5.1 Introduction

This chapter describes combustion systems of a nominal thermal capacity exceeding 100 kW. These furnaces are generally equipped with mechanic or pneumatic fuel-feeding systems. Manual fuel-feeding is no longer customary due to high personnel costs and strict emission limits. Moreover, modern industrial combustion plants are equipped with process control systems supporting fully automatic system operation.
In principle, the following combustion technologies can be distinguished:

- fixed-bed combustion,
- fluidised bed combustion,
- dust combustion.

The basic principles of these three technologies are shown in Figure 5.1 and described below [118, 119]. The fundamentals of biomass combustion are outlined in Chapter 2.1.

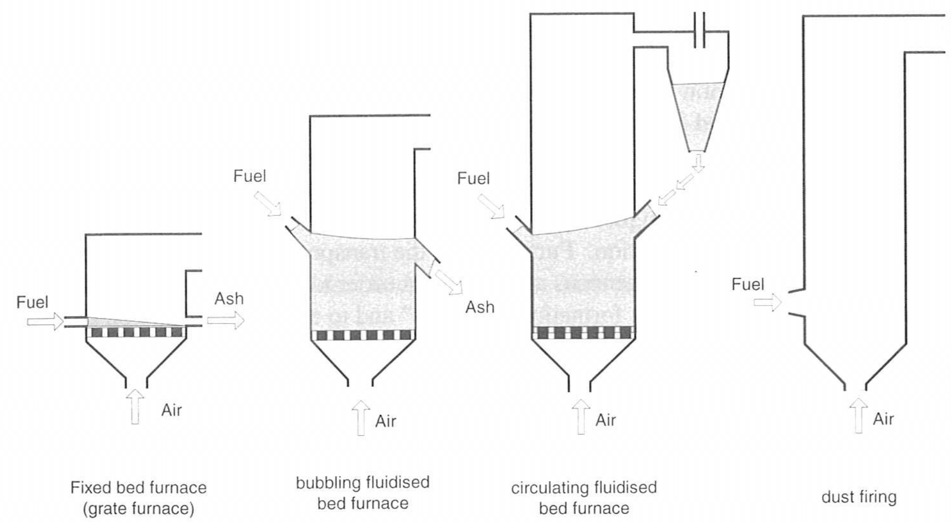

Figure 5.1: *Diagram of principle combustion technologies for biomass [118].*

Fixed-bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, in which drying, gasification, and charcoal combustion takes place. The combustible gases produced are burned after secondary air addition has taken place, usually in a combustion zone separated from the fuel bed.
Within a fluidised bed furnace, biomass fuel is burned in a self-mixing suspension of gas and solid-bed material into which combustion air enters from below. Depending on the fluidisation velocity, bubbling fluidised bed and circulating fluidised bed combustion can be distinguished.
Dust combustion is suitable for fuels available as small particles (average diameter smaller 2 mm). A mixture of fuel and primary combustion air is injected into the combustion

chamber. Combustion takes place while the fuel is in suspension, and gas burnout is achieved after secondary air addition.
Variations of these technologies are available. Examples are combustion systems with spreader stokers and cyclone burners.

5.2 Fixed-bed combustion

5.2.1 Grate furnaces

There are various grate furnace technologies available: fixed grates, moving grates, travelling grates, rotating grates, and vibrating grates. All of these technologies have specific advantages and disadvantages, depending on fuel properties, so that careful selection and planning is necessary.
Grate furnaces are appropriate for biomass fuels with a high moisture content, varying particle sizes (with a downward limitation concerning the amount of fine particles in the fuel mixture), and high ash content. Mixtures of wood fuels can be used, but current technology does not allow for mixtures of wood fuels and straw, cereals and grass, due to their different combustion behaviour, low moisture content, and low ash-melting point. A good and well controlled grate is designed to guarantee a homogeneous distribution of the fuel and the bed of embers over the whole grate surface. This is very important in order to guarantee an equal primary air supply over the various grate areas. Inhomogeneous air supply may cause slagging, higher fly-ash amounts, and may increase the excess oxygen needed for a complete combustion. Furthermore, the transport of the fuel over the grate has to be as smooth and homogeneous as possible in order to keep the bed of embers calm and homogeneous, to avoid the formation of "holes" and to avoid the elutriation of fly ash and unburned particles as much as possible.
The technology needed to achieve these aims includes continuously moving grates, a height control system of the bed of embers (e.g. by infrared beams), and frequency-controlled primary air fans for the various grate sections. The primary air supply divided into sections is necessary to be able to adjust the specific air amounts to the requirements of the zones where drying, gasification, and charcoal combustion prevail (see Figure 5.2). This separately controllable primary air supply also allows smooth operation of grate furnaces at partial loads of up to a minimum of about 25% of the nominal furnace load and control of the primary air ratio needed (to secure a reducing atmosphere in the primary combustion chamber necessary for low NO_x operation). Moreover, grate systems can be water-cooled to avoid slagging and to extend the lifetime of the materials.
Another important aspect of grate furnaces is that a staged combustion should be obtained by separating the primary and the secondary combustion chambers in order to avoid back-mixing of the secondary air and to separate gasification and oxidation zones. Due to the fact that the mixing of air and flue gas in the primary combustion chamber is not optimal because of the low turbulence necessary for a calm bed of embers on the grate, the geometry of the secondary combustion chamber and the secondary air injection have to guarantee a mixture of flue gas and air that is as complete as possible. The better the mixing quality between flue gas and secondary combustion air, the lower, the lower the amount of excess oxygen that will be necessary for complete combustion and the higher the efficiency. The mixing effect can be improved with relatively small channels where

the flue gas reaches high velocities and where the secondary air is injected at high speed via nozzles that are well distributed over the cross-section of this channel. Other means of achieving a good mixture of flue gas and secondary air are combustion chambers with a vortex flow or cyclone flow.

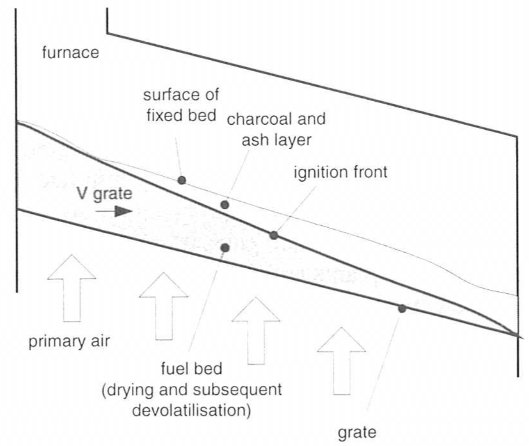

Figure 5.2: *Diagram of the combustion process in fixed fuel beds [120].*

Based on the flow directions of fuel and the flue gas, there are various systems for grate combustion plants (Figure 5.3):

- counter-current flow (flame in the opposite direction as the fuel),
- co-current flow (flame in the same direction as the fuel),
- cross-flow (flue gas removal in the middle of the furnace).

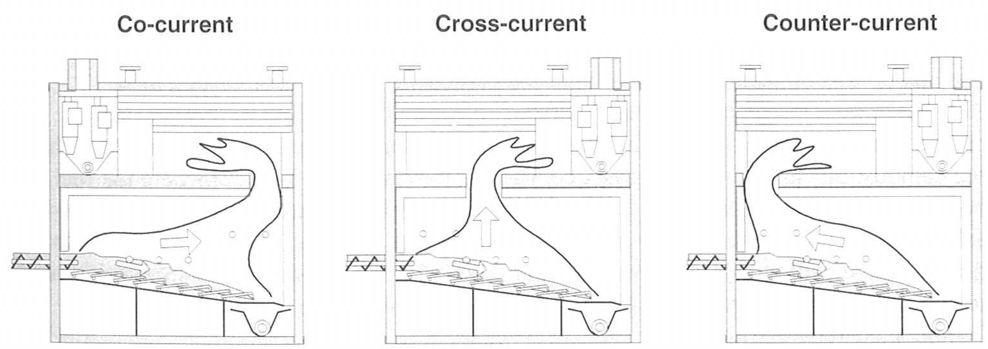

Figure 5.3: *Classification of grate combustion technologies: co-current, cross-current and counter-current [121].*

Counter-current combustion is most suitable for fuels with low heating values (wet bark, wood chips, or sawdust). Due to the fact that the hot flue gas passes over the fresh and wet biomass fuel entering the furnace, drying and water vapour transport from the fuel bed is increased by convection (in addition to the dominating radiant heat transfer to the fuel surface). This system requires a good mixing of flue gas and secondary air in the combustion chamber in order to avoid the formation of strains enriched with unburned gases entering the boiler and increasing emissions.
Co-current combustion is applied for dry fuels like waste wood or straw or in systems where pre-heated primary air is used. This system increases the residence time of unburned gases released from the fuel bed and can improve NO_x reduction by enhanced contact of the flue gas with the charcoal bed on the backward grate sections. Higher fly-ash entrainment can occur and should be impeded by appropriate flow conditions (furnace design).
Cross-flow systems are a combination of co-current and counter-current units and are also especially applied in combustion plants with vertical secondary combustion chambers.
In order to achieve adequate temperature control in the furnace, flue gas recirculation and water-cooled combustion chambers are used. Combinations of these technologies are also possible. Water-cooling has the advantage of reducing the flue gas volume, impeding ash sintering on the furnace walls and usually extending the lifetime of insulation bricks. If only dry biomass fuels are used, combustion chambers with steel walls can also be applied (without insulation bricks). Wet biomass fuels need combustion chambers with insulation bricks operating as heat accumulators and buffering moisture content and combustion temperature fluctuations in order to ensure a good burnout of the flue gas. Flue gas recirculation can improve the mixing of combustible gases and air and can be regulated more accurately than water-cooled surfaces. However, it has the disadvantage of increasing the flue gas volume in the furnace and boiler section. Flue gas recirculation should be performed after fly-ash precipitation in order to avoid dust depositions in the recirculation channels. Moreover, flue gas recirculation should not be operated in stop-and-go mode, to avoid condensation and corrosion in the channels or on the fan blades.

Travelling grate

Travelling grate furnaces are built of grate bars forming an endless band (like a moving staircase) moving through the combustion chamber (see Figure 5.4). Fuel is supplied at one end of the combustion chamber onto the grate, by e.g. screw conveyors, or is distributed over the grate by spreader-stokers injecting the fuel into the combustion chamber (see Figure 5.5). The fuel bed itself does not move, but is transported through the combustion chamber by the grate, contrary to moving grate furnaces where the fuel bed is moved over the grate. At the end of the combustion chamber the grate is cleaned of ash and dirt while the band turns around (automatic ash removal). On the way back, the grate bars are cooled by primary air in order to avoid overheating and to minimise wear-out. The speed of the travelling grate is continuously adjustable in order to achieve complete charcoal burnout.
The advantages of travelling grate systems are uniform combustion conditions for wood chips and pellets and low dust emissions, due to the stable and almost unmoving bed of embers. Also the maintenance or replacement of grate bars is easy to handle.
In comparison to moving grate furnaces, however, the fact that the bed of embers is not stoked results in a longer burn-out time. Higher primary air input is needed for complete

combustion (which implies a lower NO_x reduction potential by primary measures). Moreover, non-homogeneous biomass fuels imply the danger of bridging and uneven distribution among the grate surface because no mixing occurs. This disadvantage can be avoided by spreader-stokers because they cause a mixing of the fuel bed by the fuel-feeding mechanism applied.

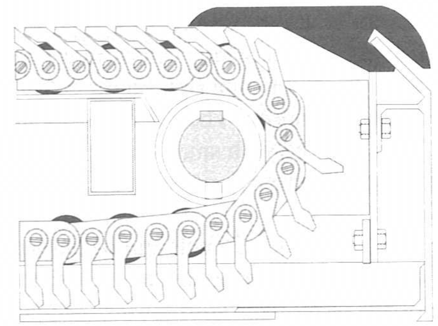

Figure 5.4: *Technological principle of a travelling grate [123].*

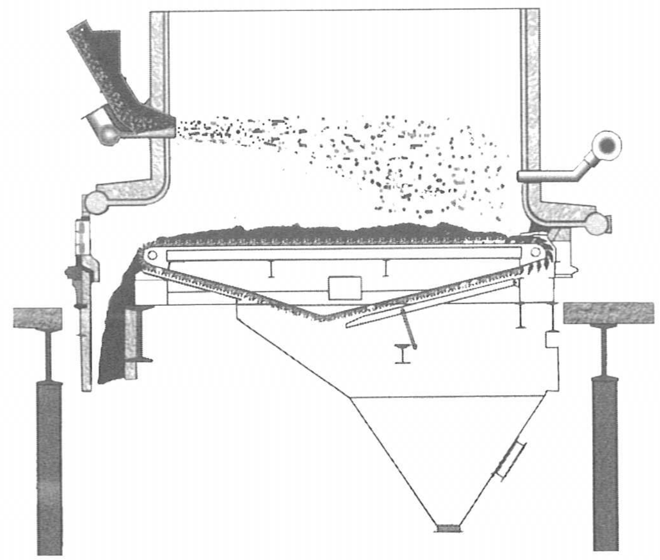

Figure 5.5: *Diagram of a travelling grate furnace fed by spreader-stokers [122].*

Fixed grate systems

Fixed grate systems are only used in small-scale applications. In these systems, fuel transport is managed by fuel feeding and gravity (caused by the inclination of the grate). As fuel transport and fuel distribution among the grate cannot be controlled well; this technology is no longer applied in modern combustion plants.

Inclined moving grates and horizontally moving grates

Moving grate furnaces usually have an inclined grate consisting of fixed and moveable rows of grate bars (see Figure 5.7). By alternating horizontal forward and backward movements of the moveable sections, the fuel is transported along the grate. Thus unburned and burned fuel particles are mixed, the surfaces of the fuel bed are renewed, and a more even distribution of the fuel over the grate surface can be achieved (which is important for an equal primary air distribution across the fuel bed). Usually, the whole grate is divided into several grate sections, which can be moved at various speeds according to the different stages of combustion (see Figure 5.6). The movement of the grate bar is achieved by hydraulic cylinders. The grate bars themselves are made of heat-resistant steel alloys. They are equipped with small channels in their side-walls for primary air supply and should be as narrow as possible in order to distribute the primary air across the fuel bed as well as possible.

In moving grate furnaces a wide variety of biofuels can be burned. Air-cooled moving grate furnaces use primary air for cooling the grate and are suitable for wet bark, sawdust, and wood chips. For dry biofuels or biofuels with low ash-sintering temperatures, water-cooled moving grate systems are recommended.

In contrast to travelling grate systems, the correct adjustment of the moving frequency of the grate bars is more complex. If the moving frequencies are too high, high concentrations of unburned carbon in the ash or insufficient coverage of the grate will result. Infrared beams situated over the various grate sections allow for adequate control of the moving frequencies by checking the height of the bed.

Ash removal takes place under the grate in dry or wet form. Fully automatic operation of the whole system is common.

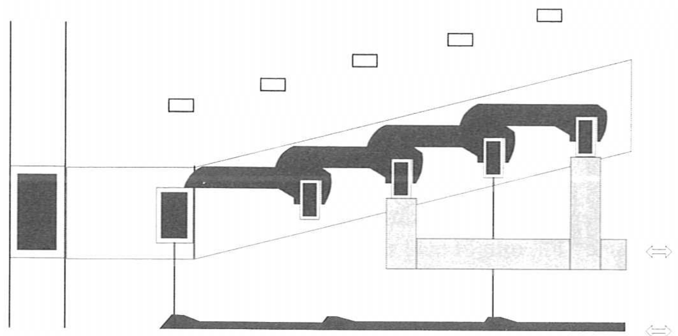

Figure 5.6: *Operating principle of an inclined moving grate [123].*

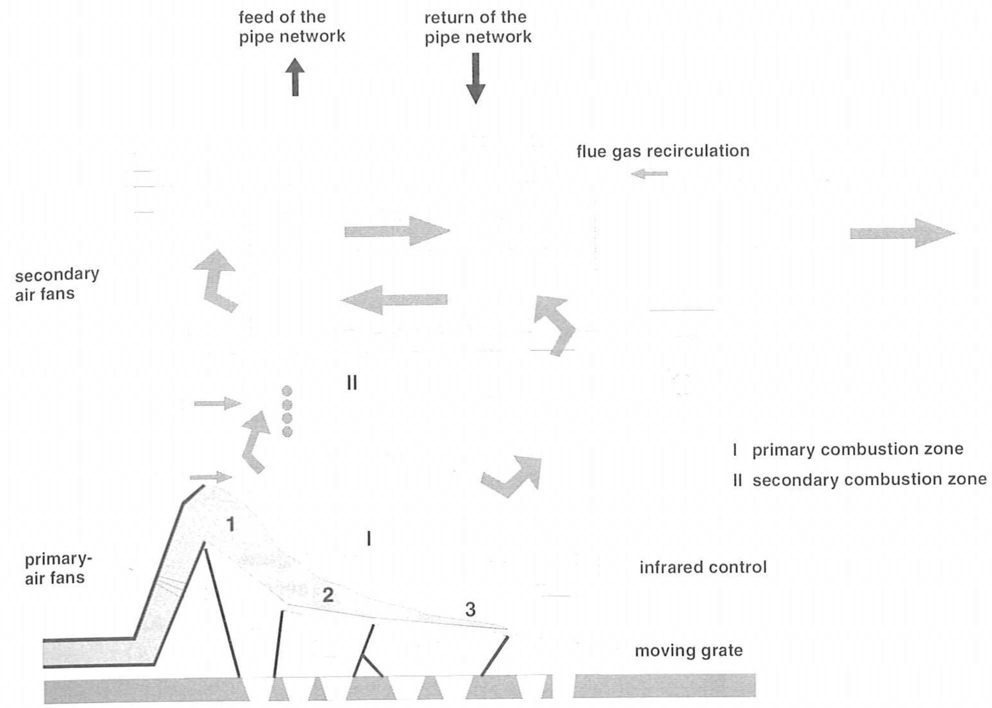

Figure 5.7: *Modern grate furnace with infrared control system and section-separated grate and primary air control [119].*
Explanations: 1....drying prevailing; 2....gasification prevailing; 3....charcoal combustion prevailing.

Figure 5.8: *Two 3,2 MWth inclined moving grate furnaces for wood chips, used for district heating in Interlaken (Courtesy of Schmid AG, Switzerland).*

Horizontally moving grates have a completely horizontal fuel bed. This is achieved by the diagonal position of the grate bars (see Figure 5.9). Advantages of this technology are the fact that uncontrolled fuel movements over the grate by gravity are impeded and that the stoking effect by the grate movements is increased, thus leading to a very homogeneous distribution of material on the grate surface and impeding slag formation as a result of hot spots. A further advantage of the horizontally moving grate is that the overall height can be reduced. In order to avoid ash and fuel particles to fall through the grate bars, horizontally moving grates should be preloaded so that there is no free space between the bars.

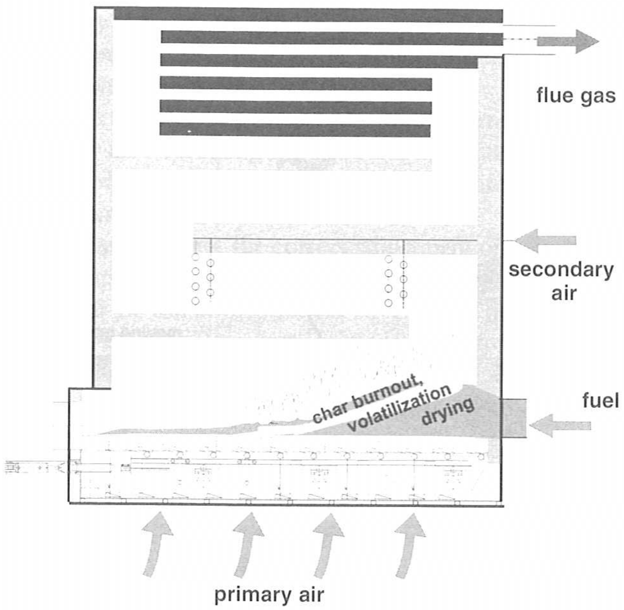

Figure 5.9: *Diagram of a horizontally moving grate furnace [106].*

Vibrating grates
Vibrating grate furnaces consist of a declined finned tube wall placed on springs (see Figure 5.10). Fuel is fed into the combustion chamber by spreaders, screw conveyors, or hydraulic feeders. Depending on the combustion process, two or more vibrators transport fuel and ash towards the ash removal. Primary air is fed through the fuel bed from below through holes located in the ribs of the finned tube walls [118]. Due to the vibrating movement of the grate at short periodic intervals, the formation of larger slag particles is inhibited, which is the reason why this grate technology is especially applied with fuels showing sintering and slagging tendencies (e.g. straw, waste wood). Disadvantages of vibrating grates are the high fly-ash emissions caused by the vibrations, the higher CO emissions due to the periodic disturbances of the fuel bed, and an incomplete burnout of the bottom ash because fuel and ash transport are more difficult to control.

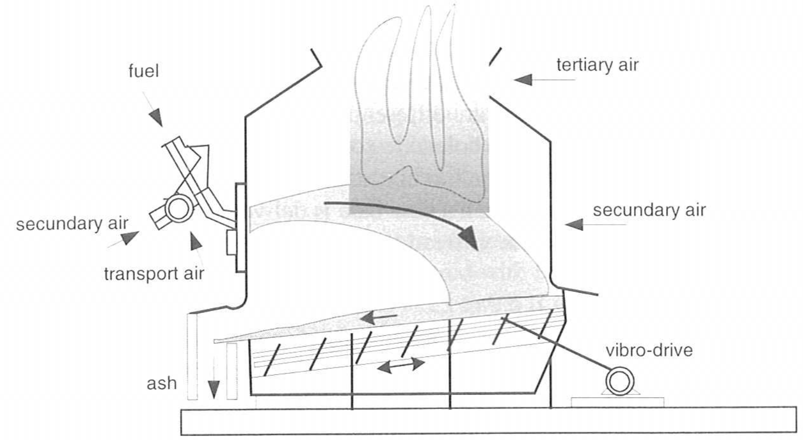

Figure 5.10: *Diagram of a vibrating grate fed by spreader stokers [118].*

Cigar burners
In Denmark, cigar burners have been developed for straw and cereal bale combustion (see Figure 5.11).

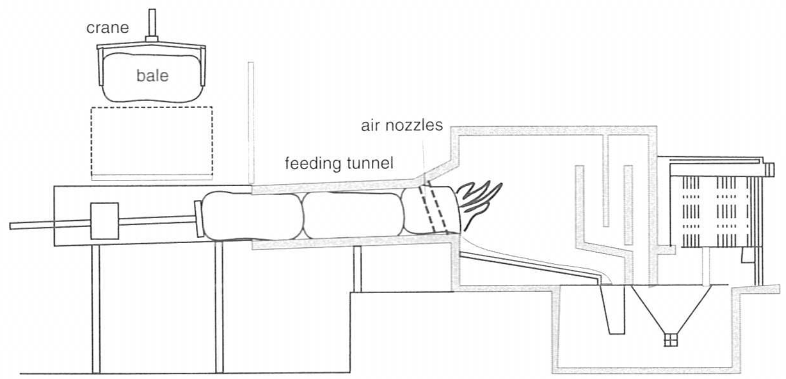

Figure 5.11: *Diagram of a cigar burner [118].*

Straw and cereal bales (as a whole or sliced) are delivered in a continuous process by a hydraulic piston through a feeding tunnel on a water-cooled moving grate. Upon entering the combustion chamber, the fuel begins to gasify and combustion of the charcoal follows while the unburned material is moved over the grate. Grate and furnace temperature control are very important for straw and cereal combustion, due to their low ash sintering and melting points and the high adiabatic temperature of combustion caused by their low moisture content. Therefore, the combustion chambers have to be cooled either by water-cooled walls or by flue gas recirculation (combinations of these two techniques are also possible). Furnace temperatures should not exceed 900°C for normal operation. Furthermore, in straw and cereal combustion very fine and light fly-ash particles as well as

aerosols are formed from condensed alkali vapours. An automatic heat exchanger cleaning system is required to prevent ash deposit formation and corrosion. Systems for shredded or cut straw also exist and operate in a similar way to the technology described – only the fuel preparation and feeding are different.
In semi-continuous systems such as whole bale combustion furnaces, in which the bales are fed in batch-wise operation into the furnace, are not recommended due to the temperature and CO peaks caused when a new bale is delivered. Current process control systems are not able to prevent these unsteady combustion conditions.

Underfeed rotating grate
Underfeed rotating grate combustion is a new Finnish biomass combustion technology that makes use of conical grate sections that rotate in opposite directions and are supplied with primary air from below (see Figure 5.12). As a result, wet and burning fuels are well mixed, which makes the system adequate for burning very wet fuels such as bark, sawdust, and wood chips (with a moisture content up to 65 wt.% (w.b.)). The combustible gases formed are burned out with secondary air in a separate horizontal or vertical combustion chamber. The horizontal version is suitable for generating hot water or steam in boilers with a nominal capacity between 1 and 10 MW_{th}. The vertical version is applied for hot water boilers with a capacity of 1-4 MW_{th}. The fuel is fed to the grate from below by screw conveyors (similar to underfeed stokers), which makes it necessary to keep the average particle size below 50 mm.
Underfeed rotating grate combustion plants are also capable of burning mixtures of solid wood fuels and biological sludge. The system is computer-controlled and allows fully automatic operation.

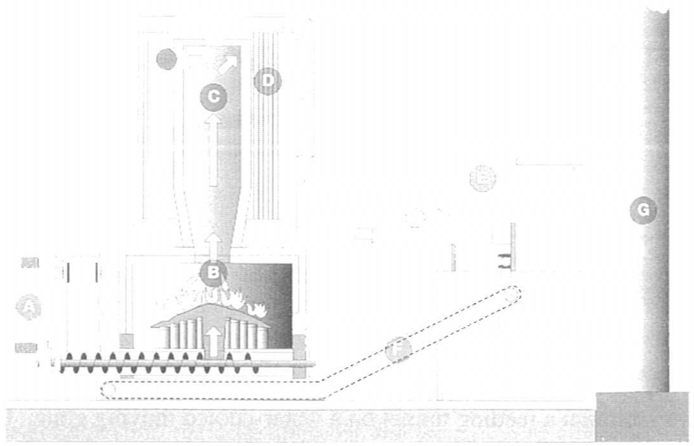

Figure 5.12: *Underfeed rotating grate [124].*
Explanations: *A...fuel feed, B...primary combustion chamber, C...secondary combustion chamber, D...boiler, E...flue gas cleaner, F...ash removal, g...stack.*

Rotating cone furnace
The rotating cone furnace basically consists of a slowly rotating inverted conical grate (see Figure 5.13). The rotating cone forms an endless and self-stoking grate enabling adequate mixture and quick ignition of fuels of varying particle size and moisture content. Rotating cone furnaces are a German development and have been used for burning waste wood and coal up to now. They can be supplied for nominal boiler capacities varying between 0.4 and 50 MW_{th} [125].
Fuel is dumped from above through a two-stage airtight lock. Primary air enters the grate through carrying bars only in grate sections covered with fuel. Due to the careful mixing of the bed of embers, a primary air ratio of $\lambda = 0.3$ to 0.6 is achieved, allowing the utilisation of fuels with low ash-melting temperatures (in the rotating cone gasification of the fuel only takes place at temperatures below 800°C). Secondary air is fed tangentially and at high speed into the cylindrical secondary combustion chamber, implying a rotational flow that ensures a good mixture of flue gas and air as well as an efficient fly-ash separation from the flue gas. The furnace walls are water-cooled steel walls in order to ensure adequate temperature control in the oxidising zone and to avoid ash deposit formations. Thus, the total combustion air ratio can be kept between $\lambda=1.2$ and 1.4, which is a very low value for fixed-bed furnaces and ensures a high combustion efficiency.
The weak points or disadvantages of this innovative combustion technology for biomass fuels are:

- the limited experience with the utilisation of various biomass biofuels at different loads as well as with the wear-out of the grate and the furnace;
- the necessary auxiliary burner needed for start-up due to the water-cooled walls;
- the necessity of shutting down the furnace periodically for removing large ash particles that accumulate in the core (this operation is performed automatically by a grappler installed); the frequency depends on the amount of mineral impurities in the fuel).

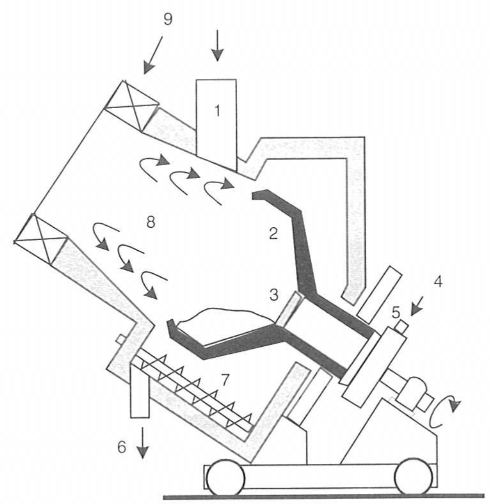

Figure 5.13: *Diagram of the rotating cone furnace [125].*
Explanations: *1...fuel feeding, 2...rotating grate, 3...bottom of the cone, 4...primary air, 5...air control, 6...ash disposal, 7...ash screw conveyor, 8...burn out zone, 9...secondary air.*

5.2.2 Underfeed stokers

Underfeed stokers (see Figure 5.14) represent a cheap and operationally safe technology for small- and medium-scale systems up to a nominal boiler capacity of 6 MW_{th}. The fuel is fed into the combustion chamber by screw conveyors from below and is transported upwards on an inner or outer grate. Outer grates are more common in modern combustion plants because they allow for more flexible operation and an automatic ash removing system can be attained easier. Primary air is supplied through the grate, secondary air usually at the entrance to the secondary combustion chamber. A new Austrian development is an underfeed stoker with a rotational post-combustion, in which a strong vortex flow is achieved by a specially designed secondary air fan equipped with a rotating chain (see Figure 5.15).

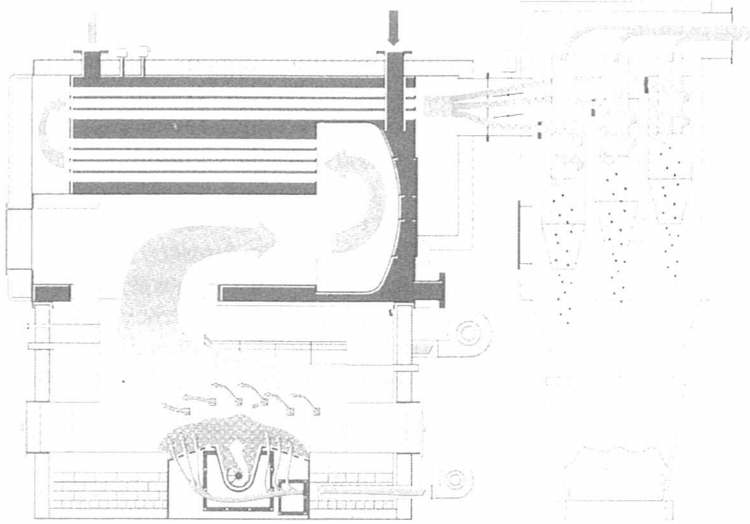

Figure 5.14: *Diagram of an underfeed stoker furnace [106].*

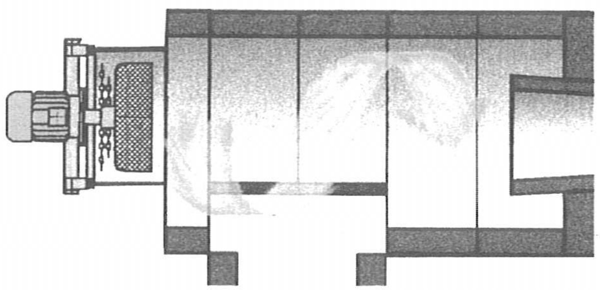

Figure 5.15: *Diagram of a post-combustion chamber with imposed vortex flow [126].*

Underfeed stokers are suitable for biomass fuels with low ash content (wood chips, sawdust, pellets) and small particle sizes (particle dimension up to 50 mm). Ash-rich biomass fuels like bark, straw, and cereals need more efficient ash removal systems. Moreover, sintered or melted ash particles covering the upper surface of the fuel bed can cause problems in underfeed stokers due to unstable combustion conditions when the fuel and the air are breaking through the ash-covered surface. An advantage of underfeed stokers is their good partial-load behaviour and their simple load control. Load changes can be achieved more easily and quickly than in grate combustion plants because the fuel supply can be controlled more easily.

5.3 Fluidised bed combustion

Fluid-bed (FB) combustion systems have been applied since 1960 for combustion of municipal and industrial wastes. Since then, over 300 commercial installations have been built worldwide. Regarding technological applications, bubbling fluidised beds (BFB) and circulating fluidised beds (CFB) have to be distinguished.

A fluidised bed consists of a cylindrical vessel with a perforated bottom plate filled with a suspension bed of hot, inert, and granular material. The common bed materials are silica sand and dolomite. The bed material represents 90-98% of the mixture of fuel and bed material. Primary combustion air enters the furnace from below through the air distribution plate and fluidises the bed so that it becomes a seething mass of particles and bubbles. The intense heat transfer and mixing provides good conditions for a complete combustion with low excess air demand (λ between 1.1 and 1.2 for CFB plants and between 1.3 and 1.4 for BFB plants). The combustion temperature has to be kept low (usually between 800-900°C) in order to prevent ash sintering in the bed. This can be achieved by internal heat exchanger surfaces, by flue gas recirculation, or by water injection (in fixed-bed combustion plants combustion temperatures are usually 100-200°C higher than in FB units).

Due to the good mixing achieved, FB combustion plants can deal flexibly with various fuel mixtures (e.g. mixtures of wood and straw can be burned) but are limited when it comes to fuel particle size and impurities contained in the fuel. Therefore, appropriate fuel pre-treatment system covering particle size reduction and separation of metals is necessary for fail-safe operation. Usually a particle size below 40 mm is recommended for CFB units and below 80 mm for BFB units. Moreover, partial load operation of FB combustion plants is limited due to the need of bed fluidisation.

Fluidised bed combustion systems need a relatively long start-up time (up to 15 hours) for which oil or gas burners are used. With regard to emissions, low NO_x emissions can be achieved owing to good air staging, good mixing, and a low requirement of excess air. Moreover, the utilisation of additives (e.g. limestone addition for S capture) works well due to the good mixing behaviour. The low excess air quantities necessary increase combustion efficiency and reduce the flue gas volume flow. This makes FB combustion plants especially interesting for large-scale applications (normal boiler capacity above 30 MW(th)). For smaller combustion plants the investment and operation costs are usually too high in comparison to fixed-bed systems. One disadvantage of FB combustion plants is posed by the high dust loads entrained with the flue gas, which make efficient dust precipitators and boiler cleaning systems necessary. Bed material is also lost with the ash, making it necessary to periodically add new material to the plant.

5.3.1 Bubbling fluidised bed combustion (BFB)

For plants with a nominal boiler capacity of over 20 $MW_{th.}$, BFB furnaces start to be of interest. In BFB furnaces (see Figures 5.16 and 5.17), a bed material is located in the bottom part of the furnace. The primary air is supplied over a nozzle distributor plate and fluidises the bed. The bed material is usually silica sand of about 1.0 mm in diameter; the fluidisation velocity of the air varies between 1.0 and 2.5 m/s. The secondary air is introduced through several inlets in the form of groups of horizontally arranged nozzles at the beginning of the upper part of the furnace (called freeboard) to ensure a staged-air supply to reduce NO_x emissions. In contrast to coal-fired BFB furnaces, the biomass fuel should not be fed onto, but into, the bed by inclined chutes from fuel hoppers because of the higher reactivity of biomass in comparison to coal. The fuel amounts only to 1 to 2% of the bed material and the bed has to be heated (internally or externally) before the fuel is introduced. The advantage of BFB furnaces is their flexibility concerning particle size and moisture content of the biomass fuels. Furthermore, it is also possible to use mixtures of different kinds of biomass or to co-fire them with other fuels. One big disadvantage of BFB furnaces, the difficulties they have at partial load operation, is solved in modern furnaces by splitting or staging the bed.

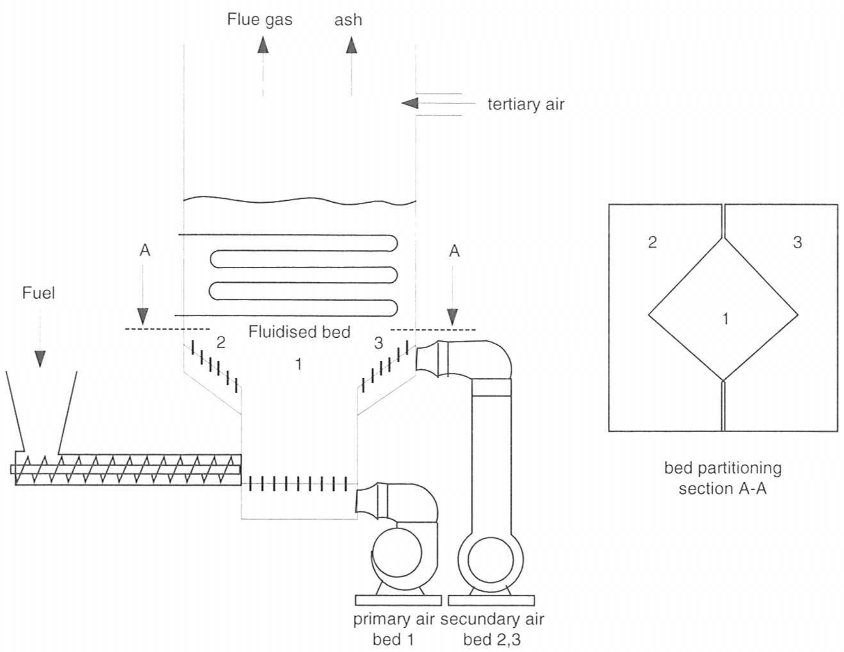

Figure 5.16: *Diagram of a BFB furnace [127].*

Figure 5.17: *A 25 MW_e woodchip-fired power plant in Cuijk, The Netherlands, with a BFB boiler.*

5.3.2 Circulating fluidised bed (CFB) combustion

By increasing the fluidising velocity to 5 to 10 m/s and using smaller sand particles (0.2 to 0.4 mm in diameter) a CFB system is achieved. The sand particles will be carried with the flue gas, separated in a hot cyclone or a U-beam separator, and fed back into the combustion chamber (see Figure 5.18). The bed temperature (800 to 900°C) is controlled by external heat exchangers cooling the recycled sand, or by water-cooled walls. The higher turbulence in CFB furnaces leads to a better heat transfer and a very homogeneous temperature distribution in the bed. This is of advantage for stable combustion conditions, the control of air staging, and the placement of heating surfaces right in the upper part of the furnace. The disadvantages of CFB furnaces are their larger size and therefore higher price, the even greater dust load in the flue gas leaving the sand particle separator than in BFB systems, the higher loss of bed material in the ash, and the small fuel particle size required (between 0.1 and 40 mm in diameter), which often causes higher investments in fuel pre-treatment. Moreover, their operation at partial load is problematic. In view of their high specific heat transfer capacity, CFB furnaces start to be of interest for plants of more than 30 MW_{th}, due to their higher combustion efficiency and the lower flue gas flow produced (boiler and flue gas cleaning units can be designed smaller).

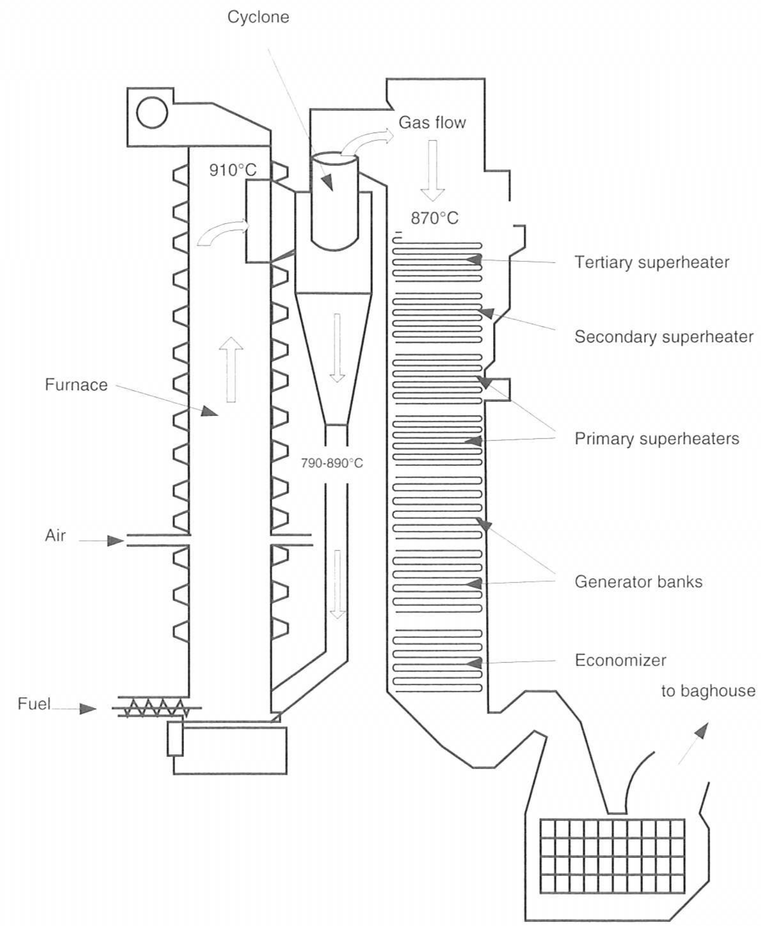

Figure 5.18: *Diagram of a CFB furnace [128].*

5.4 Dust combustion

In dust combustion systems, fuels like sawdust and fine shavings are pneumatically injected into the furnace. The transportation air is used as primary air. Start-up of the furnace is achieved by an auxiliary burner. When the combustion temperature reaches a certain value, biomass injection starts and the auxiliary burner is shut down. Fuel quality in dust combustion systems has to be quite constant. A maximum fuel particle size of 10-20 mm has to be maintained and the fuel moisture content should normally not exceed 20 wt% (w.b.). Due to the explosion-like gasification of the fine and small biomass particles, the fuel feeding needs to be controlled very carefully and forms a key technological unit within the overall system. Fuel/air mixtures are usually injected tangentially into the cylindrical furnace muffle to establish a rotational flow (usually a vortex flow). The rotational motion can be supported by flue gas recirculation in the combustion chamber. Due to the high energy density at the furnace walls and the high

combustion temperature, the muffle should be water-cooled. Fuel gasification and charcoal combustion take place at the same time because of the small particle size. Therefore, quick load changes and an efficient load control can be achieved.
Muffle dust furnaces are being used more and more for fine wood wastes originating from the chipboard industry. Figure 5.19 shows a muffle dust furnace in combination with a water tube steam boiler. This technology is available for thermal capacity between 2 and 8 MW [118]. The outlet of the muffle forms a neck, where secondary air is added in order to achieve a good mixture with the combustible gases. Due to the high flue gas velocities, the ash is carried with the flue gas and is partly precipitated in the post-combustion chamber. Low excess air amounts (λ = 1.3-1.5) and low NO_x emissions can be achieved by proper air staging. Besides muffle furnaces, cyclone burners for wood dust combustion are also in use (see Figure 5.20). Depending on the design of the cyclone and the location of fuel injection, the residence time of the fuel particles in the furnace (their burnout) can be controlled well.

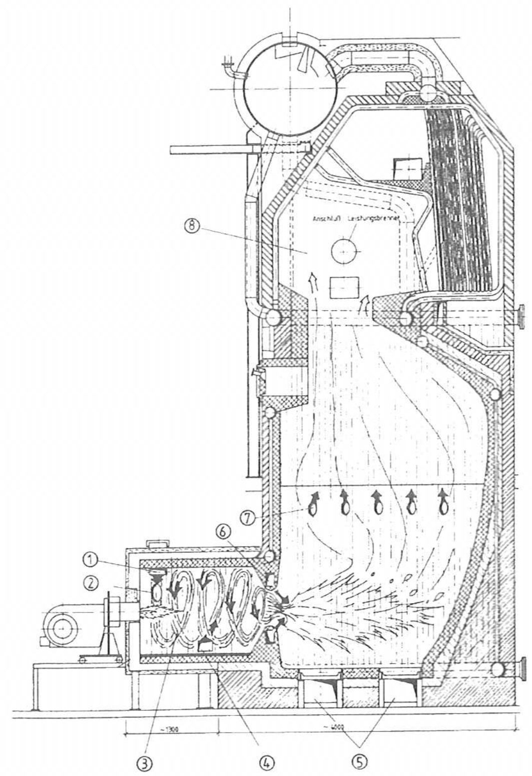

Figure 5.19: *Diagram of a dust combustion plant (muffle furnace) in combination with a water-tube steam boiler[118].*
Explanations: 1...primary air supply, 2...fuel feed, 3...gasification and partial combustion, 4...flue gas recirculation, 5...ash disposal, 6...secondary air supply, 7...tertiary air supply, 8...water tube boiler.

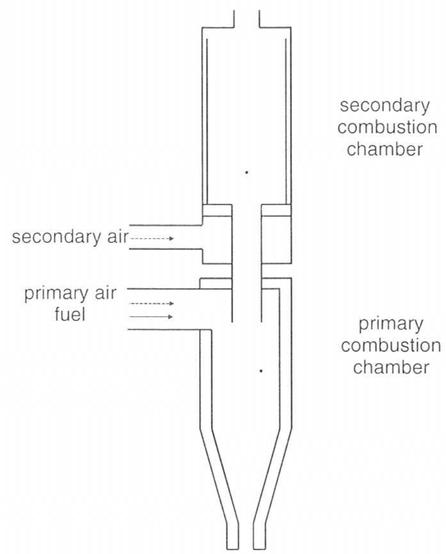

Figure 5.20: *Diagram of a two-stage cyclone burner [129].*

A disadvantage of muffle furnaces and cyclone burners is that insulation bricks wear out quickly due to thermal stress and erosion. Therefore, other dust combustion systems are being built without rotational flow, where dust injection takes place as in a fuel oil- or natural gas-fired furnace (see Figure 5.21).

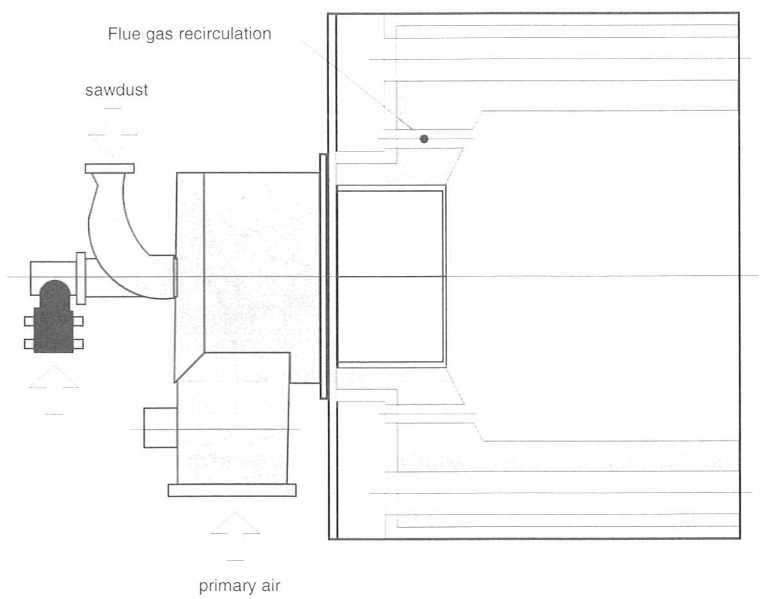

Figure 5.21: *Diagram of a dust injection furnace [118].*

5.5 Other combustion concepts

5.5.1 Whole Tree Energy® concept

One promising combustion concept under development in the USA is the so-called *Whole Tree Energy Concept*® (see Figure 5.22). The concept, which is patented in 30 countries, is based on an innovative fuel handling, drying, and combustion system. A pilot plant with a nominal boiler capacity of 10 MW_{th} has been built to test and evaluate this technology. A 50 MW_e demonstration plant is under development in central Wisconsin with an electrical efficiency of 32.5%. The total capital costs of the equipment, engineering, procurement, and construction amount to approximately 101 million US$ [130].

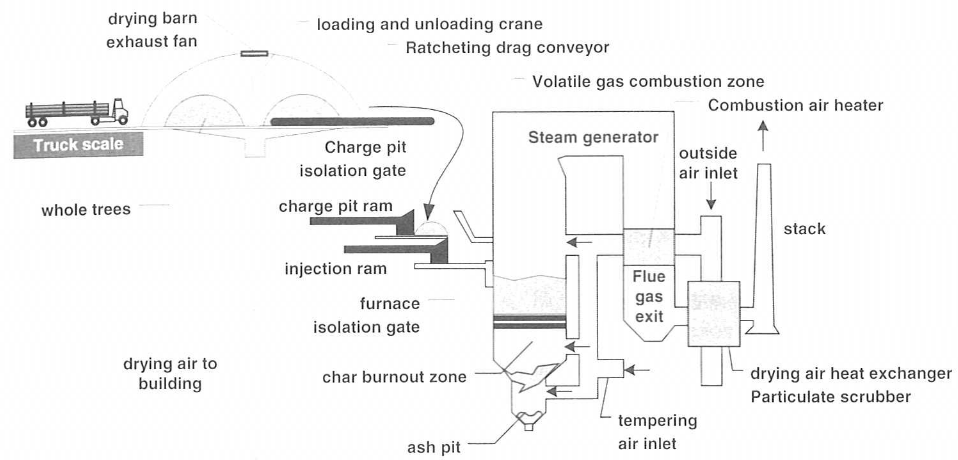

Figure 5.22: *Diagram of a 'Whole Tree Energy® power plant'.*

Because of its reduced need for fuel preparation this concept seems economically interesting. Though the process is based on commercially available equipment, the concept as a whole is radically different from conventional combustion systems and has not yet been applied in practice.

Whole trees are harvested, transported by trucks to the power plant, and stored in a large air-inflated building for 30 days. Drying from about 50 wt% (w.b.) moisture content to around 20-25 wt.% (w.b.) is achieved in a two-stage drying process using waste heat from the flue gas as an energy source. This concept reduces harvesting and handling costs and the need to reduce the size of the feedstock. The dried trees are then conveyed by a tower crane to the furnace charge box where their length is reduced by a saw to the maximum width of the furnace before they are dumped into the charging pit.

The charging pit functions as an airlock for the furnace. Combustion itself takes place in three stages. In periodic intervals, trees are dumped onto the grate, where they are gasified with pre-heated air at 350°C. The charcoal produced falls through the grate where it burns out completely, while combustible gases are mixed with secondary air above the fuel bed to achieve complete gas-phase combustion. Similar to any pile burning system, the periodic dumping of fresh wood logs onto the burning pile disturbs the combustion process and causes increased emissions. This point has to be especially considered in the further development of this technology.

5.6 Summary of combustion technologies

Table 5.1 gives an overview of the advantages and disadvantages as well as the fields of application of various combustion technologies. Regarding gaseous and solid emissions, BFB and CFB furnaces normally show lower CO and NO_x emissions due to more homogeneous and therefore more controllable combustion conditions. Fixed-bed furnaces, in turn, usually emit fewer dust particles and show a better burnout of the fly ash [131, 132, 133].

Table 5.1: *Overview of advantages, disadvantages and fields of application of various biomass combustion technologies*

Advantages	Disadvantages
underfeed stokers	
• low investment costs for plants < 6 MW(th) • simple and good load control due to continuos fuel feeding • low emissions at partial load operation due to good fuel dosing	• suitable only for biofuels with low ash content and high ash-melting point (wood fuels) • low flexibility in regard to particle size
grate furnaces	
• low investment costs for plants < 20 MW(th) • low operating costs • low dust load in the flue gas • less sensitive to slagging than fluidised bed furnaces	• no mixing of wood fuels and herbaceous fuels possible • efficient NOx reduction requires special technologies • high excess oxygen (5 - 8 Vol%) decreases efficiency • combustion conditions not as homogeneous as in fluidised bed furnaces • low emissions level at partial load operation is difficult to achieve
dust combustion	
• low excess oxygen (4 - 6 Vol%) increases efficiency • high NOx reduction by efficient air staging and mixing possible if cyclone or vortex burners are used • very good load control and fast alternation of load possible	• particle size of biofuel is limited (< 10-20 mm) • high wear out of the insulation brickwork if cyclone or vortex burners are used • an extra start-up burner is necessary

Table 5.1 *(continued).*

Advantages	Disadvantages
BFB furnaces	
• no moving parts in the hot combustion chamber • NOx reduction by air staging works well • high flexibility concerning moisture content and kind of biomass fuels used • low excess oxygen (3 - 4 Vol%) raises efficiency and decreases flue gas flow	• high investment costs, interesting only for plants > 20 MWth • high operating costs • low flexibility with regard to particle size (< 80 mm) • high dust load in the flue gas • operation at partial load requires special technology • medium sensitivity concerning ash slagging • loss of bed material with the ash • medium erosion of heat exchanger tubes in the fluidised bed
CFB furnaces	
• no moving parts in the hot combustion chamber • NOx reduction by air staging works well • high flexibility concerning moisture content and kind of biomass fuels used • homogeneous combustion conditions in the furnace if several fuel injectors are used • high specific heat transfer capacity due to high turbulence • use of additives easy • very low excess oxygen (1 - 2 vol%) raises efficiency and decreases flue gas flow	• high investment costs, interesting only for plants > 30 MW(th) • high operating costs • low flexibility with regard to particle size (< 40 mm) • high dust load in the flue gas • partial-load operation requires a second bed • loss of bed material with the ash • high sensitivity concerning ash slagging • loss of bed material with the ash • medium erosion of heat exchanger tubes in the furnace

5.7 Heat recovery systems and possibilities for increasing plant efficiency

Table 5.2 gives an overview of the potential of various options for increasing the efficiency of biomass combustion plants [134, 135]. Biomass drying is one interesting method, though the efficiency increase and cost savings are usually moderate. Advantages that can be achieved are the prevention of auto-ignitions in wet bark piles, the reduction of dry-matter losses due to microbiological degradation processes during storage, and a reduction of the necessary storage volume at the plant. However, biomass drying processes must be carefully examined for their economic advantage, considering the additional investment costs as well as the operating costs in the form of electricity consumption, and man and machine hours necessary to run the process. In most cases, biomass drying is only economic if pre-heated air is available at low or no cost (examples are solar air collectors and the utilisation of pre-heated air from flue gas condensation units – see Chapter 3.3.5). Drying biomass piles for several months by natural convection is not economic in most cases because the dry-matter losses by biological degradation

(1.0-2.0 wt.% per month) are higher than the increase of efficiency obtained when outdoor storage is considered (see Chapter 3.4.1).

Table 5.2: *Influence of various measures on the thermal efficiency of biomass combustion plants.*
Explanations: Calculations performed for wood chips and bark as fuel; GCV = 20 MJ/kg (d.b.). Abbreviations: d.b...dry basis; w.b...wet basis; NCV...net calorific value; GCV...gross calorific value; efficiency = heat output (boiler) / energy input fuel (NCV).

Measures	Potential thermal efficiency improvement, as compared to the NCV of one dry tonne of fuel (%)
• drying from a moisture content of 50 wt% to 30 wt% (w.b.)	+8.7%
• decreasing the O_2- content in the flue gas by 1.0 vol%	about +0.9%
• bark combustion: reducing the C_{org} content in the ash from 10.0 to 5.0 wt.% (d.b.)	+0.3%
• decreasing the flue gas temperature at boiler outlet by 10 °C	+0.8%
• flue gas condensation (compared to conventional combustion units)	average +17% maximum +30%

Reducing the excess oxygen content in the flue gas is an effective measure for increasing the efficiency of the combustion plant, as shown in Figure 5.23.

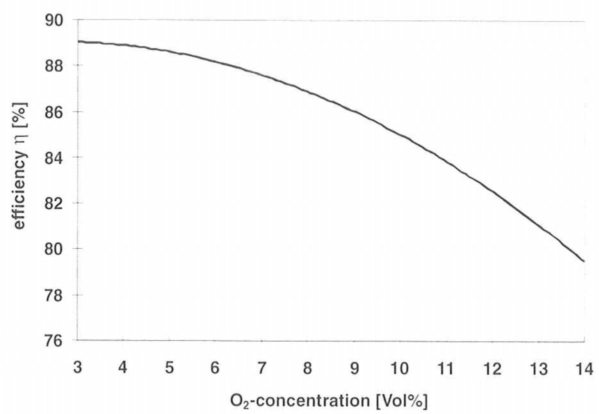

Figure 5.23: *Influence of the oxygen content in the flue gas on the plant efficiency.*
Explanations: moisture content of the fuel 55.0 wt.% (w.b.); biomass fuel used: wood chips / bark; H-content 6.0 wt.% (d.b.); gross calorific value of the fuel 20300 kJ/kg (d.b.); flue gas temperature at boiler outlet 165°C, efficiency related to the NCV of the fuel; O_2 concentration related to dry flue gas; efficiency = heat output from boiler / energy input with the fuel (NCV).

There are two technological possibilities for decreasing the excess air ratio and to ensure a complete combustion at the same time. On the one hand, an oxygen sensor is coupled with a CO sensor in the flue gas at the boiler outlet to optimise the secondary air supply (CO-λ-control); on the other hand, there are improvements of the mixing quality of flue gas and air in the furnace (as already explained). In addition, a lower excess oxygen concentration in the flue gas can also significantly improve the efficiency of flue gas condensation units, due to the fact that it increases the dew point and therefore raises the amount of recoverable latent heat of the condensing water at a certain temperature (see Figure 5.24).

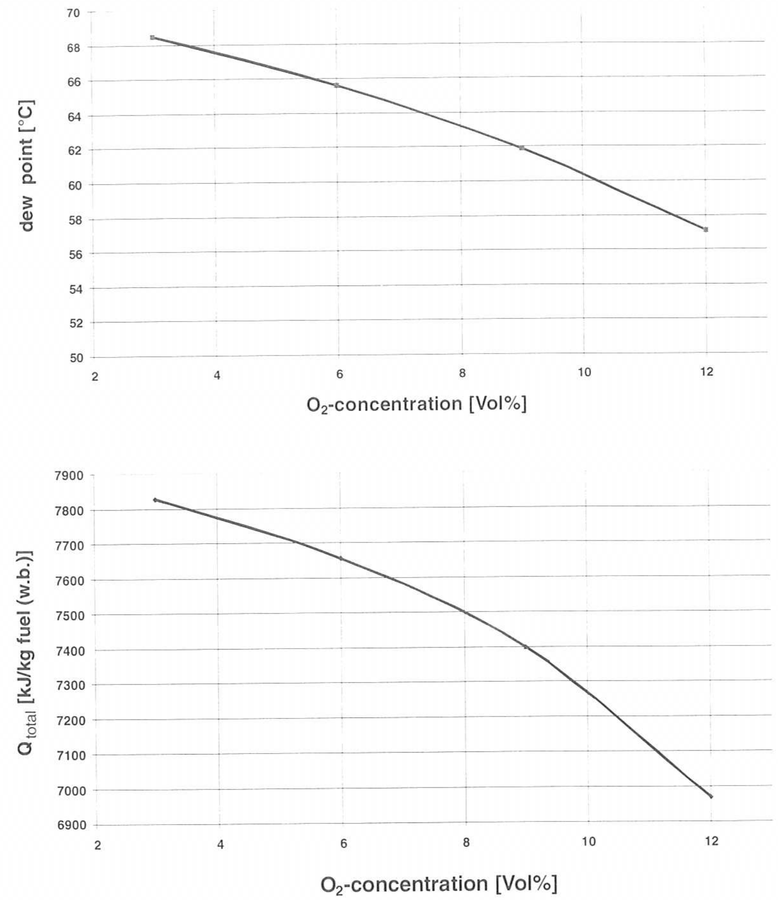

Figure 5.24: *Influence of the oxygen content in the flue gas on the heat recoverable in flue gas condensation plants.*
Explanations: dew point calculated for water in the flue gas of a wood chips and bark combustion plant; moisture content of the biomass fuel 55.0 wt.% (w.b), H-content 6.0 wt.% (d.b.); gross calorific value of the fuel 20 MJ/kg (d.b.); Q_{total} = total recoverable heat from 1.0 kg biomass fuel (w.b.) burned when the flue gas is cooled down to 55°C.

Furthermore, reducing the excess oxygen concentration in the flue gas also decreases the flue gas volume flow, which limits pressure drops and reduces the sizes of boilers and flue gas cleaning units. Of course, one has to take care that a reduction of the excess oxygen concentration in the flue gas also increases the combustion temperature, which underlines the importance of an appropriate furnace temperature control system.

Low carbon-in-ash values are of minor importance for the efficiency of the plant but of major importance for the possibility of sustainable ash utilisation, because the concentration of organic contaminants in biomass ashes normally increases with higher carbon concentrations [132, 136] (see also Chapter 8).

The most effective way to recover energy from the flue gas – and in many cases also an economically interesting technology – is flue gas condensation. In addition to the high energy recovery potential of this process (up to 20% of the energy input by the biomass fuel related to the NCV), dust precipitation efficiencies of 40-75% can be achieved. Furthermore, there is the possibility of preventing condensation of the flue gas at the chimney up to ambient temperatures of about -10°C [137, 138]. In Denmark, the majority of biomass district heating plants are equipped with flue gas condensation units. In Sweden, Finland, and Austria, the number of installations is rapidly increasing; Italy, Germany, and Switzerland also have several plants already in operation. Figure 5.25 shows the principle of a flue gas condensation unit. The whole plant normally consists of three parts, the economiser (recovery of sensible heat from the flue gas), the condenser (recovery of sensible and latent heat from the flue gas), and the air pre-heater (pre-heating the combustion air and the air used to dilute the saturated flue gas before entering the chimney).

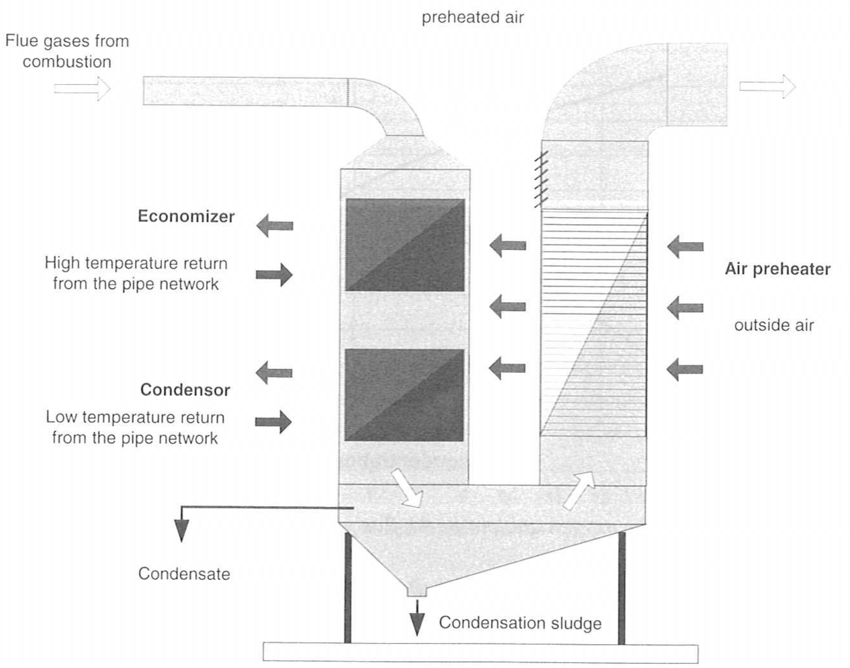

Figure 5.25: *Diagram of a flue gas condensation unit for biomass combustion plants [139].*

The amount of energy that can be recovered from the flue gas depends on the moisture content of the biomass fuel, the amount of excess oxygen in the flue gas (as already explained), and the temperature of the return of the network of pipes. The lower the temperature of the return water, the higher the amount of latent heat that can be recovered when the flue gas is cooled below the dew point (see Figure 5.26). Consequently, the energy recovery potential strongly depends on the quality of the heat exchangers, the hydraulic installations and the process control systems installed by the clients, because they determine the return temperature.

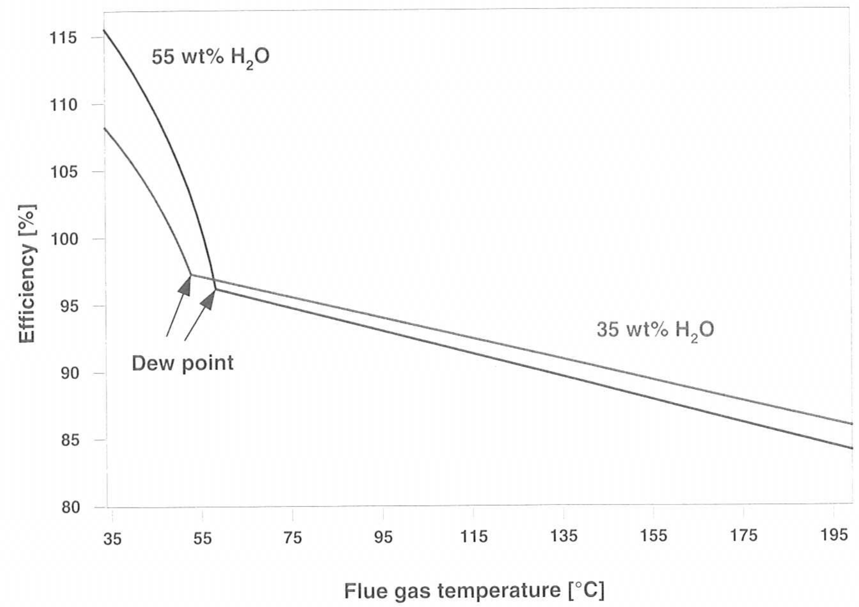

Figure 5.26: *Efficiency of biomass combustion plants with flue gas condensation units as a function of flue gas temperature.*
Explanations: oxygen concentration of the flue gas 9.5 Vol% (d.b.); biomass fuel used: wood chips / bark; H-content 6.0 wt.% (d.b.); gross calorific value of the fuel 20 MJ/kg (d.b.); dew point calculated for water; efficiency = heat output (boiler + flue gas condensation unit) / energy input fuel (NCV).

The dust precipitation efficiency of 40-75% mentioned can be significantly increased by placing a simple aerosol electrostatic filter behind the condensation unit. Early test runs showed a dust precipitation efficiency of 99.0% at temperatures below 40°C [140]. Due to the low flue gas temperature, the ESP unit can also be kept small and therefore economically acceptable. Furthermore, not only aerosols but also water droplets entrained with the flue gas achieve efficient precipitation, lowering the amount of dilution air that has to be added to the saturated flue gas leaving the condensation unit. The condensation sludge has to be separated from the condensate (by sedimentation units) because it contains significant amounts of heavy metals upgraded in this fine fly-ash fraction. It has to be disposed of or industrially utilised (see Section 8.3). Moreover, research has shown that the separation of sludge and condensate should be done at pH values > 7.5 in order to prevent dissolution of heavy metals and to meet the limiting values for a direct discharge of the condensate into rivers [141].

Flue gas condensation systems can also be operated as quench processes. The disadvantage of such systems is that quenching slightly lowers the amount of heat that can be recovered and requires even lower temperatures of the return in order to be energetically efficient. An interesting option for increasing the heat recovery potential of flue gas condensation units is a Swedish approach with an air humidifier integrated into the system (see Figure 5.27).

This technology foresees the pre-treating and moistening of combustion air by injecting condensate water into the air. By this means, the moisture content of the flue gas rises and the heat recovery potential increases accordingly. When applying this air humidification unit, one has to take care that the spray nozzles produce very fine water droplets (in order to give them enough time for evaporation) and to design the nozzles in a way that prevents malfunctions due to impurities in the condensate [142].

With regard to economic aspects, flue gas condensation is generally recommendable for biomass combustion plants. Flue gas condensation units are of interest if wet biomass fuels are utilised (average moisture content between 40 and 55 wt% (w.b.)), if the return of the network of pipes is below 60°C and if the nominal boiler capacity is above 2 MW_{th}.

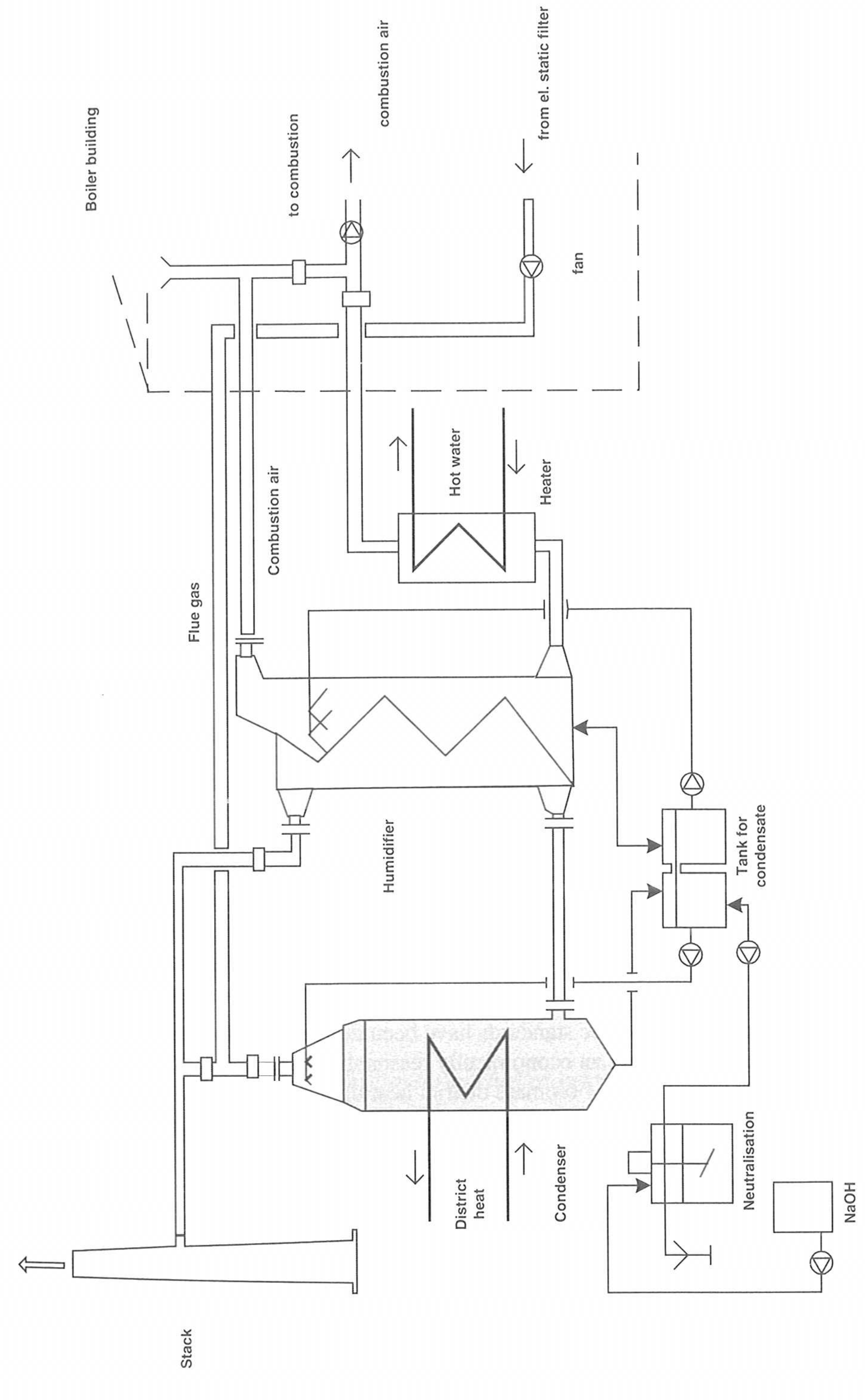

Figure 5.27: *Diagram of a flue gas condensation unit with an integrated air humidifier [142].*

5.8 Techno-economic aspects concerning the design of biomass combustion plants

Biomass combustion plants are complex systems with numerous components. In order to ensure a sustainable and economic operation of such plants, professional dimensioning and engineering are essential.
The engineering process consists of several steps as described briefly below [118, 143].

- Identification of the bases of the biomass combustion plant,
- Feasibility study,
- Planning of the design,
- Approval procedure,
- Planning of the execution,
- Initialising and placing orders,
- Supervision of the construction work,
- Commissioning test and documentation.

The main components of a biomass combustion plant are (alternative components in brackets):

- Fuel storage (long-term storage, daily storage),
- Fuel-feeding and handling system,
- Biomass furnace,
- Boiler (hot water, steam, thermal oil),
- Back-up or peak-load boiler (e.g. oil-fired boiler),
- Heat recovery system (economiser or flue gas condensation unit),
- Ash manipulation and pre-treatment,
- Flue gas cleaning system,
- Stack,
- Control and visualisation equipment,
- Electric and hydraulic installations,
- (Heat accumulator),
- (CHP unit),
- (Network of pipes for district heating plants).

Recommended technical and economic standards for biomass combustion and biomass district heating plants
In Austria, technical and economic standards have been defined for biomass district heating plants in order to secure an economically reasonable investment. Keeping these standards is a requirement for new biomass district heating or CHP projects in Austria; otherwise no investment subsidies are granted. Relevant technical and economic parameters of these standards are defined and explained in [144, 145].

$$\text{Simultaneity factor [\%]} = \frac{\text{effective peak heat load – district heating network}}{\sum \text{consumer nominal connection capacity}}$$

$$\text{Boiler full load operating hours [h p.a.]} = \frac{\text{boiler heat produced per year}}{\text{boiler nominal capacity}}$$

$$\text{Annual utilisation rate – biomass combustion plant [\%]} = \frac{\text{boiler heat produced per year}}{\text{fuel heat input (NCV) per year}}$$

$$\text{Network heat utilisation rate [kWh/m]} = \frac{\text{heat sold per year}}{\text{length of pipe network}}$$

$$\text{Annual utilisation rate – district heating network [\%]} = \frac{\text{heat sold per year}}{\text{heat produced in heating plant per year}}$$

$$\text{Specific investment (boiler) [EURO/kW]} = \frac{\text{investment costs of total system}}{\text{nominal capacity of biomass boiler}}$$

$$\text{Heat generation costs [EURO/MWh]} = \frac{\text{(capital costs + payments) per year}}{\text{heat sold per year}}$$

Plant dimensioning / boiler size
The nominal thermal capacity of a biomass district heating or heat controlled CHP plant is determined by the energy demand (heat, electricity) and has to allow for future developments. Therefore, as a first step, a detailed and precise survey of capacity and heat requirements in the supply area is necessary. Moreover, the simultaneity of heat demand of the district heating clients, described by the *simultaneity factor*, has to be taken into consideration. This factor depends on the number and type of consumers and fluctuates between 0.5 (large district heating networks) and 1 (micro-networks) [145].
In most cases, the energy demand is not constant over the whole year. The heat load of district heating networks especially varies during the year, reaching a maximum during the winter season and a minimum during summer. Therefore, on the basis of the results of the survey of capacity and heat requirements, the annual heat output line has to be calculated (see Figure 5.28). In boiler planning, a distinction must be made between base load and peak load for economic reasons. Base load is covered by one or more biomass boilers, peak load boilers are usually run on fossil energy for economic reasons. The installations of heat accumulators can also contribute to peak load coverage. This distinction between base load and peak load is necessary to achieve a high number of *full-load operating hours* of the biomass boiler and to decrease total *heat generation costs*. The correct determination of the boiler sizes depends on the capital costs of the combustion unit as well as on the operating costs (mainly fuel costs – see Table 5.3)

Table 5.3: *Comparison of specific investment and fuel costs for biomass and fuel oil-fired combustion systems [144, 146]*

combustion system	specific investment costs	fuel costs
biomass	high (about 100 € / kW [1])	low (about 15 € / MWh_{NCV})
fuel oil	low (about 20 € / kW [2])	high (about 30 € / MWh_{NCV})

[1] 5MW_{th} biomass combustion unit (fuel feeding, furnace, boiler, multicyclone, ESP, stack);
[2] 5MW_{th} fuel oil boiler with burner and stack; specific investment costs related to nominal boiler capacity.

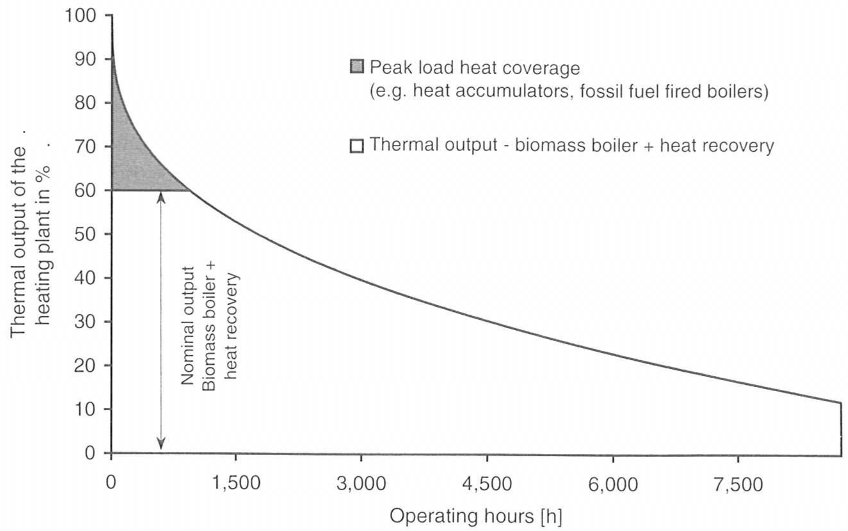

Figure 5.28: *Example of distribution between base load and peak load on the basis of the annual heat output line [145].*

Annual utilisation rate of the biomass system
The *annual utilisation rate of the biomass system* (biomass boiler + heat recovery) in the overall plant should be at least 85%. Therefore, the installation of a heat recovery system (e.g. economiser or flue gas condensation unit) is recommended.

Size of the fuel storage unit
The fuel storage unit should be small and should be designed for just-in-time operation (capacity of the biomass storage unit less than 10% of annual fuel consumption). Care should be taken to arrange for appropriate fuel supply contracts, organised fuel purchase, and regional co-ordination.

Construction and civil engineering costs
The costs of the buildings should be less than 750 € per m²; the costs of the storage unit should be less than 75 € per m³ of usable volume.

Network of pipes
The costs of the heat distribution network account for 35-55% of total investment costs of complete district heating plants. Thus, it is important to calculate the network correctly in order to achieve high rates of utilisation and to concentrate on a small and efficient network of pipes. For biomass district heating networks, the *network heat utilisation rate* should exceed 800 kWh per metre; the targeted value is 1,200 kWh per meter. Moreover, a maximum temperature spread between feed and return should be achieved. The targeted value for biomass district heating plants is 40°C or higher. The *annual utilisation rate of district heating networks* should exceed 75%.

Heat generation costs and economic optimisation
The calculation of heat generation costs is preferably based on the VDI Guideline 2067. This cost calculation scheme distinguishes four types of costs:

- capital costs (depreciation, interest costs),
- consumption-based costs (fuel, materials like lubricants),
- operation-based costs (personnel costs, costs for maintenance), and
- other costs (administration, insurance).

In comparison to energy systems run on fossil fuels, investment costs for biomass boilers including fuel supply systems and flue gas cleaning are high (see Table 5.3). Typical values for total investment costs for biomass combustion plants in Austria and Denmark are shown in Figure 5.29. Therefore, optimal plant utilisation is necessary to decrease heat generation costs. Figure 5.30 illustrates the influence of the boiler full-load operating hours on the capital costs of biomass combustion units. In order to take advantage of the decline of marginal unit costs, the *boiler full-load operating hours* of the biomass combustion unit should exceed 4,000 hours per year. For biomass CHP plants in heat-controlled operation, the target is 5,000 boiler full-load operating hours or more.

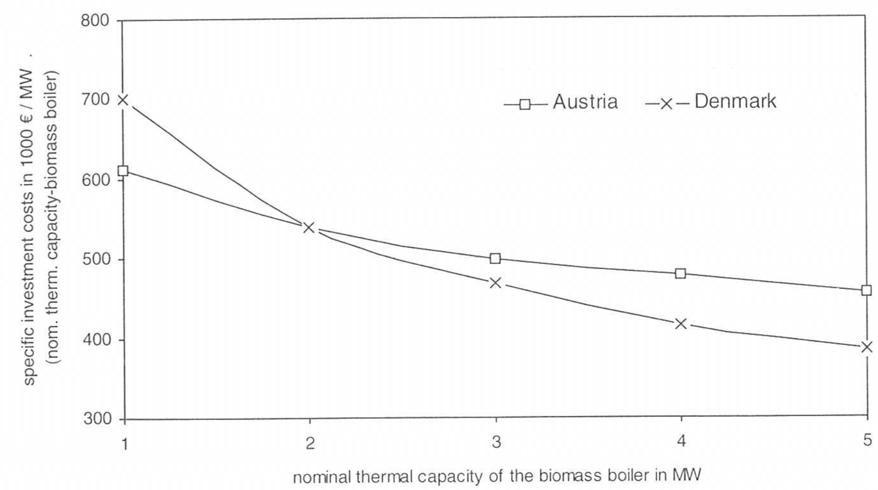

Figure 5.29: *Comparison of specific investment costs for biomass combustion plants in Austria and Denmark as a function of biomass boiler size.*
Explanations: diagram from [144], investment costs include: biomass grate furnace for wood chips, hot water fire-tube boiler, back-up boiler (fuel oil), fuel storage, fuel-feeding system, flue gas cleaning, stack, buildings, hydraulic and electric installations, engineering and construction costs (network of pipes is not included)

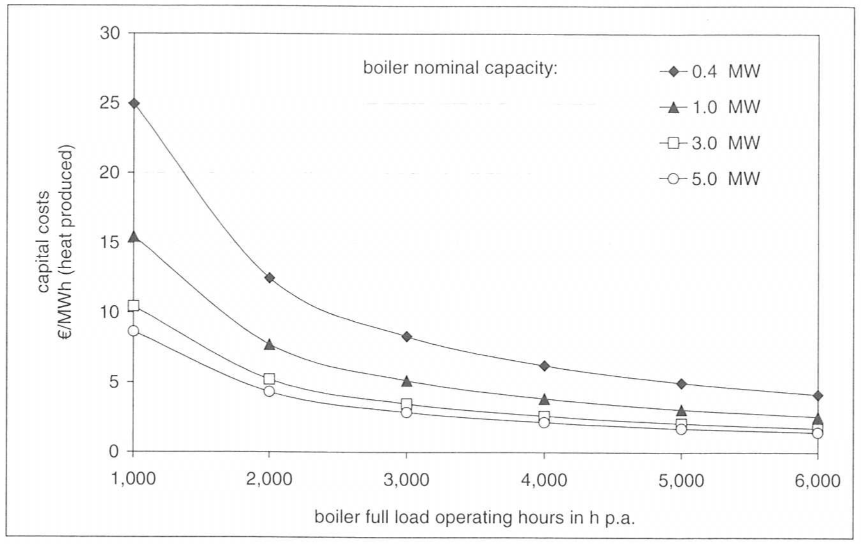

Figure 5.30: *Specific capital costs for biomass combustion systems as a function of boiler capacity and boiler utilisation..*

<u>Explanations</u>: diagram from [144], biomass moving grate furnace (inclusive hot water fire-tube boiler, fuel feeding and stack), interest rate 7% p.a., lifetime 20 years, calculations according to VDI guidelines 2067.

6 Power Generation and Co-Generation