1

PRINCIPLES OF STEAM GENERATION

CHAPTER OUTLINE

The development of the industrial age coincided with the development of heat engines (Morris, 2010). It was the steam engine that liberated man from mainly toiling the land and afforded him the means of improving his living conditions. Currently there are four main types of heat engine in use: internal combustion reciprocating engine, gas turbine, steam power, and rocket engine (Ishigai, 1999). Steam power is dominant in electricity-generating thermal power stations. The part of the process that is used to generate vapor is called steam generation.

The first steam generators developed around coal, especially to pump water away from deep coal mines. Biomass utilization for steam generation started at the same time in regions where coal was expensive. Steam generation from sustainably sourced biomass is gaining more interest as restricting global warming is gaining importance. The Intergovernmental Panel on Climate Change (2011) is of the opinion that, compared to the fossil energy baseline, one can achieve 80–90% fossil carbon dioxide (CO_2) emission reductions when using energy generated from biomass. The International Energy Agency (2014) in their world energy outlook expects bioenergy electricity generation in their 450 scenario to increase fivefold from 2012 to 2040.

1.1 Introduction

A steam generator that uses combustion as its main heat source is often called a boiler. Water that is converted to steam

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is the most common fluid used in heat engines, which convert heat to work. Steam generation was actually first introduced in apparatus designed to convert heat to the work required for pumping water from mines. For process applications, heat from a steam generator can be used directly to serve the required process purposes (e.g., district heating by steam). In steam generation the heat source, combustion, and the working fluid are separated, typically by a wall of heat-resistant material (e.g., steel tubes).

Electricity generation is one of the main uses of steam generators with a turbine. We can compare currently predominant electricity-generating options in Table 1.1. It can easily be seen that none of the currently prevalent processes totally fulfills the most desired features.

Of the listed processes the most typical ones for new installations are still coal-fired boilers, natural gas combined cycle and biomass-fired steam generators. It should be pointed out that biomass is a renewable source of electricity and produces no net fossil CO_2 (IPPC, 2011).

> ***Biomass is a primary source of food, fodder and fibre and as a renewable energy (RE) source provided about 10.2% (50.3 EJ) of global total primary energy supply (TPES) in 2008.*** *Traditional use of wood, straws, charcoal, dung and other manures for cooking, space heating and lighting by generally poorer populations in developing countries accounts for about 30.7 EJ,*

Table 1.1 Comparison of electricity Generation Options (Rogan, 1996)

Process	Cost of Electricity	Reliability/Availability Technology	Reliability/Availability Fuel	Environmental Emissions	Environmental CO_2 (t/MWh)
Most desirable	Low	High	High	Zero	Zero
Coal (pulverized fuel combustion)	Low	High	High	Low	1.0
Coal (advanced)	Medium	?	High	Lower	0.8
Natural gas (combined cycle)	Low	High	Varies	Lower	0.6—0.4
Nuclear	Medium	High	High	Zero	Zero
Biomass	Medium	High	Varies	Low	1.5
Solar/Wind	High	?	Varies	Zero	Zero
Fuel cells	High	?	Varies	Lower	0.3
Hydro	Low	High	Varies	Zero	Zero

> *and another 20 to 40% occurs in unaccounted informal sectors including charcoal production and distribution. TPES from biomass for electricity, heat, combined heat and power (CHP), and transport fuels was 11.3 EJ in 2008 compared to 9.6 EJ in 2005 and the share of modern bioenergy was 22% compared to 20.6%. (IPPC, 2011).*

All CO_2 produced by biomass combustion is absorbed back into the forests and other natural biomass, assuming sustainable practices are used.

What will the role of steam boilers be in the future? The world energy consumption keeps on increasing. Currently about 70% of world electricity generation is done using thermal processes. Even with a shift to renewable sources, electricity generation based on steam power plants will continue to grow. In spite of progress in renewable energy, world coal consumption is still expected to grow (IEA, 2015). If we can significantly increase steam generation from biomass, we have the possibility to dramatically decrease our carbon footprint.

1.1.1 History of Steam Generation

There is evidence of the use of steam for motive power as far back as the Ancient Greeks (the first mention is by Heron in 200 BC). The Greeks and Romans used water heaters that have many of the features of modern boilers. Their hot water boilers were for domestic use only. The one in Fig. 1.1 (Croft, 1922) was internally fired, made from bronze and had a water tube grate. You placed the fuel on the grate and let it burn using a natural draft to transfer the heat from combustion to the water inside.

After 1600 there was renewed interest in steam. The French, English, and Russians used steam to drive water up into water fountains. Some of the people involved with the first applications of steam were Frenchman Denis Papin, Englishman Samuel Morland, and Italians Galileo Galilei and Evangelista Torricelli.

1.1.1.1 Early Boilers

Boilers were first used for industrial application in England in the 1700s, initially for pumping water from mines. These boilers had a very low efficiency, but as fuel supply was plentiful and the duty required could not be met by manual labor, they replaced horse-driven pumps.

The first practical steam engine was made by Thomas Savery in 1698. Even though it produced positive power, the operation could not be kept going for very long. One of the first commercially successful boilers was John Newcomen's boiler in 1712,

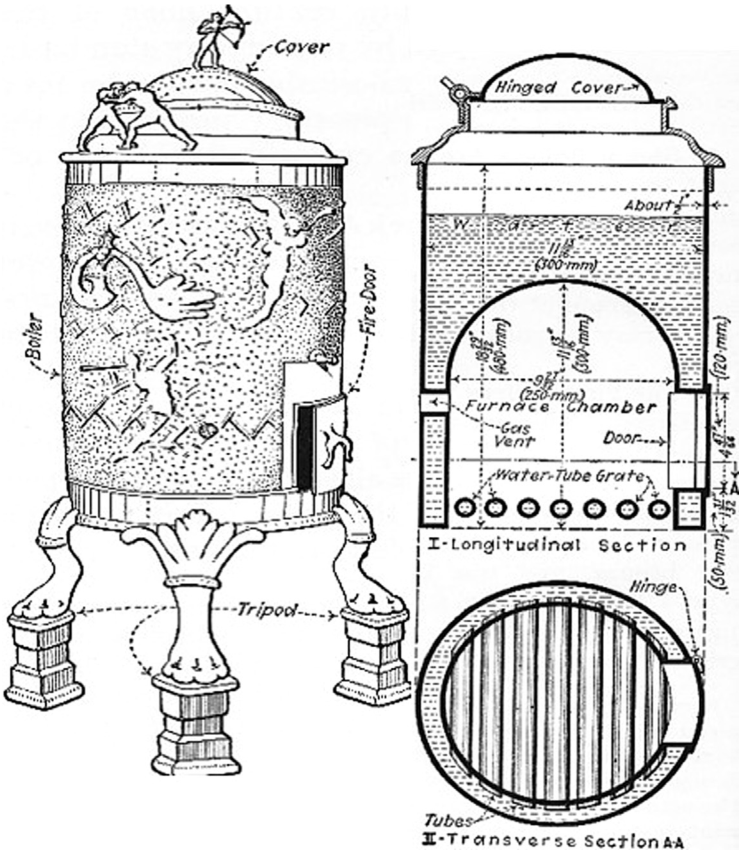

Figure 1.1 Pompeian water heater (Croft, 1922).

Figure 1.2 (Ishigai, 1999). It was the first example of a steam-driven machine capable of an extended period of operation.

This type of boiler was called the shell or spherical boiler. It was made using soldering and bent metal sheets. The Newcomen's boiler was made from copper, but iron soon replaced copper for increased pressure. Soldering was done with lead. The available steam temperature increased up to 150°C.

The first industrial biomass boiler was most probably built by Mårten Trievald in 1728 (Ångteknik, 1945), Fig. 1.3. It was one of the first outside England and was built at Dannemora Grufwor, Sweden with the intention to pump water out of the copper mines there. Because of the lack of coal, it was fired with wood (Lindqvist, 1984).

The first steam engine in the United States was built in 1754 to pump water from Schuyler Copper Mine in New Jersey (Hunter, 1985). Little is known about it except that it was built

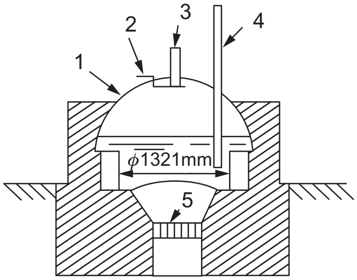

Figure 1.2 Newcomen's boiler: 1—Shell over the boiling water; 2—Steam valve; 3—Steam pipe; 4—Float for water level; 5—Grate (Ishigai, 1999).

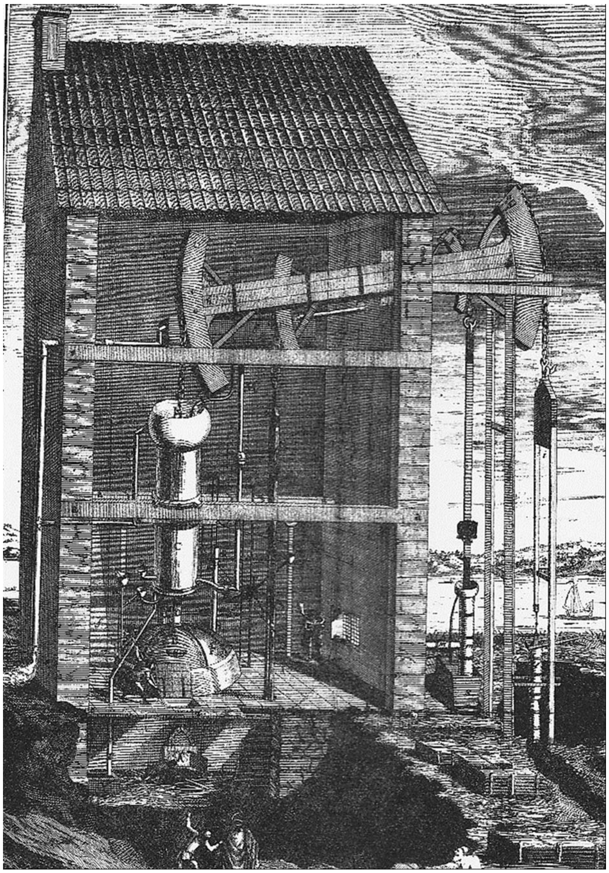

Figure 1.3 Mårten Trievald's 1728 boiler.

from components imported from England and reportedly operated for more than half a century.

Later the spherical design was replaced by a wagon-type design for increased capacity. The wagon type also had a higher heat transfer surface per unit volume of water so efficiency was increased (Dickinson and Jenkins, 1981).

James Watt's improved steam engine led to rapid growth in steam boilers. Even though the efficiency of steam production was about 2%, these boilers could be used for extended periods of time. Boulton and Watt supplied the steam boiler and engine to Robert Foulton's 1807 famous first steamboat, *Clermont*, which started the era of commercial steamboat operation.

Steam production from boilers steadily increased. Pressure stayed low because of problems with reliable construction. One or two bars overpressure was the norm. Because of the low pressure there were few explosions resulting in fatalities.

The next development was the cylindrical steamboat boiler, which was invented by Oliver Evans and Richard Trevithick around 1800. The flue gas passed through and around two cylinders joined together, Fig. 1.4 (Forsman-Saraoja, 1928). Hence it was given the name cylindrical boiler. It had a larger heat transfer surface per unit of working fluid than the wagon boiler. Therefore the cylindrical boiler could be built more cheaply than the earlier boilers. In England these boilers were called the Lancashire and Cornish boilers.

Contaminants in the feedwater tended to settle in the bottom. For wagon boilers, which were heated by the flue gas from the bottom, this was a constant source of problems. Cylindrical boilers had the advantage that they could be built so that heat was transferred through less clogged portions of the pressure vessel. It was also easier to increase the design pressure of cylindrical boilers and in the mid-1850s the boiler pressure reached 4–8 bars. Because there was only a minor efficiency increase associated with a pressure increase when steam engines were used, the drive to increase pressure was low.

Many of the early cylindrical boilers were made of cast iron as making reliable joints was still very difficult. But development of riveting and steel making processes soon made cast iron obsolete. Cylindrical boilers were later expanded to contain several passes and eventually developed into the fire tube boiler (Lobben, 1930).

The water tube boiler was created at the end of 1800. It was first used to run the largest steam engines but it quickly became the boiler type of choice for steam turbines. The developing new industry, electricity generation, demanded boilers to drive large generators.

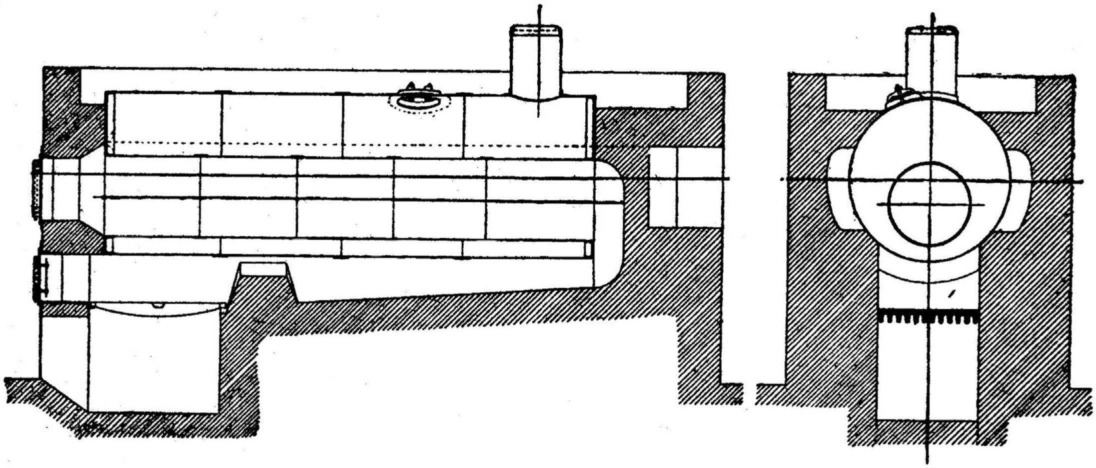

Figure 1.4 Cylindrical boiler (Forsman-Saraoja, 1928).

Water tube boilers employed a new principle. Heat in flue gas was transferred to the tubes containing water/steam by radiation and convection. The large number of tubes and the use of cross gas flow increased the available heat transfer surface and heat transfer rate. Boilers of this type could again be built for higher pressure and with a larger heat transfer surface per unit of working fluid than the fire tube boiler, Fig. 1.5 (Croft, 1922).

Wilcox, which manufactured water tube boilers, eventually merged with Babcock to form Babcock & Wilcox. The company became widely known when its boilers were employed by the Thomas Edison Company in the world's first utility electricity-generating station in Pearl Street, New York, in 1882.

1.1.1.2 Manufacturing Developments

In Wilcox's water tube boiler we can see the internal bracing put into increase the boiler's ability to withstand overpressure. Design features that aided in balancing stresses can be seen in almost all of the boilers of this era. The steel used for boiler construction started to improve dramatically as new steel manufacturing processes came into use. The Bessemer converter and Siemens-Martin open hearth steel making processes were invented around 1860. Mannesman's seamless tube manufacturing was patented in 1885. Steel prices decreased. The quality of steel improved and thicker and heavier pieces of steel could be manufactured. All this helped boiler design and manufacture.

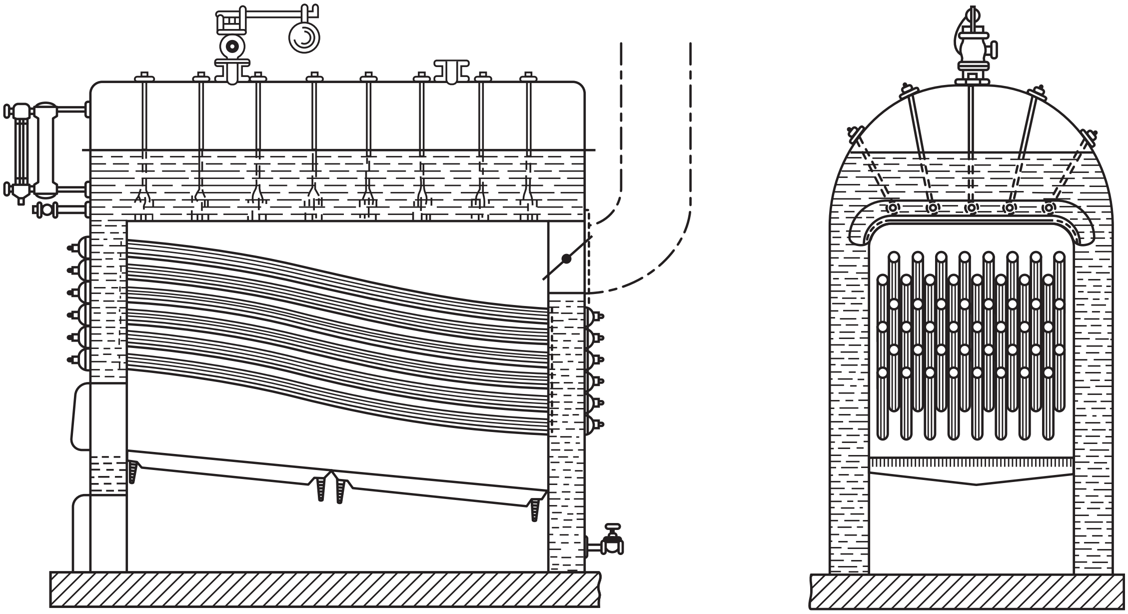

Figure 1.5 Wilcox's water tube boiler, 1856 (Croft, 1922).

Tubes could be made inexpensively and with higher quality than plate. Steel manufacture limited the practical plate thickness to 20 mm, so the use of tubes instead of sheets for boilers started to dominate. Soldering was replaced by riveting. In riveting, two sheets of metal are joined together by inserting very hot steel nuts, which are forged to form while still hot (Shields, 1961). When rivets cool down, they shrink, creating a tight seam. Riveting quickly became the main manufacturing method. Riveting remained the most used manufacturing method until the 1950s.

Another manufacturing development was the invention of forming. Here the metal is pressed with a mechanical device until the metal is permanently deformed. In boiler manufacture, forming is mostly used in the creation of rolled joints. In rolling, a tube is fastened to a drilled hole in a metal sheet by the expansion of the tube by thinning its wall. The principle employed is simple. A tube is placed in a tight-fitting hole. A special tool is inserted into the tube. By applying pressure that exceeds the steel's deformation pressure, the tube's thickness is decreased, a small section at a time. While the tube's thickness decreases, the tube's diameter increases. When the tube's outer diameter is larger than the hole's diameter, a tight join has been created. The rolling of tubes is a very successful method of low pressure joining. Rolling is successfully used even today in commercial boilers under 10 MPa.

The era of large boilers began with the invention of welding. Welding forms the basis of modern steam boiler manufacture. Welding is universally used in all modern boiler manufacture. The 1930s saw the first application of welding to boiler manufacture. With the development of X-ray technology to inspect the welds, welding became popular during the World War II.

Around 1955 the fully welded furnace (membrane wall) was developed. This meant high savings in maintenance and started rapid unit size increases.

1.1.1.3 Increasing Efficiency

The end of the 20th century saw interest in increasing the energy efficiency of boilers and steam engines. Public tests and a gradual understanding of thermodynamics changed the steam engine design criteria. Increasing the working pressure increased the power from the steam engine but also decreased fuel consumption. The United States was initially slower than England in adopting high pressure boilers, Table 1.2. Increased pressure in the boiler meant a larger flue gas exit temperature.

Process efficiency could be increased by decreasing the flue gas exit temperature. Installing economizers in the flue gas canals behind the boilers was one means of doing this (Barth, 1911). (The incoming water was heated in the economizers.)

The problem remained of how to build boilers that could withstand increasing pressures. The next innovative step was the emergence of the drum boiler. This coincided with the spread of a new manufacturing technology: forming. This allowed a cheap and reliable joint to be made between a drum and a tube. This meant that boilers could be built with just

Table 1.2 Increase of working pressure (MPa) of boilers in England and the United States

Year	1800	1818	1830	1843	1852	1870	1888	1900
England	0.12	0.26	0.34	0.40	0.66	0.83	1.00	1.37
United States	0.14	0.15	0.17	0.19	0.22	0.51	1.25	2.07

Source: Data from Hills, 1989 and Thurston, R.H., 1897. Promise and potency of high pressure steam. Transactions of ASME, vol. 18. pp. 1896–1897.

tubes and drums. A new class of boiler—the multiple drum tube boiler—had been born. Some early designs incorporated a number of drums (Stultz and Kitto, 1992). Soon a boiler with at least two drums became standard.

The larger the diameter and the higher the operating pressure, the thicker the shell needed to be. Therefore the size of the shell boiler was limited to low pressures and small sizes. If larger units were required, multiple boilers needed to be operated. In late 1800 some 10 water tube boilers could be connected to a single steam engine or turbine. With drums and tubes connecting them, much larger boilers than before could be built. The steam drum was beneficial and the manufacture of larger units was much easier. With this design there was better control of water quality. A mud drum could be used to blow out unwanted contaminants.

The requirement for still greater unit sizes meant larger furnace volumes were needed. This meant that combustion and heat transfer were separated. Previously, refractory-lined furnace walls were lined with water tubes (Effenberger, 2000). The first boilers with water tubes on all walls were introduced in the 1920s.

The late 19th and early 20th centuries witnessed the emergence of electric lighting for individual homes and electric utility business. Pioneering work was done by Thomas Edison in the United States. This meant that the steam generation market started to grow fast and required the unit size to increase rapidly (Thomas, 1975). Steam engines were soon replaced by steam turbines, and the steam generation capacity of a single boiler climbed steadily upwards.

The early boilers did not have superheating as steam engine efficiency did not improve significantly with the inlet steam temperature. It was not until after the introduction of the steam turbine by Laval that superheaters started to be built. Reheating was first used in the 1930s but remained scarce until after the World War II.

1.1.1.4 Forced Flow Boilers

Economics drove the engineers to continue to increase the efficiency and unit size of boilers. To further increase efficiency the maximum allowable working pressure limit by natural circulation needed to be replaced. Two solutions emerged. In 1928 the La Mont forced circulation boiler was patented. In it the natural circulation was aided by a pump. Another solution involved replacing the steam-water side configuration with a straight flow path. The first supercritical boilers emerged c1930. Depending

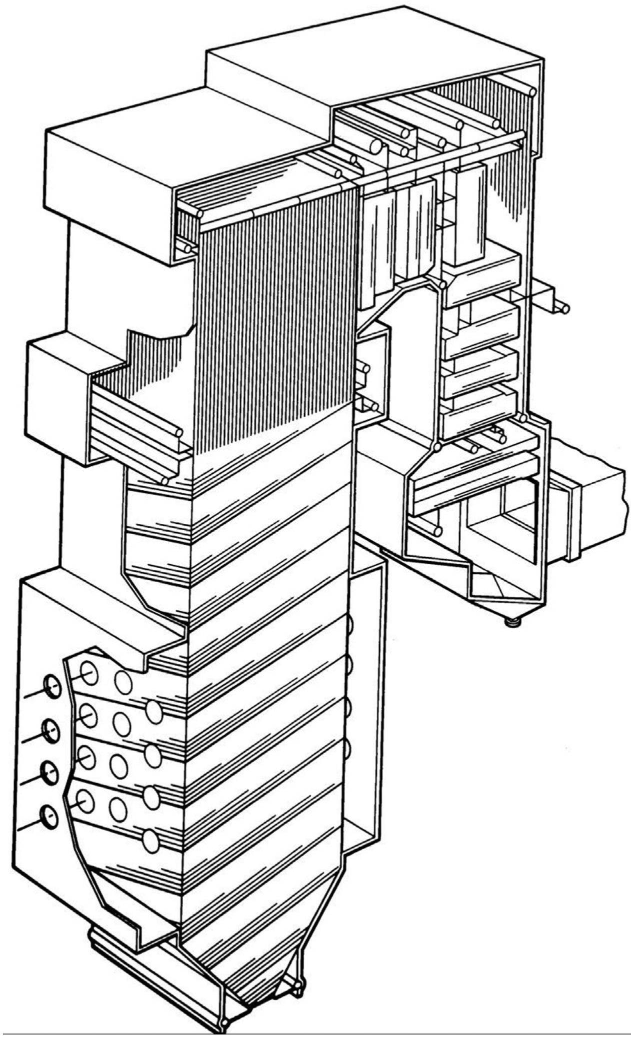

Figure 1.6 Benson boiler (Stultz and Kitto, 1992).

on the layout of their surfaces and the owner of the patent, they were called Sulzer, Benson, and Ramzin boilers (Fig. 1.6).

One of the early pioneers of once-through boilers was Englishman Mark Benson. His first idea for a once-through boiler was registered in 1923. It was not until 1957 that the first commercial boiler operated above 2212 MPa pressure. This unit at Ohio Power Company's Philo plant had an output of 85 kg/s steam at 31.37 MPa and 621°C. Because of the high manufacturing costs and exotic materials required in superheaters, subcritical units remained those that were most often built.

1.1.1.5 Oxyfuel Combustion

Instead of air one can use oxygen to burn fuel (Stanger et al., 2015). Using oxygen to burn biomass means that flue gases contain mostly CO_2 and water vapor. Oxyfuel combustion when water vapor is condensed results in high CO_2 concentration flue gases. Oxygen-enriched combustion has been tried on an industrial scale, but no large commercial unit exists yet. Oxyfuel combustion is one of the leading technologies for capturing CO_2 from biomass power plants with CO_2 capture and storage. If produced CO_2 is stored permanently, this means negative greenhouse gas emissions (European Technology Platform for Zero Emission Fossil Fuel Power Plants, 2012).

1.1.2 Modern Boiler Types

There are a large number of different designs for steam generators. Classification of boiler types is usually done by looking at the arrangement of their pressure parts (e.g., large-volume boilers and water tube boilers). Another typical classification is according to the use (e.g., recovery boilers, utility boilers, and heat recovery steam generators). The boilers are can also be classified by the firing method they employ (e.g., fluidized bed boilers, grate boilers, and boilers fired by pulverized coal).

1.1.2.1 Large-Volume Boilers

The fire tube boiler was created in the 1800s, Fig. 1.7. Its main use was to run steam engines for motive power. One of the first

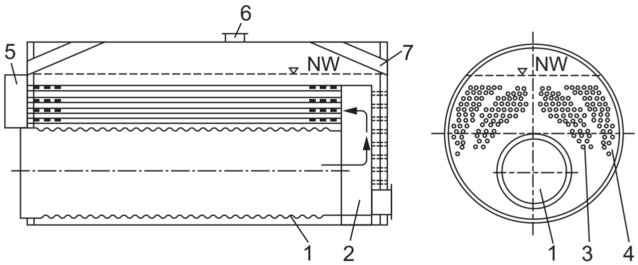

Figure 1.7 Typical design of industrial fire tube boiler: 1—Fire tube; 2—Smoke chamber; 3 and 4—Gas tubes; 5—Gas exhaust; 6—Steam outlet (Effenberger, 2000).

brand names for this type of boiler was the Lancashire boiler, which used two parallel fire tubes. It was used to power steamboats and railroad engines and to run industrial machinery via belt drives. The main design features of fire tube boilers are pressure 1–1.6–2.4 MPa, max. 4.0 MPa, steam temperature saturated, max. 400°C, and steaming rate ~10 kg/s, max. 50 kg/s. In addition to steam generation, a large number of fire tube boilers are used to heat hot water for residential or commercial use.

Fire tube boilers are large-volume boilers. A large vessel, filled with water, is pierced with tubes of various sizes. Radiative heat transfer occurs mainly in the fire tube at the bottom. Convective heat transfer takes place in the large number of parallel gas tubes in the top. Hot flue gas transfers heat through tubes to the water. Saturated steam is led out from the top. The number of flue gas passes depends on the unit size and ranges from 2 to 4.

1.1.2.2 Pulverized Solid Fuel Fired Boilers

Most thermal power plants are built to fire pulverized solid fuels, especially coal. Pulverized coal-fired units, which can cofire biomass, tend to be large. They often have a tower construction. This means that all heat transfer surfaces are placed on top of each other, with no backpass. The benefits of coal-fired units are reliability and proven technology. The drawback is their fuel. Coal generates a large amount of CO_2. Reducing nitrogen oxide (NOx) and sulfur dioxide (SO_2) requires large additional investments in modern plants.

Pulverized firing can also be applied to biomass fuels. The drawback is the large amount of electric efficiency that is required to crush biomass to the required, small diameter particles. Pulverized firing has successfully been applied to peat. Very recently several large (10–100 MWth) boilers firing pellets have been built.

1.1.2.3 Fluidized Bed Boilers

The 1970s saw the introduction of a new combustion method: fluidized bed firing (Caillat and Vakkilainen, 2013). Fluidized bed firing development started in 1922 when Winkler patented his coal gasification concept. The first use of a circulating fluidized bed (CFB) as a chemical reactor was patented by Lurgi in the 1960s. In fluidized bed firing a hot inert bed is used to maintain stable conditions. Fluidization means that the inert bed is mixed constantly and well. The stable temperature promotes fast combustion and, with a low furnace temperature,

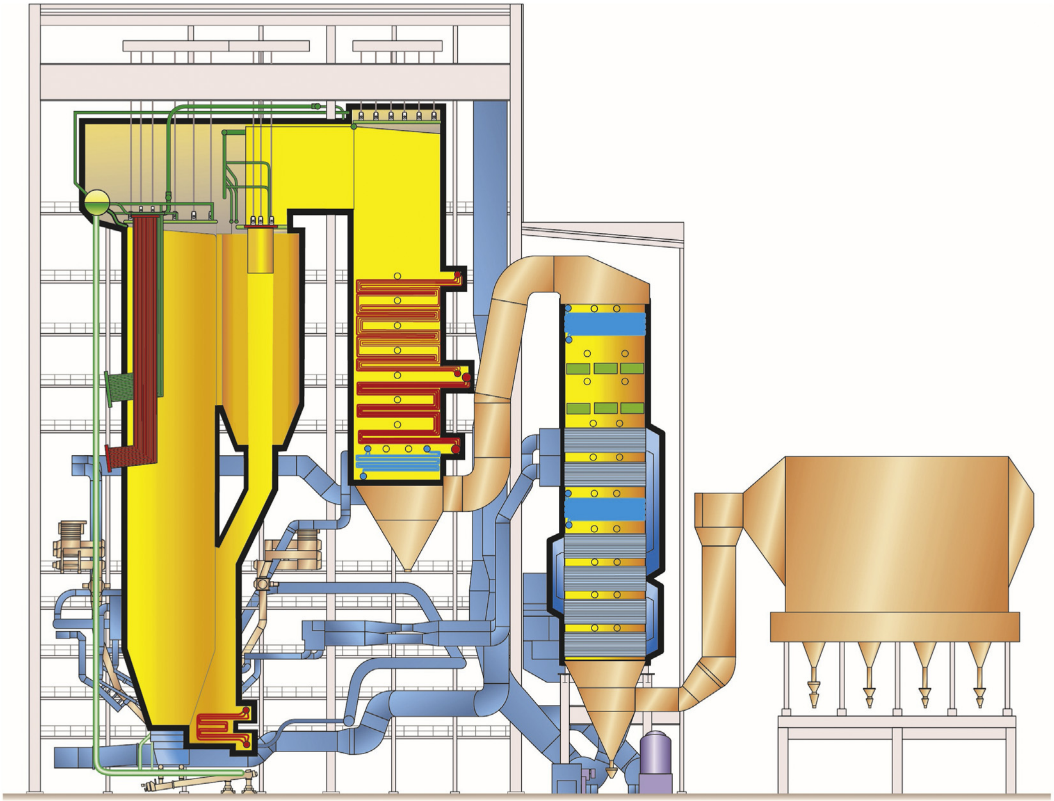

Figure 1.8 Modern circulating fluidized bed boiler. Courtesy of Amec Foster Wheeler.

excellent emissions. Only a small percentage of the fluidized bed boiler bed mass is from the burning fuel.

There are two main types of fluidized bed boilers: the bubbling fluidized bed (BFB) boiler and the CFB boiler. In the BFB boiler the bottom of the furnace has a solid/gas suspension, known as a fluidized bed, which behaves like a liquid. In the CFB boiler, Fig. 1.8, there is no sharp decrease of solid particles but solids travel continuously from the dense bottom of the furnace to the top. The CFB furnace can be said to consist of a suspension of sand, ash, flue gas, and burning fuel at a fairly even temperature. The solids drawn from the furnace with the CFB flue gases have to be separated and recirculated back to the lower furnace.

The main application of the BFB is in units smaller than 300 MWth. The CFB is used in larger units up to a size of +500 MWe (Hupa, 2005), and even larger units of 800 MWe have been proposed (Giglio, 2012). Fluidized bed firing is used especially with biofuels and when emission performance requires low NOx or low sulfur emissions. Low NOx is achieved because of the low furnace temperature (low bed temperature). SO_2 control is easily achieved because calcium carbonate can be inserted into the bed, where it reacts with the sulfur. The main reason for the lack of use of BFB technology in large units is that the bed itself must be made very large (Singer, 1991).

BFB firing is very suited to retrofitting old boilers. There have been many cases where old grate boilers have been retrofitted by replacing the lower part of the furnace.

1.1.2.4 Heat Recovery Boilers

Heat recovery steam generators (HRSGs) are very popular. They are often combined with a gas turbine or diesel generator, and produce additional electricity with the steam. These combined cycle units have very high electricity-generating efficiencies and good partial load characteristics. There have been several studies suggesting that biomass could be used in these combined cycle plants, but commercially they are rarely used.

There are two main arrangements. In a horizontal tube HRSG the evaporative tubes are placed horizontally. This type of arrangement is very popular in large units. In horizontal tube HRSGs the flue gas passage is often square. Vertical-type HRSGs have their main heat exchanger tubes in a vertical position. HRSGs of this type are popular with smaller unit sizes and are often much higher than they are wide (Fig. 1.9).

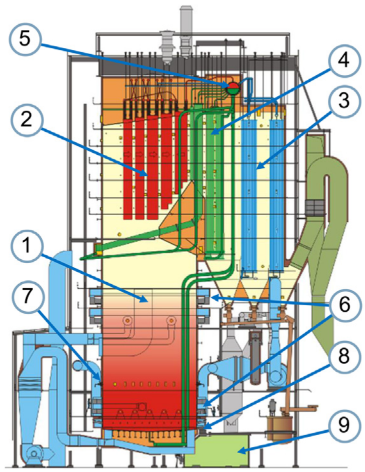

Figure 1.9 Recovery boiler. courtesy of Andritz.

1.1.2.5 Recovery Boilers

In a recovery boiler concentrated black liquor burns in the furnace. Simultaneously inorganic process chemicals are reduced to be subsequently used in kraft pulping. Thus the recovery boiler serves three main purposes (Vakkilainen, 2005): First, it burns the organic material in the pulping residue (black liquor) to generate high pressure steam. Second, it recycles and regenerates used chemicals in the black liquor. Third, it minimizes discharges from several waste streams in an environmentally friendly way.

1.1.2.6 Package Boilers

The name package boiler comes from the fact that these boilers can be brought to the site as a single piece. Their transportation resembles the handling of a large package or container. The whole boiler is manufactured at the boiler shop. Package boilers are used in small plants to fire biomass. Their steam pressure is less than 6.4 MPa. Because of their compact structure, the investment cost is low and the delivery time is short. Steam drum, mud drum, and wall placement differ in the main types of package boiler.

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