

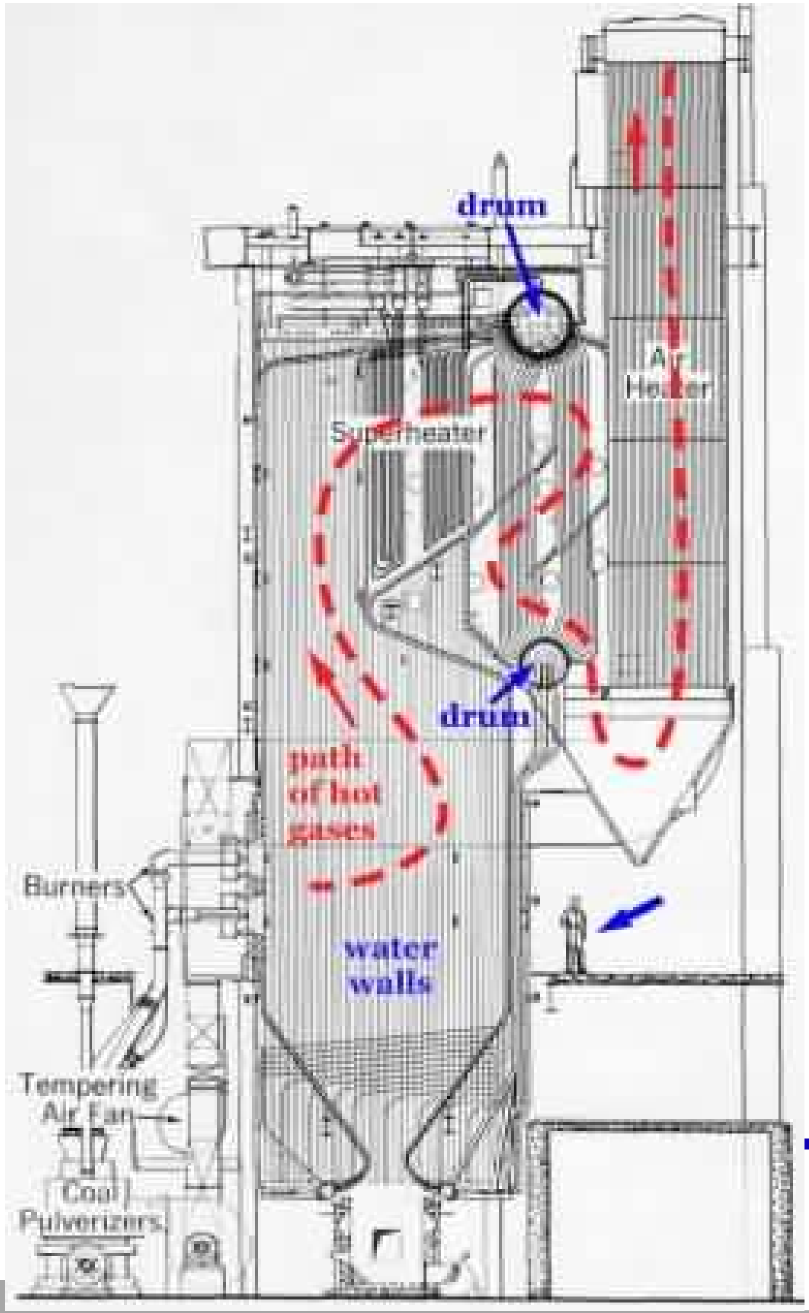
Economizer tubes (e) in the downward gas duct.

Air heater (*q*) as a regenerative preheater, or as a tube bundle at the exit of the gas duct.



Source: Karl Schröder ”Grosse Dampfkraftwerke”, Springer-Verlag 1966

Furnace & water-tube walls



Boilers are built entirely on-site, all tubes are welded together by hand, only some tube bundles of the gas duct may arrive preassembled but they still need to be fitted and installed by hand. Enormously difficult, costly, dirty and time-consuming job, demanding very skilled workforce.

Source: http://school.mech.uwa.edu.au/~dwright/DANotes/cylinders/applications/applications.html

Retention time of a burning particle

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Retention time is the average time that the burning fuel particles (and the produced hot gases) spend in the furnace zone and along the gas path – all the way from ignition to the boiler exit. This is a main design parameter for the boiler size and for the effective combustion process.

Too short retention time = incomplete combustion and/or insufficient heat exchange in the gas duct.

Too long retention time = slower flow of gases through the boiler = large, bulky and costly equipment.

Optimum retention time, depending on the type of fuel burned, would result in optimum boiler size and well balanced thermal loading of the furnace and the heat exchangers.

Other important parameters: rated thermal output; type of fuel; moisture and ash content of the fuel; steam pressure and temperature; desired performance at partial (off-design) loading…

The typical retention time in a modern heavy-loaded boiler fired with pulverized coal or with oil/gas fuels is about several seconds!

Steam boiler & steam plant process layout

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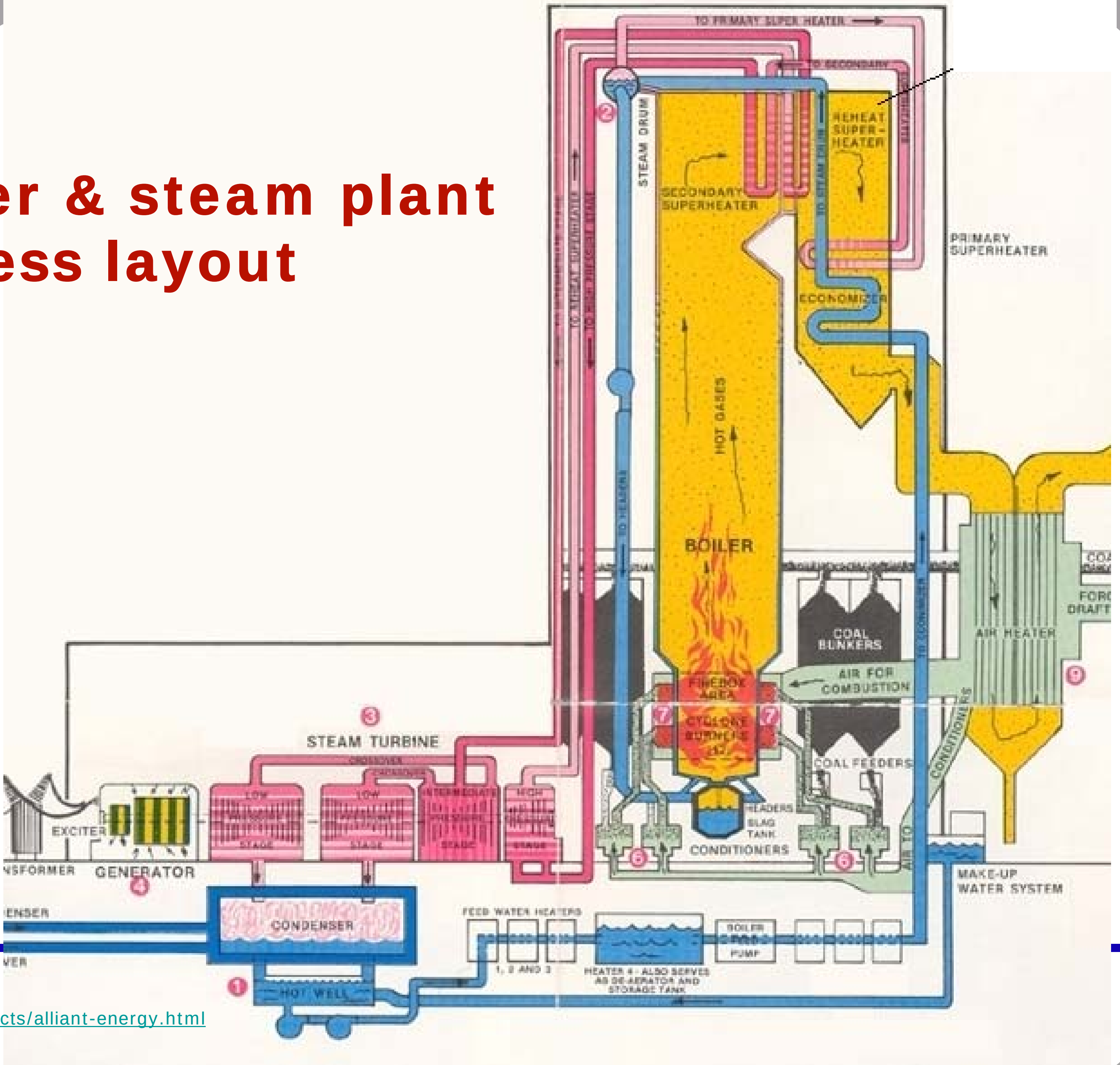

Source: www.jamarcompany.com/projects/alliant-energy.html

Shell-&-Tube (fin-tube) Air Preheater

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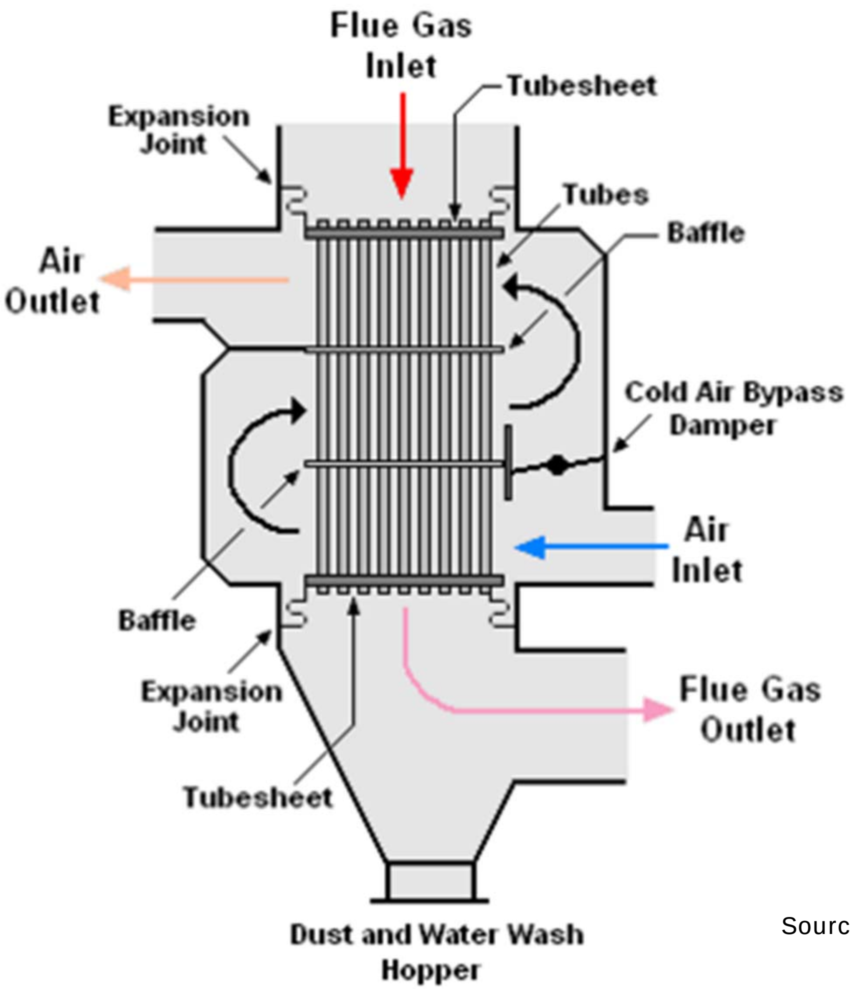


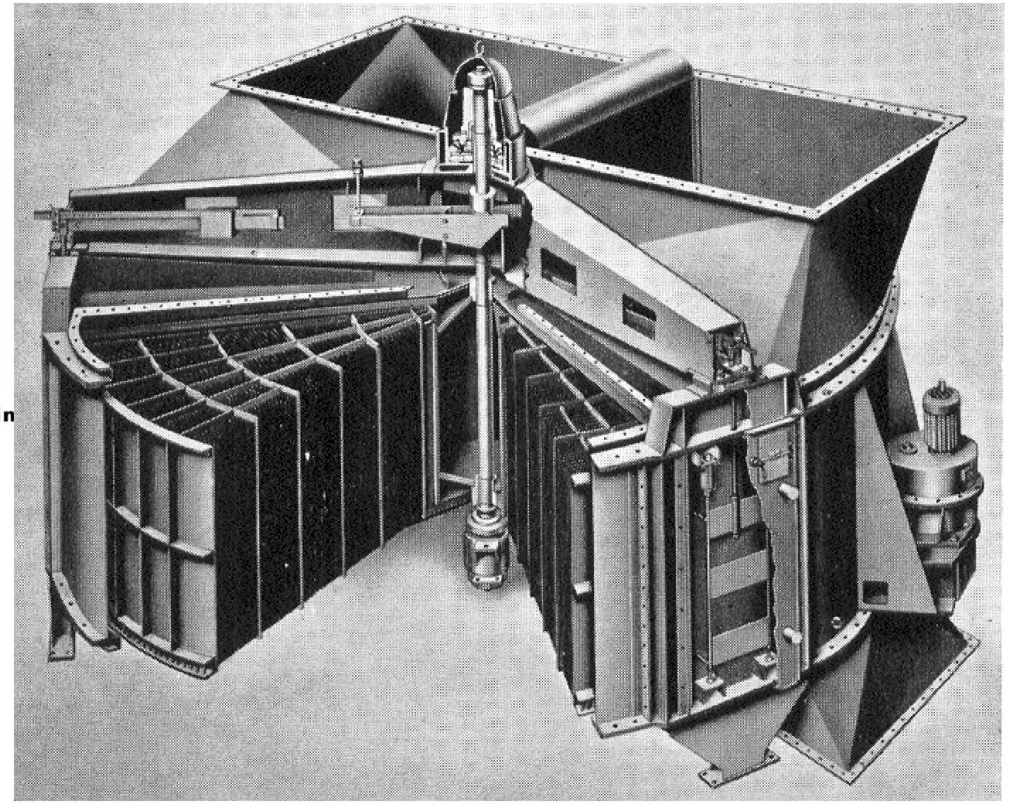
Used in small- to medium-size boilers.

Becomes very bulky for large-scale applications due to poor gas-to-air heat exchange process across the tubes.

Source: http://en.citizendium.org/wiki/Air_preheater

Regenerative Air Preheater (Ljungström)

The most commonly used air preheater for large steam boilers –
a massive rotating disk containing solid material acting as short-term heat storage



Source: Karl Schröder ”Grosse Dampfkraftwerke”, Springer-Verlag 1966

Source: www.balcke-duerr.com

Example of Mass and Energy Balance for the regenerative air preheater

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Source: Karl Schröder
"Grosse Dampfkraftwerke",
Springer-Verlag
1966

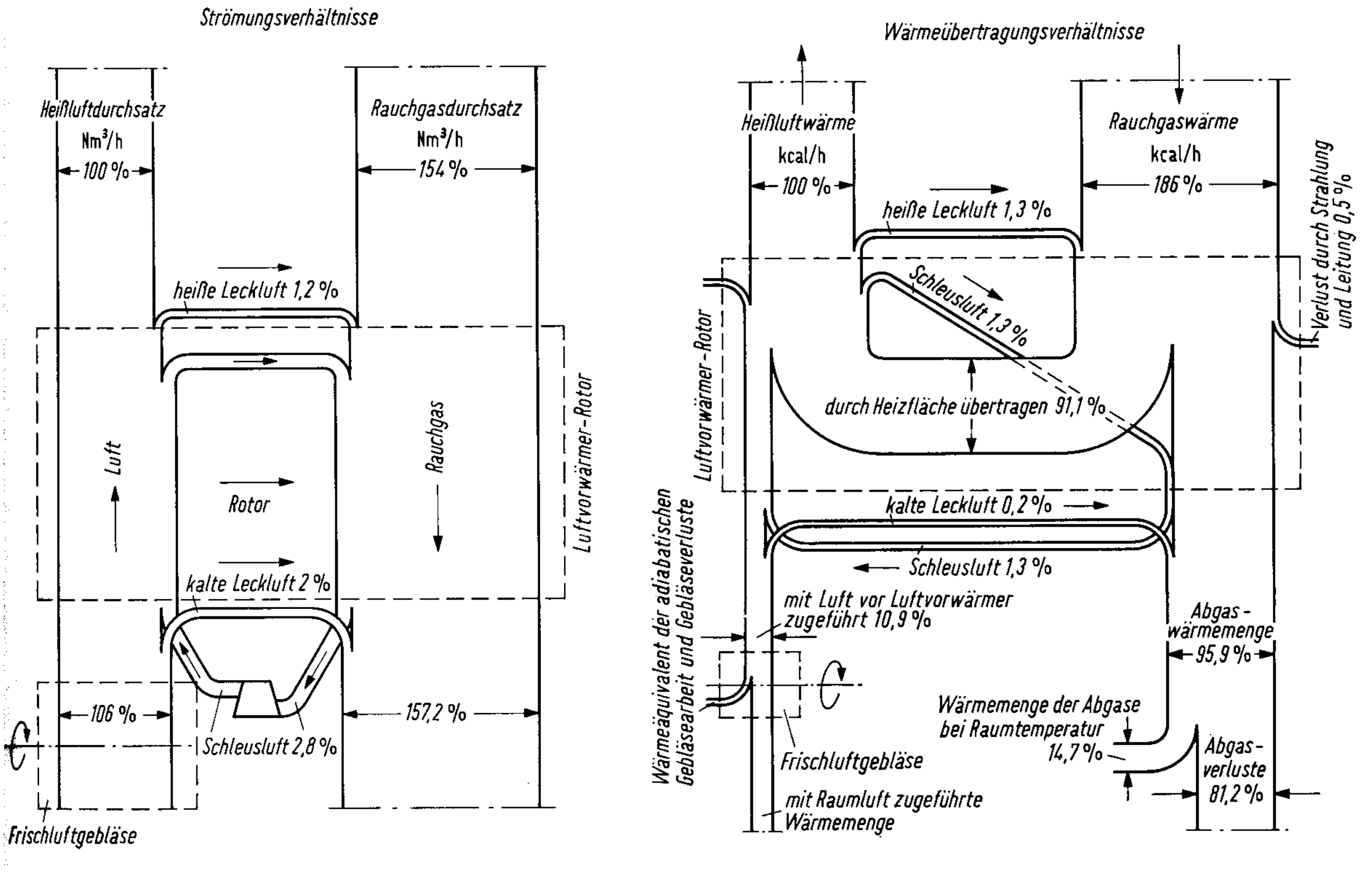

Abb. 165. Strömungsverhältnisse und Wärmeübertragungsverhältnisse beim Ljungström-Luftvorwärmer

Once-through Steam Boiler

Used for **supercritical steam cycles**. Also called "Benson" boiler.

No steam drum, no recirculation. All water passing the furnace walls is evaporated completely.

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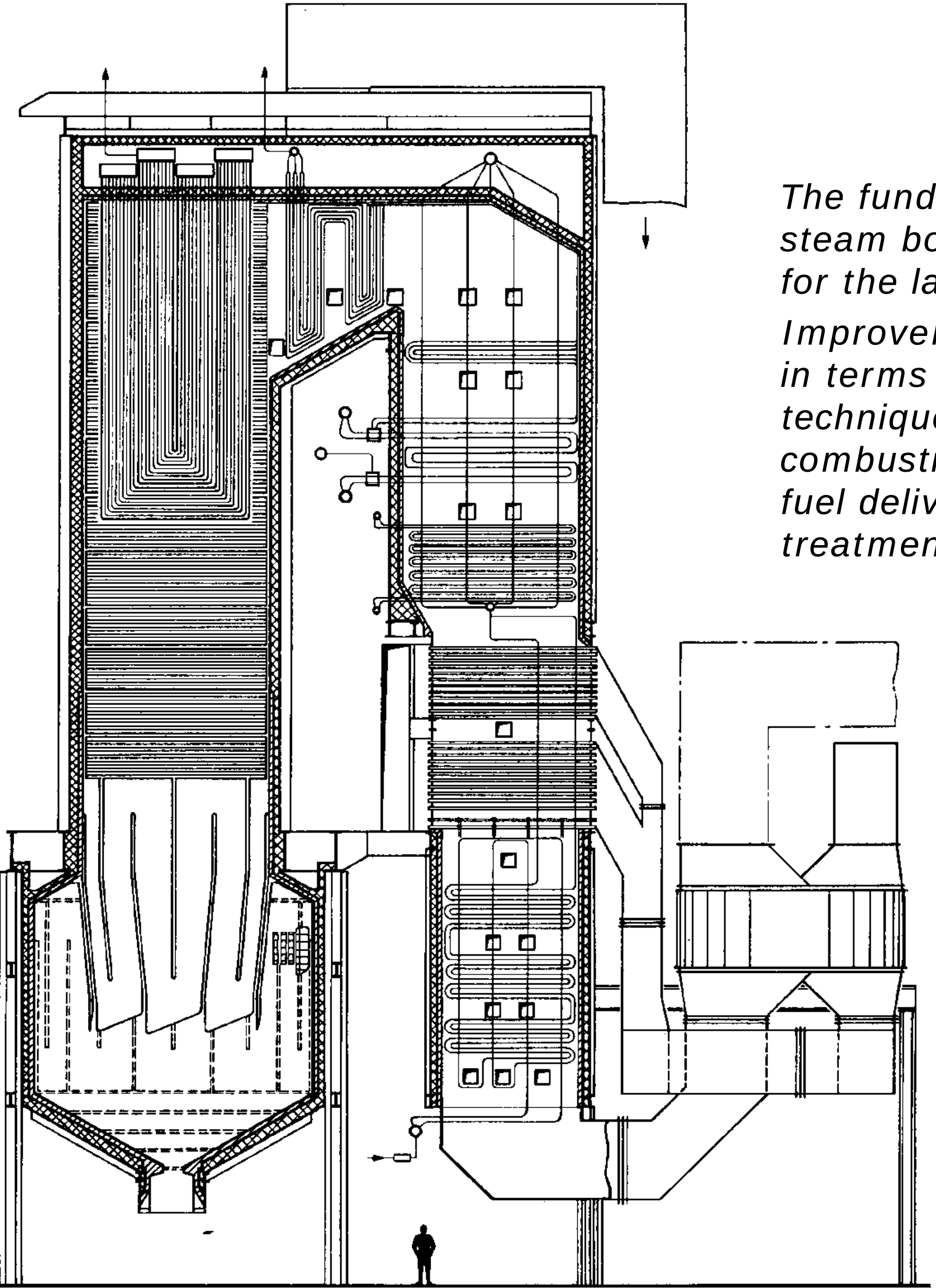


Source: Karl Schröder "Grosse Dampfkraftwerke", Springer-Verlag 1966

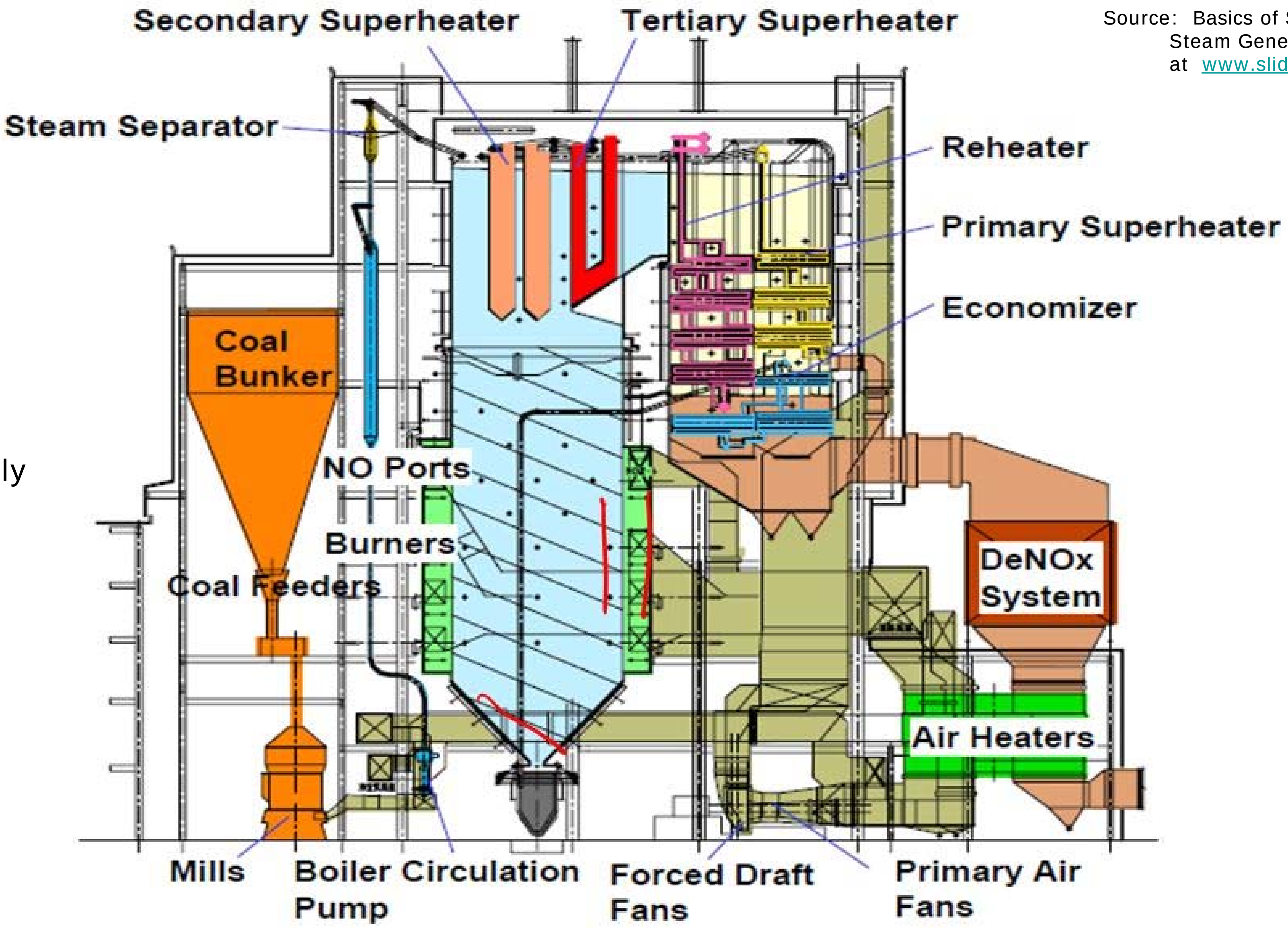
The fundamental design of steam boilers remains the same for the last ~100 years.

Improvements are made only in terms of materials, welding techniques, operation & control, combustion zone fluid dynamics, fuel delivery and flue gas treatment methods & systems.

Benson boiler with spiral wall tubes

Source: Basics of Supercritical Steam Generators, at www.slideplayer.com

Steam separator needs to be used instead of a drum, to safeguard the superheaters from receiving water droplets that have not evaporated fully



Fluidized Bed biomass-fired steam boiler

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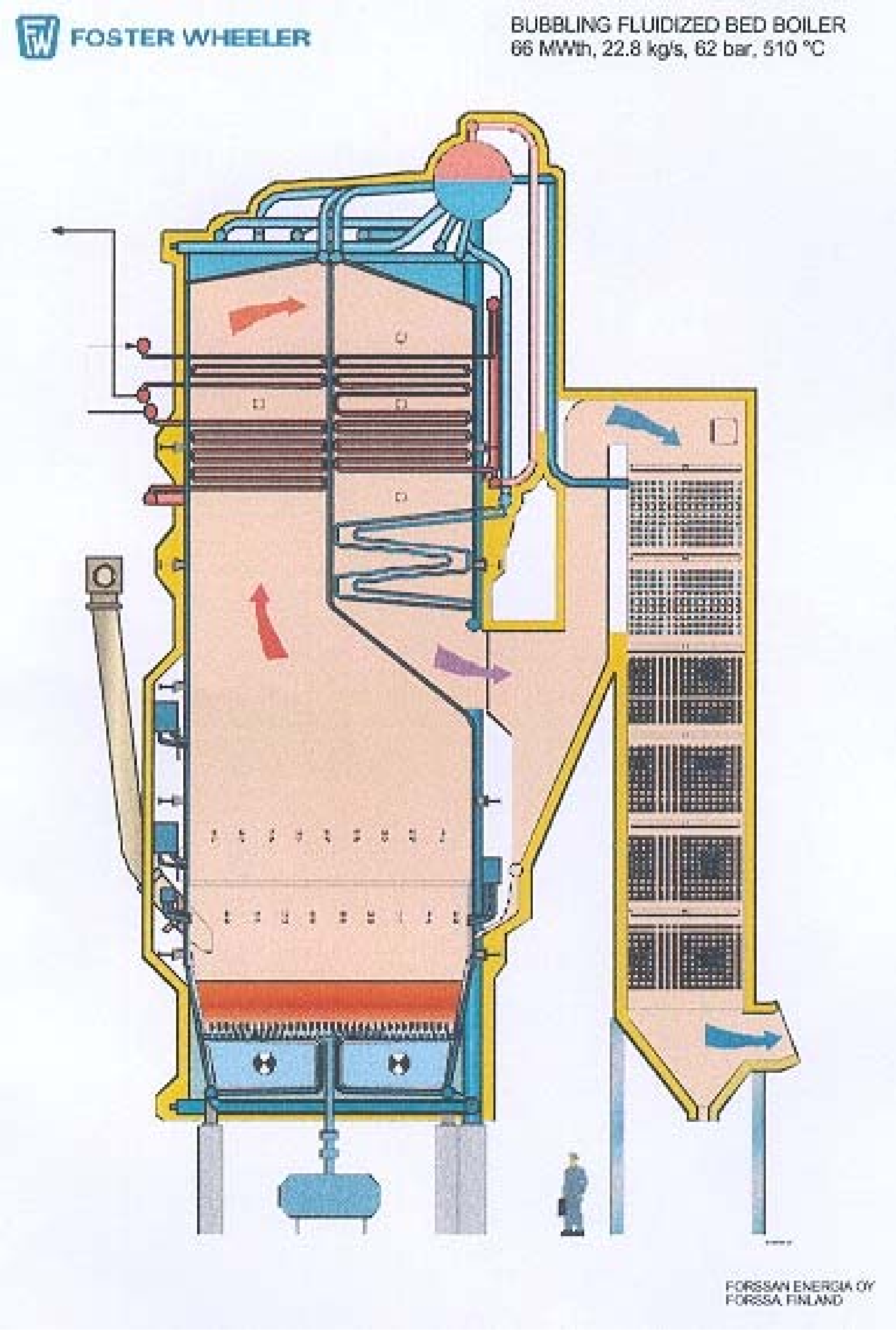
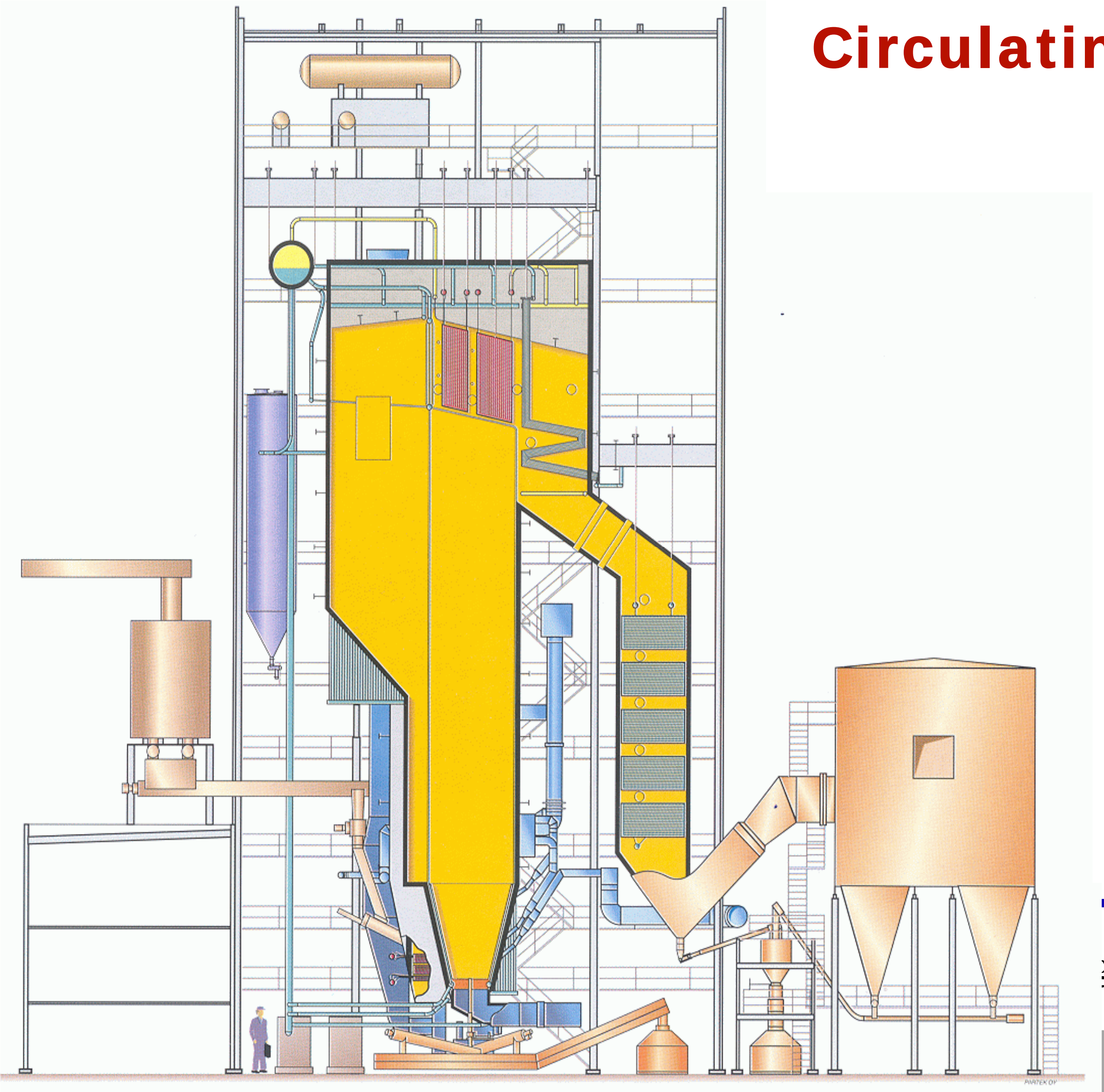
Achieves low NOx emissions and complete combustion for slow-burning solid fuels at long retention time





Circulating Fluidized-Bed Boiler

Usually used for coal, but also applicable to biomass or solid waste fuels

<u>Example Steam Data:</u>

Total fuel input	86.3 MWth
Steam flow	30.5 kg/s
Steam pressure	89 bar
Steam temperature	480°C
Feedwater temperature	120°C

<u>Wood waste fuel</u>	
Sulphur	0.07%
Moisture	~30 %
Ash	3%
LHV	12 MJ/kg

Advanced Biomass Combustion

The straw-fired boiler at the Avedøre steam power plant near Copenhagen, Denmark.
Superheat and reheat at 600^{o}C; with specific ash handling solution.

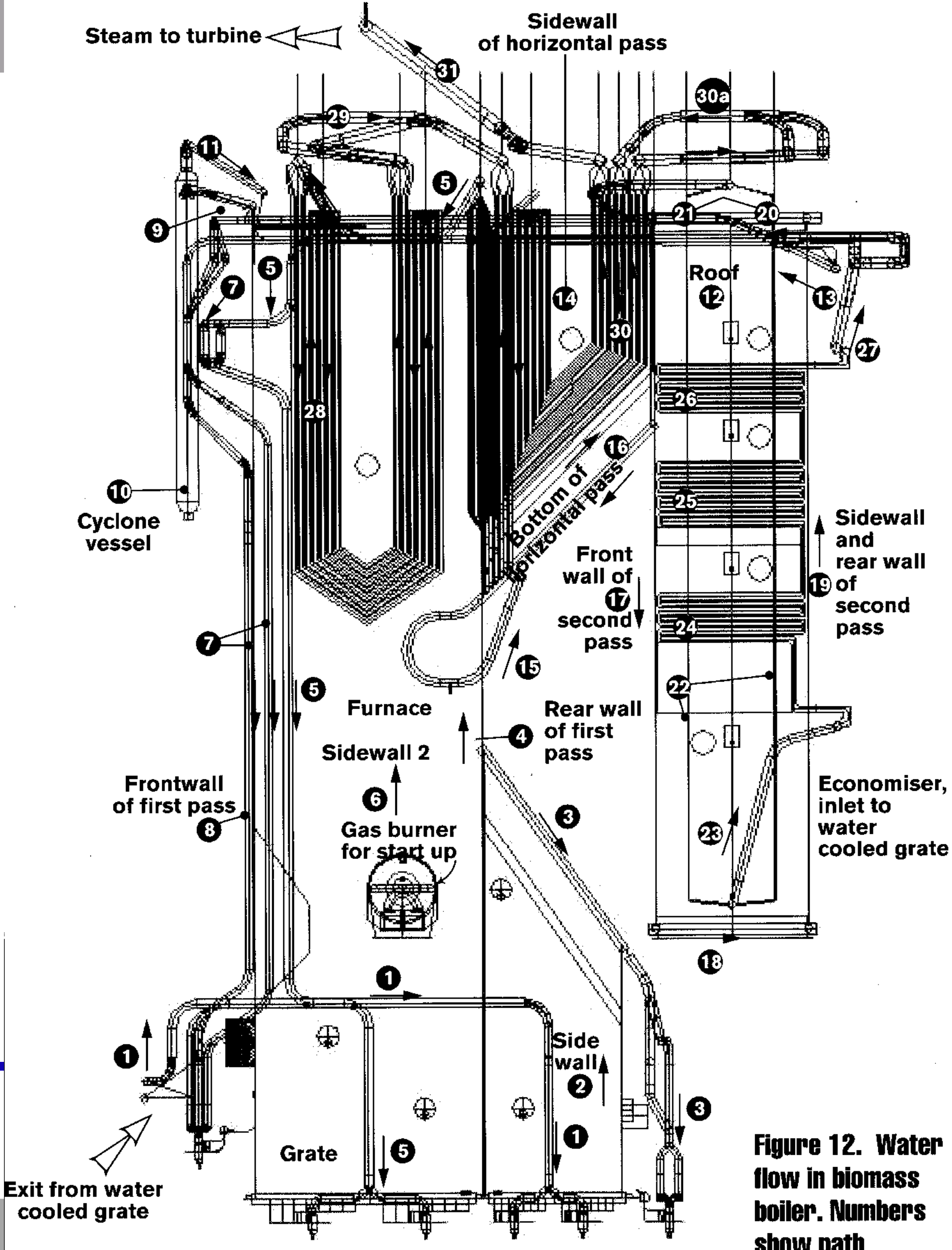


Figure 12. Water flow in biomass boiler. Numbers show path

Grate Combustor or Incinerator

Most common for biomass or waste (MSW) fuels, which cannot be crushed/pulverized and entrained in the air flow.

Fuel rolls down along the grate as it dries, ignites, and burns out slowly.

Air is supplied from below the grate (primary) and above the combustion zone (secondary).

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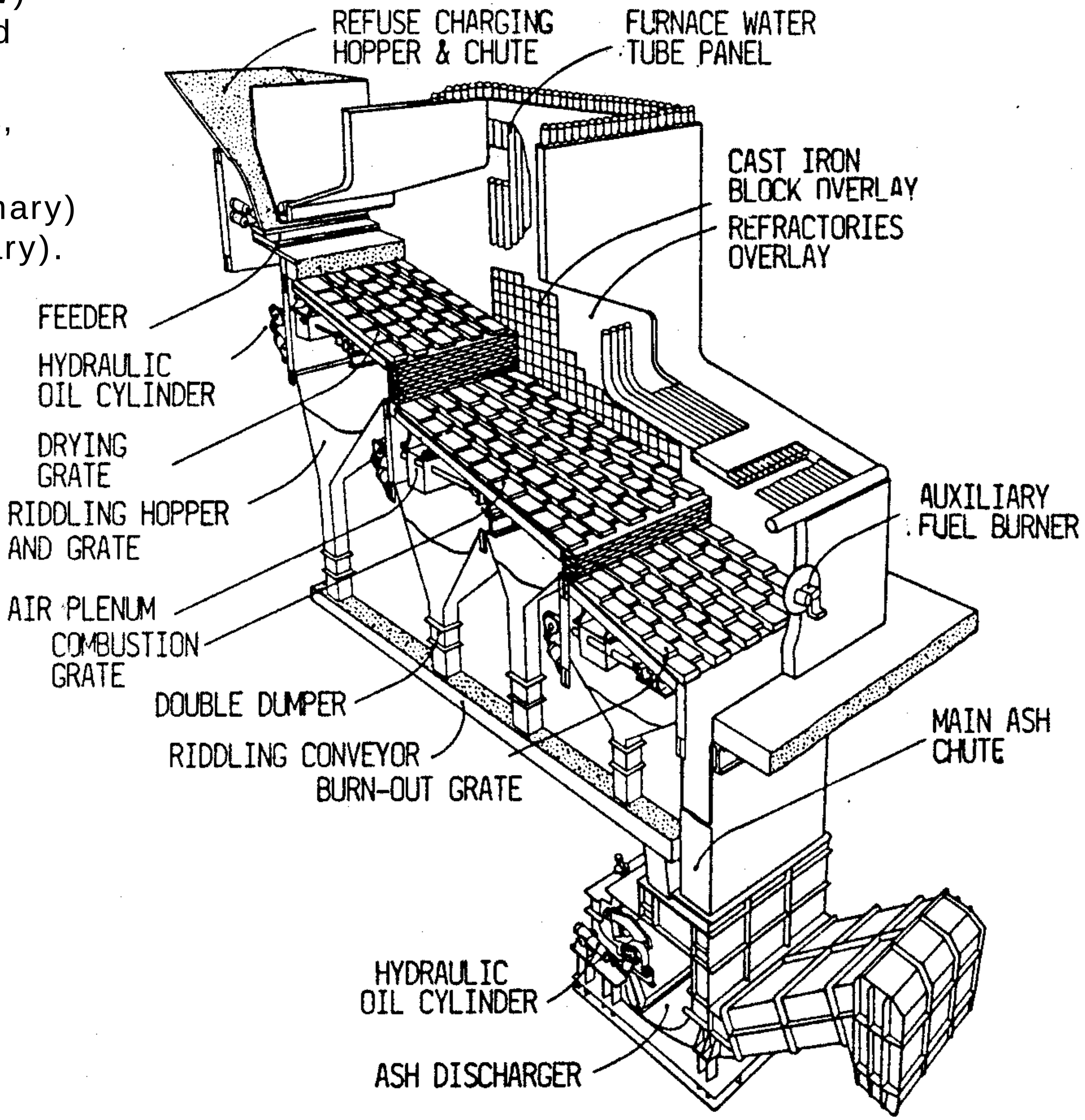
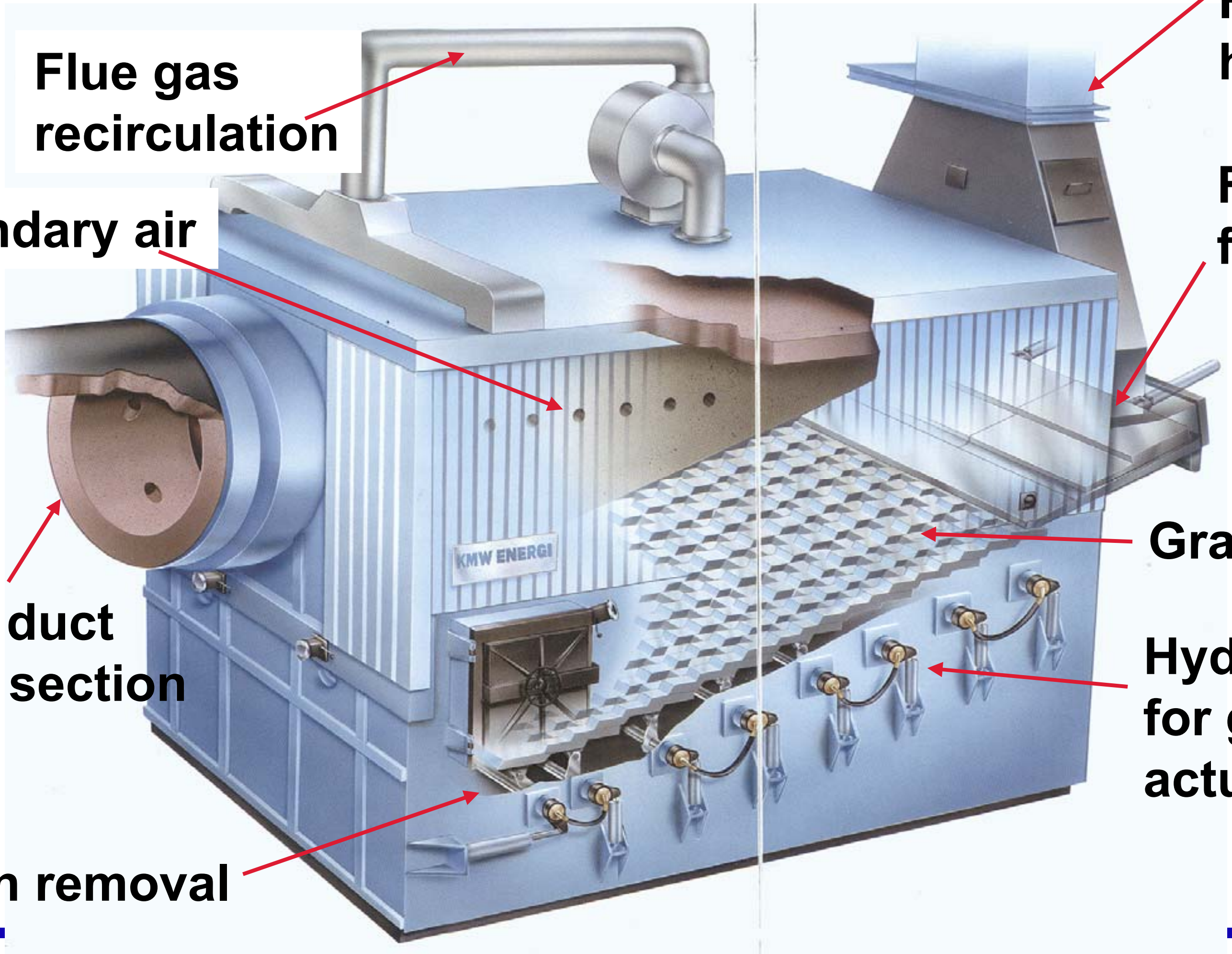


Small-scale biomass furnace with traveling or vibrating grate



Flue gas recirculation

Fuel supply hopper

Secondary air

Fuel feeder

Grate surface

Exhaust duct to boiler section

Hydraulics for grate actuation

Ash removal

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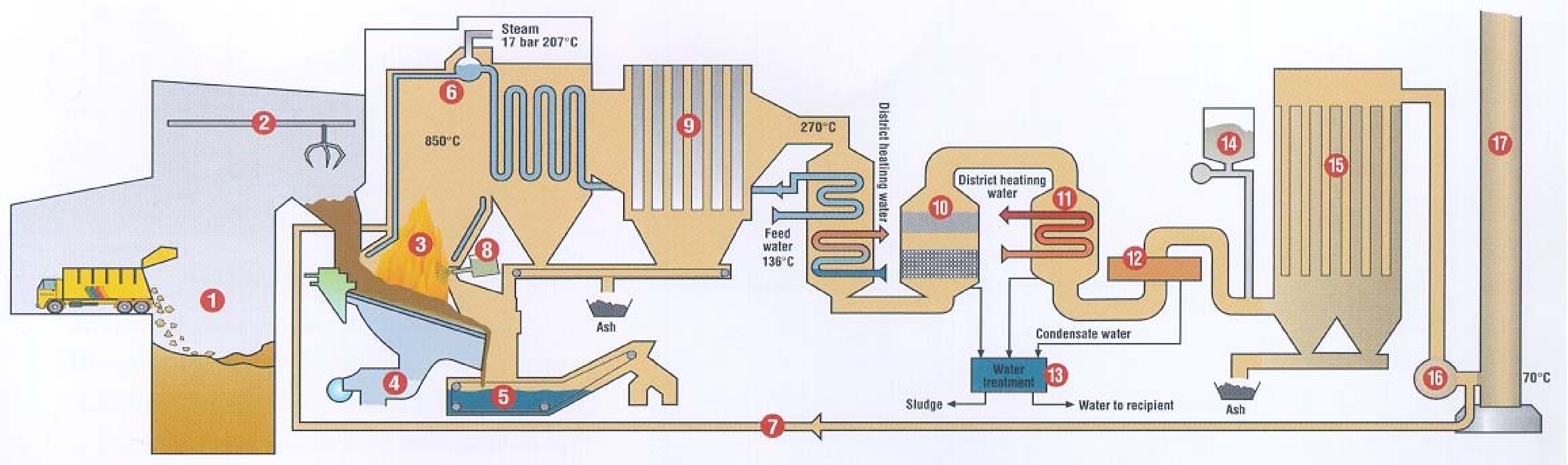
Source: www.kmwenergy.com

Municipal Waste Incineration Process



Municipal Solid Waste (MSW) incinerator with heat recovery and flue gas cleaning – showing here the old unit at the Gärstad plant, Tekniska Verken AB in Linköping, Sweden.

The flue gas treatment section is larger than the boiler itself. Vicious pollutants could be produced during incineration of waste, therefore rigorous flue gas cleaning is required.

Heat Recovery Steam Generator

Generating steam by using any available flow of hot gases coming from another process, with or without additional combustion, usually from gas turbine exhaust or industrial furnaces.

Horizontal and vertical arrangements of a typical HRSG for combined cycles:

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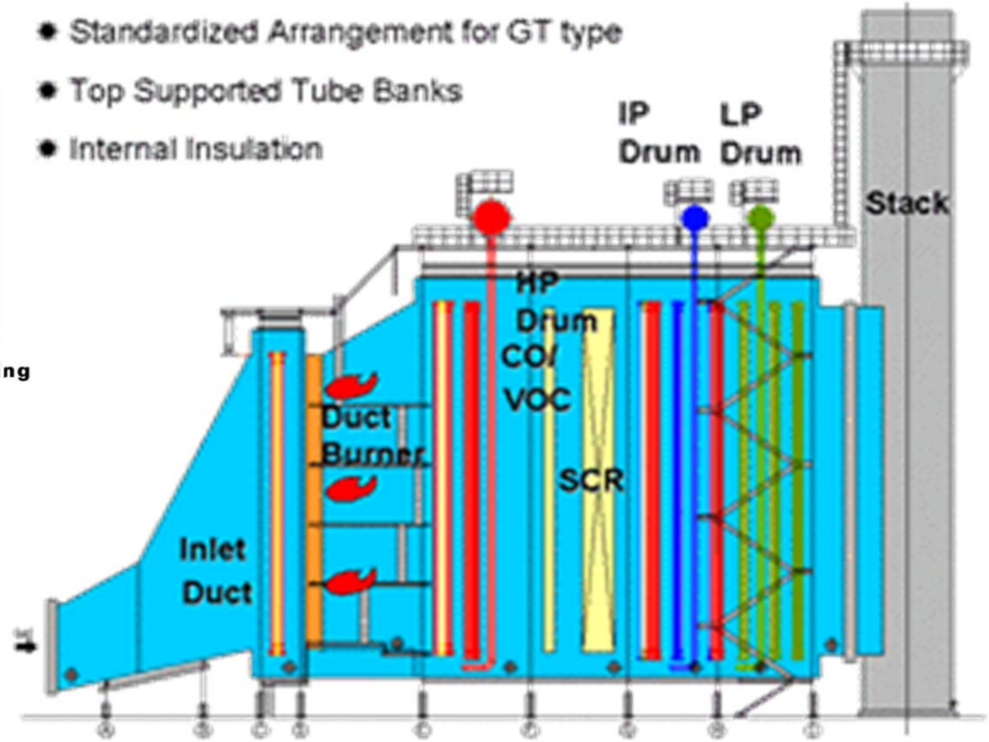
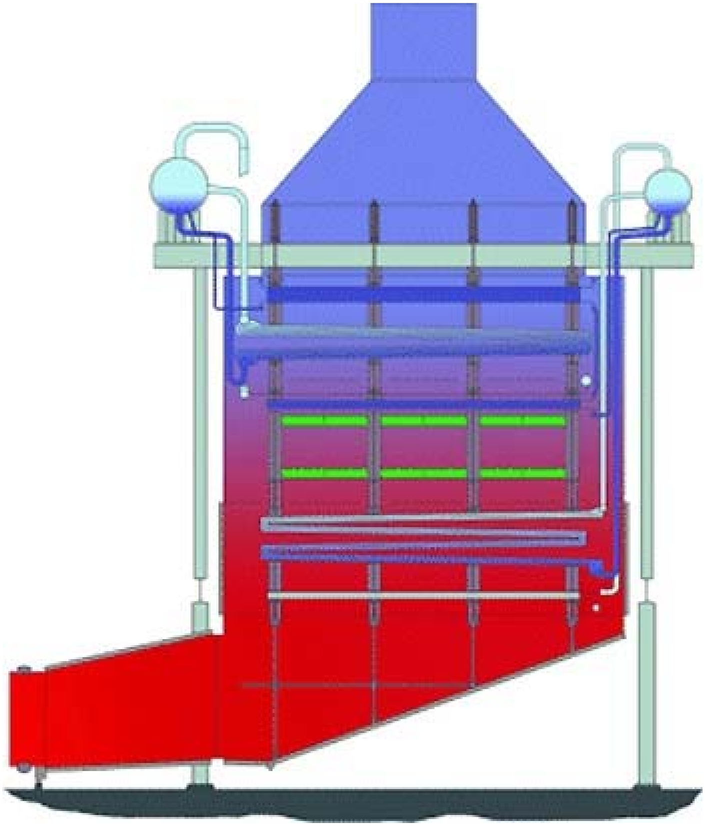


Source: www.bhpi.com.ph



Source: www.cicloscombinados.com

Pollution from the power sector

Pollutants are resulting primarily from the combustion process in the boiler furnace (or in a combustion chamber), not by the thermodynamic cycle itself.

- **Local pollution (dust, soot, flyash)**
  Solution: Higher chimney for better spreading of flue gases in the atmosphere. Scrubbing away fly-ash to >99% by electrostatic precipitators (large plants) or in bag-filters (smaller plants).

- **Regional pollution (SOx, NOx, other acid or toxic compounds)**
  Solution: DeSOx and DeNOx systems plus low-NOx burners are now state-of-art for all new boilers. Gas scrubbers continue to be improved. Other pollutants can be captured by the bottom-ash or extracted from the gas flow by water-wash or absorption/adsorption processes; or entrained in the fly-ash and separated in the ash filter or in the de-SOx unit.

- **Global pollution (CO_2)?**
  Solution for fossil fuels: *Carbon capture before or after combustion by several possible methods...*
  Follow the lecture about CO_2 capture and sequestration later in this course.

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Energy losses in a boiler

Types of losses in a typical steam boiler:

- Thermal losses with the high temperature of flue gas released to the atmosphere through the stack (after all heat exchangers).
  Cannot be too low because gases should be able to rise high and spread out well in the atmosphere, plus that corrosive condensation on cold surfaces should be avoided.
- Thermal losses with ash being discarded from the combustion zone.
  Heat from ashes could be used for feedwater preheating in various sorts of "ash coolers".
- Chemical losses with unburned solid fuel particles (soot).
  Should be decreased by combustion improvements.
- Chemical losses with unburned gaseous compounds – mostly CO (carbon monoxide) and UHC (unburned hydrocarbons).
  Again, should be decreased by combustion improvements.
- Mass losses with water blow-down for salt control and with steam injection in gas duct for cleaning of soot from tubes.
  Mostly unavoidable and comparatively small.
- Thermal losses with heat radiation from boiler walls to surroundings.
  Decreased by better outside wall insulation. If the boiler is housed in a building, the air for combustion will be taken from the upper part of the building so that most of the radiation and convection loss is thus brought back into the boiler with the warm air.

Defining the boiler efficiency

Can be done in two ways – direct and indirect:

Direct efficiency calculation:

Energy transferred to steam
vs. Energy contained in the fuel

Challenges:

Both the steam flow and the fuel mass flow can often be very difficult to measure precisely!

Indirect efficiency calculation:

Measuring all major losses and subtracting them from unity

Advantages:

It is often easier, cheaper and more precise to measure the loss parameters rather than the steam and fuel flows!

Major losses can be defined by measurements of temperature and chemical composition, very easy.

Sometimes the indirect method is the only applicable option for assessment of old boilers or at partial load conditions.