secondary air is established after the boiler is installed. Using this relation, these parameters can be adjusted to keep the boiler water temperature at a given value.

Modification of an existing biomass boiler
Existing boilers can often be modified to successfully achieve reduced emission levels, higher thermal efficiency, and improved control of heat output. An example is given below:
For a 500 kW_{th} Nolting underscrew feeder wood combustion plant with cyclone, TNO installed a λ sensor in order to control the combustion process and heat output. Also, flue gas recirculation was applied and the combustion chamber was modified. Table 8.9 shows that as a result of the optimisation, the efficiency increased while the emissions were effectively reduced [277].

Table 8.9: *Effect of optimisation on emissions and efficiency (at 11% O_2, dry)*

Property	Before optimisation			After optimisation		
	1	2	3	1	2	3
CO [mg/m_o^3]	3,516	4,439	4,327	82	313	103
C_xH_y [mg/m_o^3]	262	303	269	2.0	28	2.0
NO_x [mg/m_o^3]	772	722	764	652	872	706
Dust [mg/m_o^3]	219	235	214	99	157	106
Flue gas temperature [°C]	163	164	158	109	162	132
Flue gas losses [%]	17	-	17	7	-	8
Losses due to incomplete combustion [%]	1.5	-	2.0	0.1	-	0.1
Overall efficiency [%]	81	-	81	93	-	92

This example illustrates that it is possible to significantly reduce boiler emissions and increase efficiency with relatively simple process modifications.

8.2.3.7 Staged-air combustion

Staged-air combustion is widely applied in biomass combustion applications, also in small-scale applications. However, the possibilities for an accurate control of the combustion air are usually limited in small-scale applications, which may result in higher emission levels. Staged-air combustion makes a simultaneous reduction of both emissions from incomplete combustion and NO_x possible through a separation of devolatilisation and gas phase combustion. This results in improved mixing of fuel gas and combustion air. In the first stage, primary air is added for devolatilisation of the volatile fraction of the fuel, resulting in a fuel gas consisting mainly of CO, H_2, C_xH_y, H_2O, CO_2 and N_2. For NO_x emission reduction, also the fuel gas content of NH_3, HCN and NO is of particular interest. In the second stage, sufficient secondary air is supplied to ensure a good burnout and low emission levels from incomplete combustion.
An improved mixing of fuel gas and secondary air reduces the amount of secondary air needed, resulting in higher flame temperatures, and also a lower overall excess air ratio. Hence, emissions from incomplete combustion are reduced by a temperature increase, which speeds up the elementary reaction rates, and improved mixing, which reduces the residence time needed for mixing the fuel gas and the secondary combustion air. However, this does not mean that the NO_x emission level is automatically reduced as well. An efficient reduction of both emissions from incomplete combustion and NO_x emissions can only be achieved by optimisation of the primary excess air ratio.
As mentioned before, fuel nitrogen is converted to NO (> 90%) and NO_2 (< 10%) through a series of elementary reaction steps, called the fuel NO_x mechanism. Important primary nitrogen-containing components are NH_3 and HCN. However, significant amounts of NO and N_2 may also be found in the pyrolysis gas. If sufficient O_2 is available, NH_3 and HCN will mainly be converted to NO through different reaction routes. However, in fuel-rich conditions NO will react with NH_3 and HCN, forming N_2. This mechanism is utilised as a primary NO_x reduction measure. By optimising the primary excess air ratio, temperature and residence time a maximum conversion of NH_3 and HCN to N_2 can be achieved. Figure 8.5 shows the ratio between the Total Fixed Nitrogen amount (includes all nitrogen-containing species except N_2) and the fuel nitrogen content (TFN/Fuel-N) as a function of primary excess air ratio for chemical kinetic calculations in two ideal flow reactors, utilising a detailed elementary reaction scheme. A typical pyrolysis gas composition from wood was used as fuel gas composition. As can be seen, the choice of flow reactor highly influences the reduction potential, and illustrates the importance of mixing effects. The PFR (Plug Flow Reactor) and the PSR (Perfectly Stirred Reactor) can be regarded as the two extremes among mixing models. The reduction potential is also influenced by the choice of nitrogen-containing species in the fuel gas. The reduction potential for NH_3 as nitrogen-containing species is, in general, higher than it is for HCN, as the conversion of HCN to N_2 requires a longer and more complex reaction path. Temperature, residence time, and initial fuel nitrogen content also influence the reduction potential.

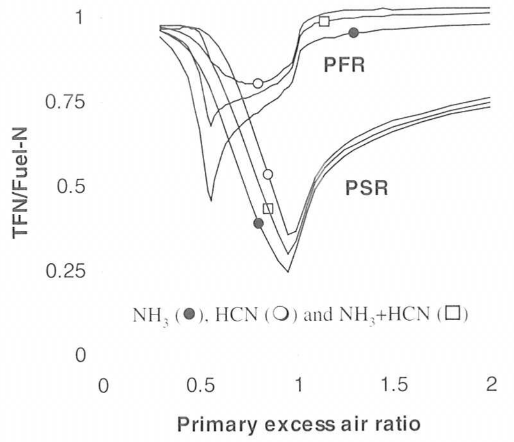

Figure 8.5: *TFN/Fuel-N ratio for NH_3, HCN, and a mixture of 50% NH_3 and 50% HCN as a function of primary excess air ratio at a constant temperature (1173 K), residence time (100 ms), and fuel-N content (1000 ppm) for two ideal flow reactors, a PFR and a PSR [278].*

In a 25 kW test reactor [279] with fixed bed updraught gasification and separate reduction chamber, followed by gas phase combustion, it has been shown that an NO_x reduction of up to 50-75% can be achieved by staged-air combustion. The percentage increases with increasing fuel-N content, at optimum conditions:

- residence time in the reduction chamber ≈ 0.5 s (> 0.3 s);
- reduction chamber temperature ≈ 1100-1200°C;
- primary excess air ratio ≈ 0.7.

The NO_x emission level as a function of primary excess air ratio is shown in Figure 8.6 for the 25 kW test reactor, with two-stage combustion and a reduction chamber temperature of 1150°C. An additional reduction can be achieved by staging the primary air. If the use of a separate reduction chamber is not applicable, then the NO_x emission reduction potential decreases, but it can still be significant if efficient air staging is applied in the combustion chamber. To ensure a constant primary excess air ratio and reduction chamber temperature, a suitable combustion process design and accurate combustion process control are necessary. Further references: [280, 281, 282, 283, 284, 285].

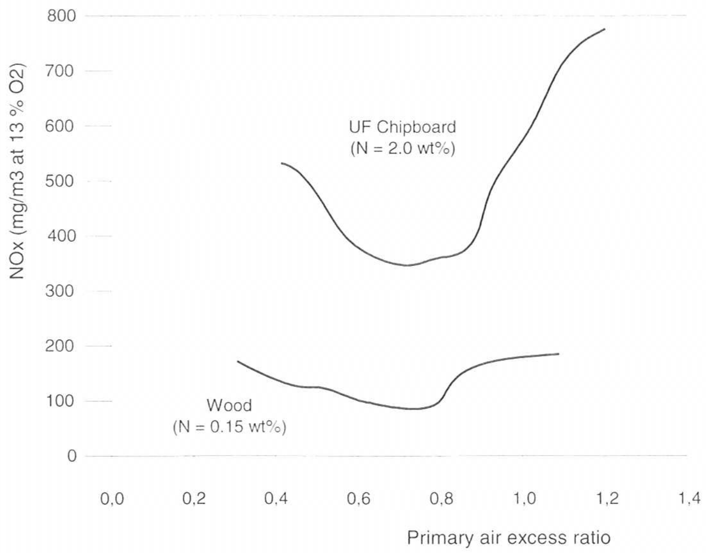

Figure 8.6: *NO_x emission level as a function of primary excess air ratio for the 25 kW test reactor [279].*

8.2.3.8 Staged fuel combustion and reburning

Staged fuel combustion and reburning are other possible methods for NO_x reduction in biomass combustion applications. The primary fuel is combusted with an excess air ratio above 1, and no significant NO_x reduction occurs. A secondary fuel is then injected into the flue gas after the primary combustion zone, without additional air supply. A sub-stoichiometric reducing atmosphere is created in which NO_x formed in the primary zone may be reduced, by reactions with NH_3 and HCN formed from the secondary fuel (if the secondary fuel contains nitrogen), in a similar manner as for staged-air combustion (see Figure 8.7). Additionally, NO is converted back to HCN by reactions with HCCO and CH_i radicals (i = 0-3) formed from the secondary fuel. This is called reburning. Under typical reburning conditions, HCCO appears to be the most effective radical for removing NO [286]. Finally, a sufficient amount of air is added after the reducing zone to achieve a good burnout with an overall excess air ratio above 1.

The potential of staged fuel combustion was investigated in an understoker furnace [279], where the secondary fuel was introduced on a second grate above the main fuel bed with an energy input ratio of approximately 70% primary and 30% secondary fuel. An NO_x reduction of 52-73% was achieved with a temperature in the reduction zone of approximately 700°C. Hence, an NO_x reduction potential similar to that of staged-air combustion can be achieved at a significantly lower temperature level in the reduction zone. The optimum overall excess air ratio in the reduction zone is approximately between 0.7-0.9. As is the case in staged-air combustion, residence time and initial fuel nitrogen content also influence the reduction potential. The properties of the secondary fuel will also be of importance, especially the fuel-N and the volatile content.

Staged fuel combustion requires automatic feeding of the primary and secondary fuel, and the secondary fuel must be easily adjustable. This limits the use of staged fuel combustion to large-scale biomass combustion applications since a suitable combustion process design with two fuel-feeding systems as well as an accurate combustion process control is necessary. Natural gas, fuel oil, pyrolysis gas, biomass powder, sawdust, or similar fuels can be used as secondary fuels. Further references: [287, 288, 283].

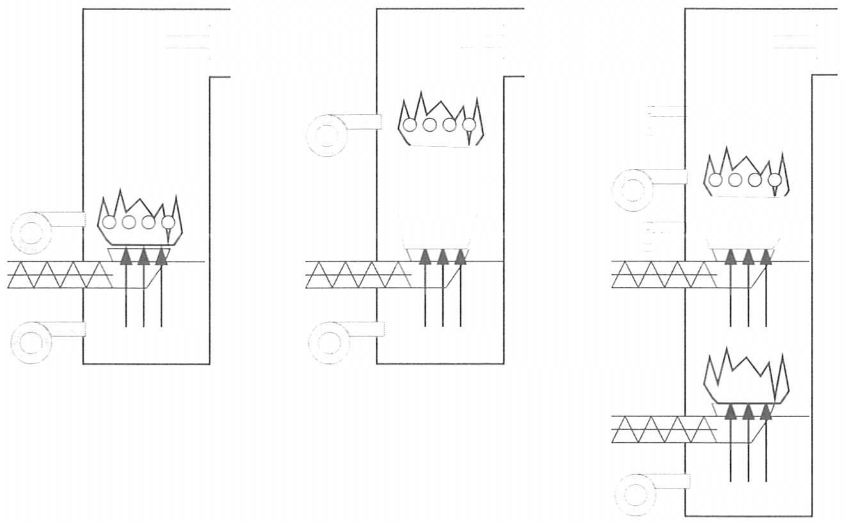

Figure 8.7: *Three principles of combustion. Diagrams from left to right: conventional combustion, staged-air combustion, and staged fuel combustion [289].*

8.2.3.9 Catalytic converters

Catalytic converters are utilised to some degree in small-scale biomass combustion applications such as wood-stoves and wood log boilers. The catalytic converter is usually placed in the flue gas channel after the combustion chamber. A catalytic converter introduces the possibility for heterogeneous reactions. The catalytic surfaces of the catalytic converter provide free surface sites where the reactants adsorb, react, and finally desorb as products from the catalytic surface. The activation energy for the reactions at the catalytic surface is in general much lower than it is for the equivalent gas phase reactions. Catalytic converters can therefore efficiently reduce the level of emissions from incomplete combustion in the flue gas at low flue gas temperature levels. If properly ignited, the catalytic converter can oxidise unburned flue gas components at flue gas temperatures down to about 130°C [270].

A catalytic converter consists of a durable, heat-resistant ceramic composition that is extruded into a cellular, or honeycomb, configuration. After extrusion, this ceramic monolith is fired and then covered with a noble-metal catalyst (usually platinum, rhodium or palladium, or combinations of these) or metal oxides. It is of paramount importance that the catalyst has a high thermal stability and a good poison-resistance to avoid its deactivation.

The emission reduction efficiency of the catalyst depends on several variables, such as catalyst material, surface area, operation temperature, temperature profile over the catalytic converter, residence time, mass transport limitations, homogeneity of mixing before the catalytic converter, and emission component. Emission reduction efficiencies of 70-93% for CO, 29-77% for CH_4, 80-100% for other hydrocarbons, 43-80% for PAH, and 56-60% for tar have been reported for a wood-stove with forced draught [290]. A limiting factor for the reduction potential obtainable in small-scale biomass combustion applications is the pressure drop over the catalytic converter. Natural draught is often used in wood-stoves and fireplaces. This limits the possible surface area of the catalytic converter.

A comparison of the emission levels of a wood-stove equipped with a catalytic converter with the emission levels of a traditional wood-stove and with an advanced downdraught staged-air wood-stove [291] under similar operating conditions, has shown that the wood-stove with the catalytic converter achieved the lowest CO emission levels by far. However, for hydrocarbons and particles the difference was smaller, especially compared to the advanced downdraught staged-air wood-stove. In batch combustion units, such as wood-stoves and fireplaces, a significant fraction of the total CO emission level will originate from the char combustion phase due to, usually, too low temperatures for effective gas phase conversion of CO, formed from the heterogeneous char oxidation, to CO_2.

Catalytic converters are not widely applied in small-scale wood combustion units today. In most IEA countries, the emission limits can be met without a catalytic converter.

8.2.4 Secondary emission reduction measures

Secondary measures can be applied to remove emissions from the flue gas once it has left the boiler. For virgin wood combustion, particle removal is of particular relevance. For other types of biomass, additional secondary measures may be necessary, depending on the elementary composition and the fuel characteristics of the selected biomass fuel, and the combustion technology.

In this chapter, emission reduction measures for removal of primarily particles, NO_x and SO_x are presented. Other components that also can be reduced by secondary measures are HCl, heavy metals, and PCDD/F. However, secondary emission reduction measures for these components will not be presented in detail. HCl emission levels are reduced in wet throwaway processes applied for SO_x reduction. Furthermore, adsorptives such as activated lignite can be used for a combined extraction of HCl, SO_2, and PCDD/F. PCDD/F emission levels can be reduced by an efficient particle separation at temperatures well below the temperature range of the de novo synthesis. Emissions of heavy metals can be significantly reduced in particle-collecting devices such as bag filters or electrostatic filters.

8.2.4.1 Particle control technologies

Not every particle control technology suits every need. Among the determining factors are the particle's size, required collection efficiency, gas flow size, allowed time between cleanings, the detailed nature of the particles, and the presence of tars in the flue gas. The following rules of thumb [199] may be helpful in selecting particle control technologies for biomass combustion applications:

1. Sticky particles (e.g. tars) must be collected in a liquid, as in a scrubber, or in a cyclone, bag filter, or an electrostatic filter whose collecting surfaces are continually coated with a film of flowing liquid. There must also be a way to process the contaminated liquid thus produced.
2. Particles that adhere well to each other but not to solid surfaces are easy to collect. Those that do the reverse often need special surfaces, e.g. Teflon-coated fibres in filters that release collected particles well during cleaning.
3. The electrical properties of the particles are of paramount importance in electrostatic filters, and they are often significant in other control devices where friction-induced electrostatic charges on the particles can aid or hinder collection.
4. For non-sticky particles larger than about 5 μm, a cyclone separator is probably the only device to consider.
5. For particles much smaller than 5 μm one normally considered electrostatic filters, bag filters, and scrubbers. Each of these can collect particles as small as a fraction of a micron.
6. For large flows the pumping cost makes scrubbers very expensive; other devices are preferable.
7. Corrosion resistance and dew point must always be considered.

Figure 8.8 shows the collection efficiencies for some proven particle control technologies as a function of particle diameter. Table 8.10 summarises the typical sizes of particles removed by several proven particle control technologies, and typical removal efficiencies. Below, the following particle control technologies will be discussed:

- settling chambers,
- cyclones,
- multicyclones,
- electrostatic filters,
- bag filters,
- scrubbers,
- panel bed filter,
- rotating particle separator.

Table 8.10: *Summary of typical sizes of particles removed by various particle control technologies.*

Particle control technology	Particle size (μm)	Efficiency (%)
Settling chambers	> 50	< 50
Cyclones	> 5	< 80
Multicyclones	> 5	< 90
Electrostatic filters	< 1	> 99
Bag filters	< 1	> 99
Spray chambers	> 10	< 80
Impingement scrubbers	> 3	< 80
Cyclone spray chambers	> 3	< 80
Venturi scrubbers	> 0.5	< 99

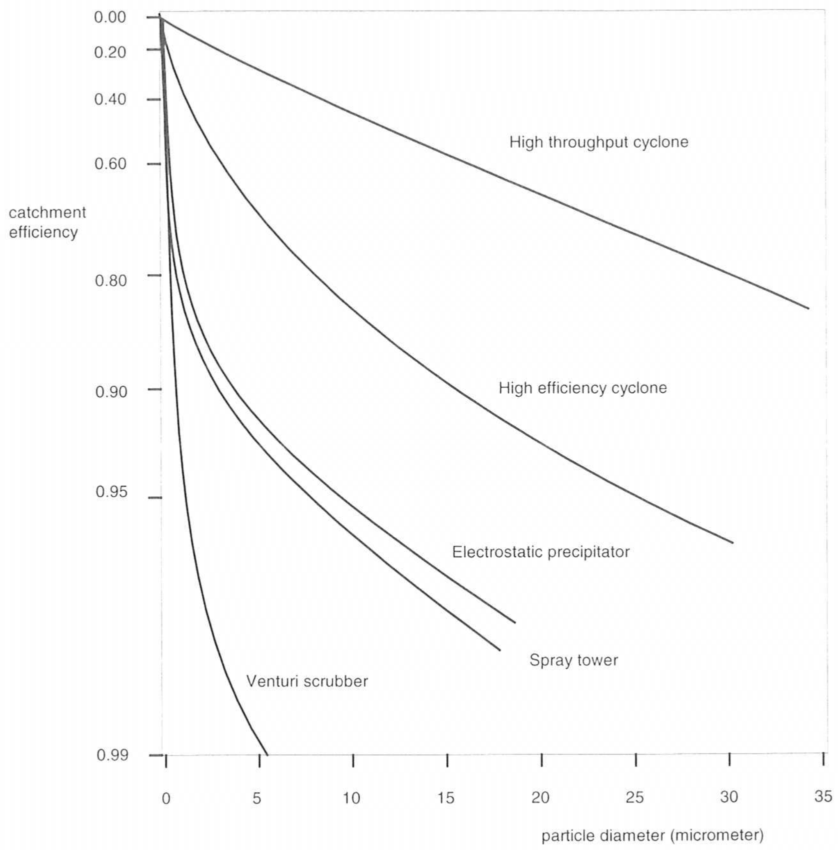

Figure 8.8: *Collection efficiencies for various particle control technologies [202].*

Settling chambers

Principle of operation: Particle separation in a settling chamber is based on the principle of gravity, see Figure 8.9. The main disadvantage of this method is the low collection efficiency. However, it is still widely applied because of its ability to extinguish the flame. Typical characteristics of a settling chamber are given in Table 8.11.

Advantages:
- Low pressure loss.
- Simplicity of design and maintenance.
- High capacity.
- Low costs.
- Ability to extinguish the flame.

Disadvantages:
- Much space required.
- Low collection efficiency.

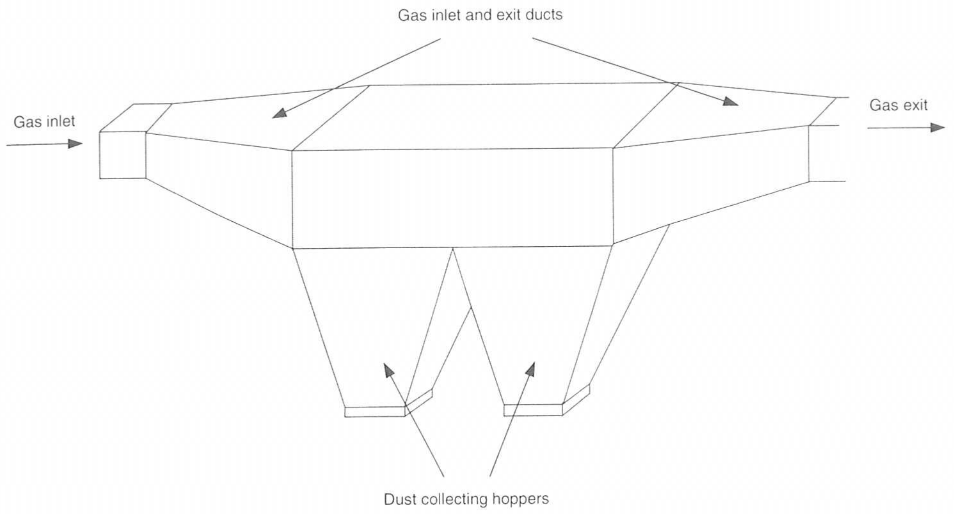

Figure 8.9: *Settling chamber [202].*

Table 8.11: *Characteristics of a settling chamber.*

Principle	Gravity
Separation efficiency	App. 10% for particles < 30 μm App. 40% for particles < 90 μm
Gas velocity	1 - 3 m/s
Pressure drop	< 20 Pa
Temperature range	< 1300°C
Pressure range	< 100 bar
Application	First separation step

Cyclones

Principle of operation: Particle separation in a cyclone is based on the principle of gravity in combination with centrifugal forces. Gas and solid particles are exposed to centrifugal forces, which can be done in two ways:

- gas flows into the cyclone in tangential direction;
- gas flows into the cyclone in axial direction, and is brought into rotation using a fan.

Because of the centrifugal forces, particles hit the wall and slide down into a container. Figure 8.10 illustrates the principle. Cyclones have higher collection efficiency than settling chambers due to the centrifugal force principle.

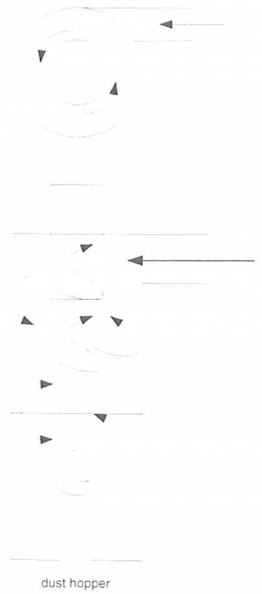

Figure 8.10: *Principle of a cyclone [205].*

Advantages:

- Simplicity of design and maintenance.
- Little floor space required.
- Dry continuous disposal of collected dusts.
- Low to moderate pressure loss.
- Handles large particles.
- Handles high dust loadings.
- Temperature independent.
- Low costs.
- Ability to extinguish the flame.

Disadvantages:

- Much head room required.
- Low collection efficiency of small particles.
- Sensitive to variable dust loadings and flow rates.
- Tars may condense in the cyclone.

The energy loss is mainly determined by the pressure drop over the cyclone and is about 0.2 kWh per 1000 m^3 of flue gas. Typical characteristics of a cyclone are given in Table 8.12.

Table 8.12: *Characteristics of a cyclone.*

Principle	**Gravity in combination with centrifugal forces**
Separation efficiency	85 - 95%
Gas velocity	15 - 25 m/s
Pressure drop	60 - 150 Pa
Temperature range	< 1300°C
Pressure range	< 100 bar
Application	First or final particle separation step

Multicyclones

The separation efficiency of a cyclone can be improved by increasing the centrifugal force through reduction of the cyclone diameter. In order to prevent loss of capacity, several cyclones can be used in parallel; this is named a multicyclone, as illustrated in Figure 8.11. Disadvantages of multicyclones, however, are their more complicated, and therefore more expensive, construction and increased pressure drop, and therefore higher energy consumption.

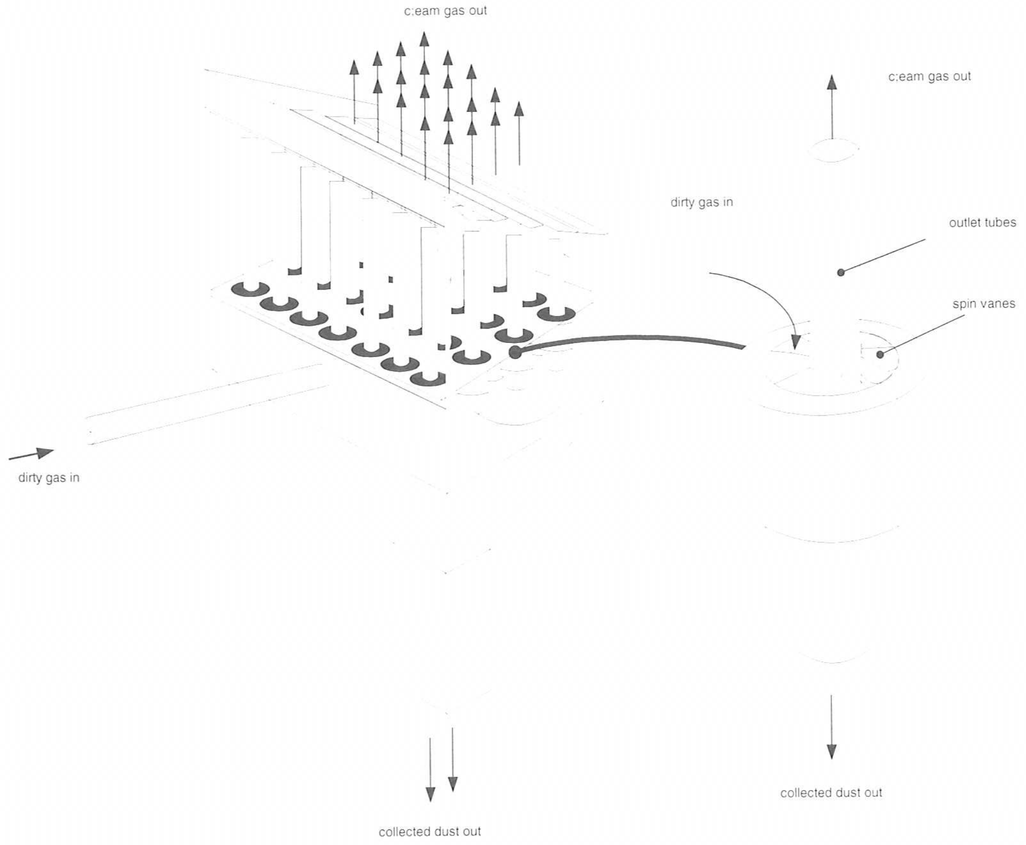

Figure 8.11: *Principle of a multicyclone [205].*

Electrostatic filter

Principle of operation: The principle of an electrostatic filter is illustrated in Figure 8.12. In an electrostatic filter, the particles are first electrically charged. Then they are exposed to an electrical field in which they are attracted to an electrode. Periodically, this electrode is cleaned through vibration, by which the dust falls off the electrode into a collection unit.

In practice, separation can be done in one or two stages. Most of the electrostatic filters found in practice are one-stage filters. In case of two-stage separation, charging of the particles is first done in a very strong electric field, after which a relatively weak field separates the particles.

Advantages:
- Above 99% efficiency obtainable.
- Very small particles can be collected.
- Particles may be collected wet or dry.
- Pressure drops and power requirements are small compared with other high-efficiency collectors.
- Maintenance is nominal unless corrosive or adhesive materials are handled.
- Few moving parts.
- Can be operated at high temperatures up to 480°C.
- Applicable for high flue gas flow rates.

Disadvantages:
- Relatively high initial costs.
- Sensitive to variable particle loadings or flow rates.
- Resistivity causes some material to be economically uncollectable.
- Precautions are required to safeguard personnel from high voltage.
- Collection efficiencies can deteriorate gradually and imperceptibly.
- Voluminous.

Table 8.13 illustrates some typical characteristics of an electrostatic filter. For typical wood burning applications up to 1,5 MW_{th}, dust emissions under 50 mg/m^3_0 can be obtained with electrostatic separation.

Table 8.13: *Characteristics of an electrostatic filter.*

Principle	Electrical charging of particles
Separation efficiency	95 - 99.99%
Gas velocity	0.5 - 2 m/s
Pressure drop	15 - 30 Pa
Temperature range	< 480°C
Pressure range	< 20 bar
Application	final particle separation step

In the development of electrostatic separators, the following recent trends can be recognised:

- Reduced presence of dust particles in the filtered air through further optimisation of the geometry of the electrodes and the gas distribution. The distance between the electrodes has been increased to about 800 mm, so that the velocity of charged dust particles, and consequently the throughput, can be increased.
- Application of advanced, microprocessor-based controllers of high-voltage generators and cleaning mechanisms, according to the filter load and specific dust characteristics. This effectively reduces the energy consumption.
- Application of new construction materials that allow operation above temperatures of 480°C.
- Application of pressure vessels and airtight isolators that allow operation above 20 bar.
- Application of pulsated electrode voltage, in order to limit reversed flow of highly charged particles.

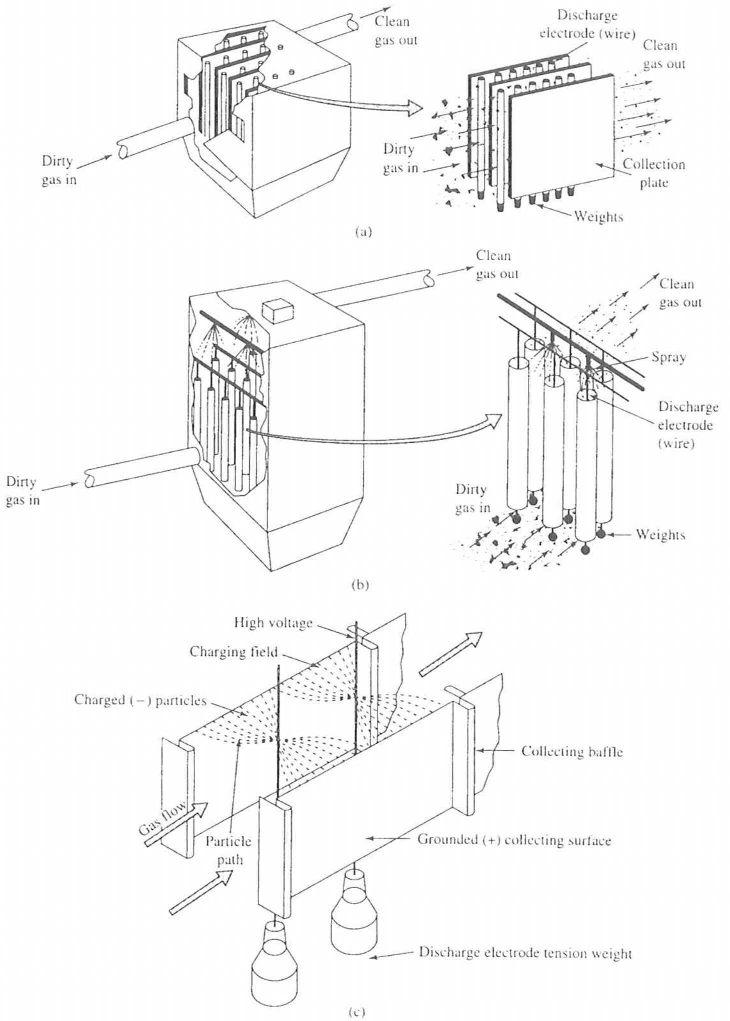

Figure 8.12: *Electrostatic filters: (a) plate type, (b) tube type, (c) detailed view of plate type filter element [205].*

Bag filters

Principle of operation: As Figure 8.13 shows, the construction of a bag filter is relatively simple. It consists of a filter or cloth, tightly woven from special fibres and hung up in a closed construction through which flue gas passes. The separation efficiency of bag filters is quite high, even with high flue gas flow rates and high particle content.

Advantages:

- Above 99% efficiency obtainable.
- Dry collection possible.
- Decrease of performance is noticeable.
- Collection of small particles possible.

Disadvantages:

- Sensitive to filtering velocity.
- High-temperature gases must be cooled.
- Affected by relative humidity (condensation).
- Susceptibility of fabric to chemical attack.
- Voluminous.
- Operating temperature limited to about 250°C.
- Tars may condense and clog the filter at low operating temperatures.
- Limited lifetime of the cloth (2-3 years).

The first layer of particles in fact improves the filtration efficiency. However, as more particles settle on the cloth, the pressure drop increases. Therefore, periodically the cloth is cleaned by vibration or pressurised air. Cloth filters are usually manufactured in cylindrical shapes. For heavily loaded filters (>100 m^3/m^2h), flue gas flows inward. For lightly loaded filters (<100 m^3/m^2h) flue gas flows outward.

Bag filters are usually made of various elements, which can be cleaned in turn with pressurised air. Since the fraction of elements that are cleaned at one moment is rather small compared to the total area, pressure variations over the filter are limited. Since the pressure drop is relatively low and constant (around 1000-3000 Pa), the filter can be operated with a constant flue gas flow.

The operating temperature range is limited to about 250°C; above this, as well as when unburned carbon is present in the fly ash, there is a significant fire risk. In order to limit the amount of particles settling on the filter and to reduce the chance of fire through sparks, a cyclone can be used. When too low operating temperatures are used, tars present in the flue gas may condense and clog the cloth.

The materials commonly applied for bag filters (textile, polymers) can resist temperatures up to around 250 °C. Recent developments are focussed on the improvement of cloth cleaning and the application of materials that can operate at higher temperatures. Examples are glass fibre, special polymers, metal fibre, and ceramic fibre. When using metal or ceramic fibre, flue gas temperatures up to 600°C to 800°C can be used. The selection of fibre material is primarily determined by flue gas temperature, more than chemical resistance. Table 8.14 gives an overview the temperature resistance of applicable bag filter materials.

For bag filters, the following recent developments can be recognised:

- Increased collection efficiency through application of finer cloth fibres, better distribution of dust over the filter area, and use of microprocessor-controlled cleaning devices.
- Energy conservation through the use of microprocessor controls which optimises and reduces the use of pressurised air for cleaning of the filter.

- Reduction of the filter dimensions through increase of the specific filter area load, and optimisation of the geometry of various components.

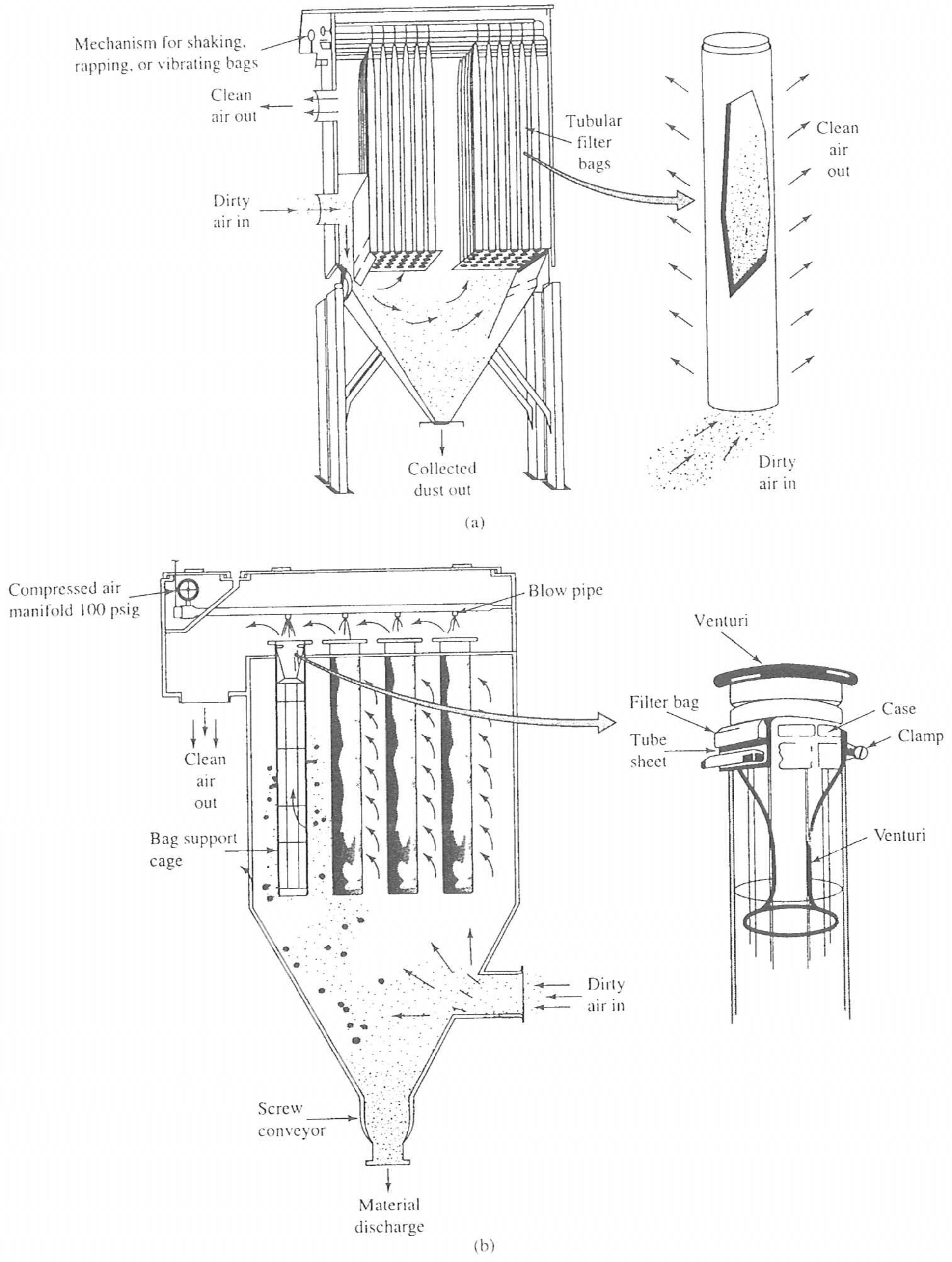

Figure 8.13: *Bag filters: (a) shaker bag filter, (b) pulse-jet bag filter [205].*

Table 8.14: *Temperature resistance of applicable bag filter materials.*

Material	Maximum operating temperature [°C]	
	Dry gas	Humid gas
Polypropylene	90	90
Polyacrylnitril	130	120
Polyester	150	135
Polyphenylsulphide	180	180
Polyamide	220	180
Polyimide	260	240
Polytetrafluorethylene	250	250
Glass fibre	295	280
Metal (Inconel)	600	550
Ceramic fibre	850	850

Scrubbers

Principle of operation: In scrubbers, particles are scrubbed out from the flue gas by water droplets of various sizes, depending on the type of scrubber used. The particles are removed by collision and interception between droplets and particles. Upon impact, the particles are wetted and carried by the water droplet, thus effecting removal. The more droplets that are formed, the more efficient the unit will be. Therefore, the droplets must be small. Smaller-diameter spray nozzles will produce smaller droplets but will also result in higher pressure drops, consuming more energy. Since efficiency increases as the droplet size decreases, efficiency increases with increasing pressure drop.

Flue gas scrubbing and condensation are often done in a scrubber-condenser, which contributes to lower emissions of particles and simultaneously higher energy efficiency of the plant.

Figure 8.14 shows various types of scrubbers. Parts (a) and (b) show ordinary spray chambers, a countercurrent scrubber and a cross-flow scrubber, respectively. In a countercurrent scrubber, flue gas is introduced at the bottom side of the unit and flows upward countercurrent to the settling of the atomised liquid droplets. In a cross-flow scrubber, flue gas flows cross-flow to the settling of the atomised spray water droplets. Although two sets of sprays atomise the water in horizontal directions, the settling of the resulting droplets is still downward, cross-flow to the direction of the flue gas. Part (c) shows a venturi scrubber and part (d) shows a cyclone spray chamber, which is a combination of an ordinary spray and a cyclone. Several other types of scrubbers exist, such as plate scrubbers, packed-bed scrubbers, baffle scrubbers, impingement-entrainment scrubbers, and fluidised bed scrubbers. These will not be presented here.

Advantages:

- Simultaneous gas (SO_2, NO_2, HCl) absorption and particle removal.
- Ability to cool and clean high-temperature, moisture-laden gases.
- Corrosive gases and mists can be recovered and neutralised.
- Reduced dust explosion risk.
- Efficiency can be varied.

Disadvantages:

- Corrosion, erosion problems.
- Added cost of wastewater treatment and reclamation.
- Low efficiency on submicron particles.
- Contamination of effluent stream by liquid entrainment.
- Freezing problems in cold weather.
- Reduction of buoyancy and plume rise.
- Water vapour contributes to visible plume under some atmospheric conditions.

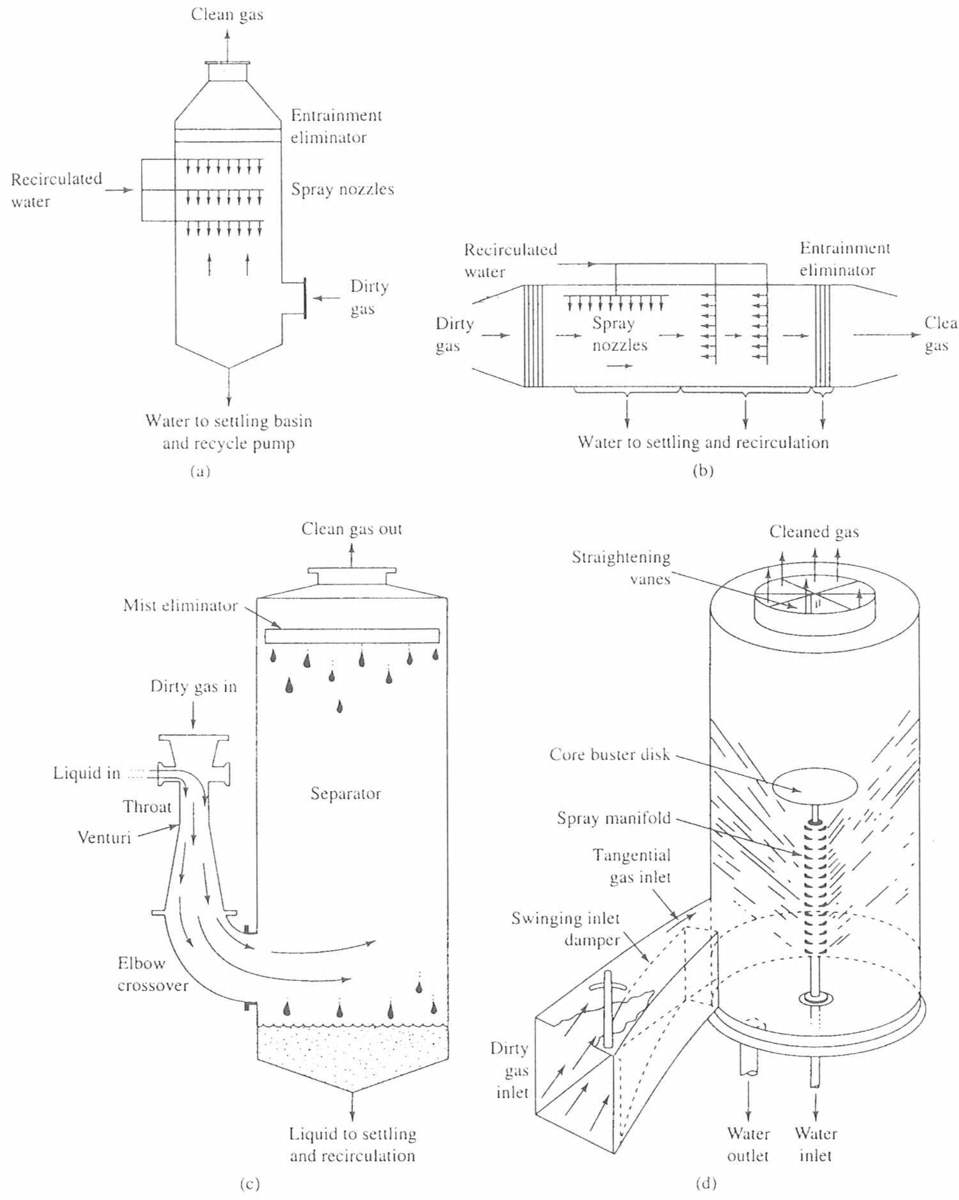

Figure 8.14: *Scrubbers: (a) counter-current spray chamber, (b) cross-flow spray chamber, (c) venturi scrubber, (d) cyclone spray chamber [205].*

Panel bed filter

A recent development in Norway is the panel bed filter. The filter uses sand and other granulates to filter dust from flue gases. The concept was developed by Prof. Squires (USA) and further developed by SINTEF/NTNU Thermal Energy and Hydropower in Trondheim, Norway. Among the most important advantages of this filter as compared to a dust filter are its temperature resistance as well as its reduced sensitivity to sparks that may cause dust explosions. Figure 8.15 illustrates that the filter consists of layers of fine and course sand, physically separated and enclosed with strips that can open in one direction.

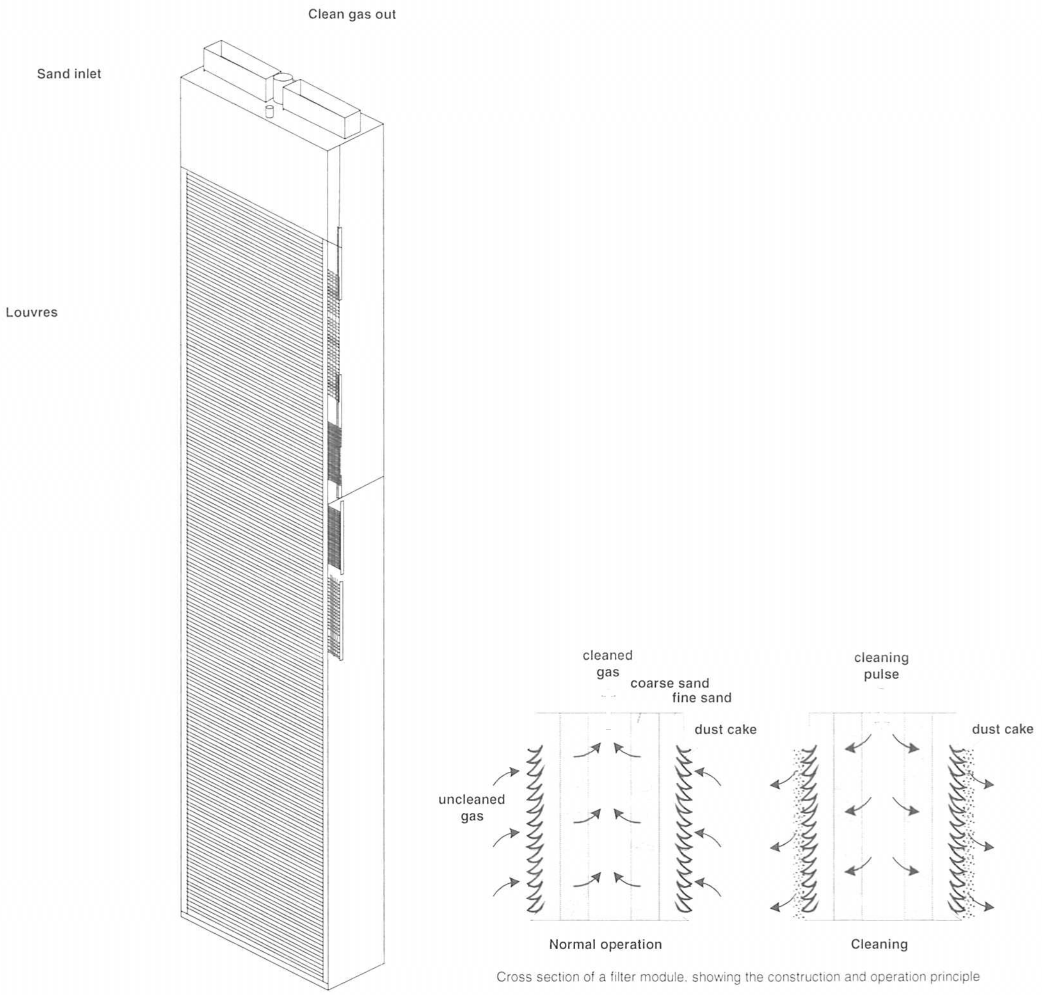

Figure 8.15: *Panel bed filter [292].*

Both the investment costs and the principle of a panel bed filter are similar to that of a bag filter. At the high-pressure side, a dust cake builds up. Dust in the flue gas that passes this cake first enters a layer of fine sand, then a layer of coarse sand. After a certain time of operation, the pressure drop over the dust cake is increased to a level at which the filter is automatically cleaned. Pulsated pressurised air from the low-pressure side will slightly open the strips on the high-pressure side, thereby removing the dust layer together with a small amount of fine sand. Sand and dust are then separated. The fine sand can be recycled into the filter, while the dust can be removed. The characteristics of a panel bed filter are summarised below:

- Temperature resistant until 700°C, and insensitive to fluctuations in temperature and presence of any hot dust particles.
- Resistant against corrosive elements contained in the gas.
- The filter material is relatively cheap and can easily be replaced.
- Since the specific filtration capacity is about 6 to 10 times higher than that of a bag filter, the filter area can be effectively reduced.
- Low operating and maintenance costs.
- Capable of removing dust with particle sizes < 1 mm, and emission levels below 5 $mg/m^3{}_0$ at 13% O_2 are achievable.

Rotating particle separator

Another recent development is the rotating particle separator [293, 294, 295] (see Figure 8.16), developed in the Netherlands.

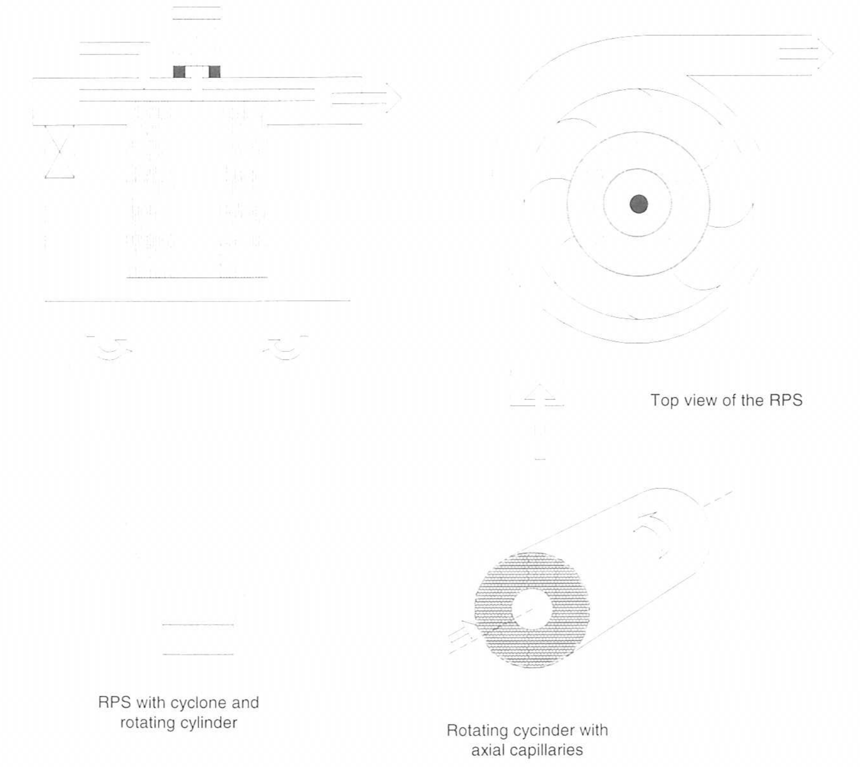

Figure 8.16: *Schematic view of the rotating particle separator [293].*

The technology can either be used together with a conventional multicyclone or instead of an electrostatic filter. Several field tests are presently being carried out in biomass combustion plants. The separation efficiency depends on the particle size. It is claimed that for particles greater than 1 µm, separation efficiencies up to 99.9% can be achieved. The fly-ash concentration can be limited to 50 mg/m$^3_0$ at 11% O_2.

In the rotating particle separator, flue gases first enter a circular movement by means of an integrated fan. Here, heavy particles are forced outwards by centrifugal forces and fall down into the ash pit, while the light particles pass through a rotating filter element. This filter element consists of a multitude of axial channels. The liquid and solid particles are pushed against the channel walls and are periodically removed by passing air or water flowing through these channels at high velocity.

8.2.4.2 NO_x control technologies

Nitrogen oxides (NO_x) are often lumped together with sulphur oxides (SO_x) as air pollution control problems, because of the similarities between the two:

- NO_x and SO_x react with water and oxygen in the atmosphere to form nitric and sulphuric acids, respectively. These two are the principal contributors to acid rain. Because the acid rain process removes both NO_x and SO_x from the atmosphere, neither is believed to be increasing in concentration in the global atmosphere.
- NO_x and SO_x undergo atmospheric transformations leading to or contributing to the formation of PM_{10} (particles of 10µm or less in diameter) in urban areas.
- In high concentrations, NO_x and SO_x are severe respiratory irritants.
- NO_x and SO_x are released to the atmosphere in large quantities from fossil fuel combustion. Coal-fired power plants are the largest emitters. Emissions of NO_x and SO_x from biomass combustion, however, are substantially lower, and are caused by the fuel nitrogen and fuel sulphur content in the fuel, respectively. For SO_x this is due to a much lower sulphur content in biomass compared to coal. For NO_x it is partly due to a generally lower nitrogen content in biomass compared to coal, and partly due to fuel nitrogen being the only NO_x contributor of significance in biomass combustion, while additionally both thermal and prompt NO_x is of importance in coal combustion.

However, focusing on biomass combustion applications, the following major differences can be pointed out between fuel NO_x and SO_x formation:

- Formation of NO_x in combustion chambers can be greatly reduced by optimisation of the combustion process through primary NO_x emission reduction measures, such as staged-air combustion and staged fuel combustion. No such optimisation is practically possible for SO_x. However, in special combustion applications such as fluidised bed reactors, lime or limestone injection may be used to convert SO_x to anhydrite ($CaSO_4$), which then can be removed from the flue gas in the form of particles.
- The ultimate fate of sulphur oxides removed by pollution control or fuel-cleaning processes is to be turned into $CaSO_4$, which is an innocuous, low solubility solid, commonly deposited in landfills. There is no correspondingly cheap, innocuous, and insoluble salt of nitric acid, so landfilling is not a suitable solution for the NO_x we collect in pollution control devices. The ultimate fate of NO_x is to be converted into molecular nitrogen.

- It is relatively easy to remove SO_2 from combustion gases by dissolving SO_2 in water and causing a reaction with alkali. Aqueous SO_2 quickly forms sulphurous acid, which reacts with the alkali and then is oxidised to sulphate. Collecting nitrogen oxides this way is not nearly as easy because NO, the principal nitrogen oxide present in combustion flue gas, has a very low solubility in water. Unlike SO_2, which quickly reacts with water to form acids, NO must undergo a two-step process to form an acid, in which NO first reacts with oxygen to form NO_2, which then reacts with water to form HNO_3. The first reaction is relatively slow. It is fast enough in the atmosphere to lead to the formation of acid precipitation in the several hours or days that the polluted air travels before encountering precipitation. However, it is too slow to remove significant quantities of NO in the few seconds that a flue gas spends in a wet limestone scrubber used for SO_2 control. Some of the NO_2 in the flue gas is removed in such scrubbers, but normally only a small fraction of the total nitrogen oxides is NO_2 (<10%).

NO_x emissions can be controlled both by primary emission reduction measures, as shown in Section 8.2.3, and/or by secondary emission reduction measures. The secondary emission reduction measures involve chemical treatment of the flue gas after the combustion chamber aimed at converting NO_x to N_2.

The secondary NO_x emission reduction measures applicable for NO_x reduction in biomass combustion applications are mainly Selective Catalytic Reduction (SCR) or Selective Non-Catalytic Reduction (SNCR). Both utilise injection of a reducing agent, mainly ammonia or urea, to reduce NO_x to N_2, with or without a catalyst, respectively. Additionally, catalytic converters optimised for NO_x reduction can be placed after the combustion chamber in small-scale biomass combustion applications, like catalytic converters optimised for reduction of emissions from incomplete combustion, which were discussed under primary emission reduction measures. This is not a commonly used NO_x control technology for biomass combustion applications, but it is widely used for NO_x control in motor vehicles.

Selective Catalytic Reduction (SCR)

SCR reduces NO_x to N_2 by reactions with, usually, ammonia or urea in the presence of a platinum, titanium, or vanadium oxide catalyst. The stoichiometric equations for SCR are:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$3\ NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

SCR operates optimally in a temperature range of 220-270°C [279] using ammonia, and 400-450°C using urea, where a vaporised reducing agent is injected. Approximately an 80% NO_x reduction has been reported for SCR in fossil fuel combustion [200], where it is the most widely used secondary NO_x control technology. However, Nussbaumer [249] reported up to 95% NO_x reduction at 250°C without significant slippage of ammonia in a wood-firing system. A platinum-based catalyst is typically used. It is usually carried on an alumina support. The properties of the catalyst must be weighed against the properties of and the impurities in the fuel. For the SCR process, the long-term behaviour of the catalyst can be a problem, as deactivation is likely. Figure 8.17 and Figure 8.18 show a low dust and high dust wood-firing system with SCR.

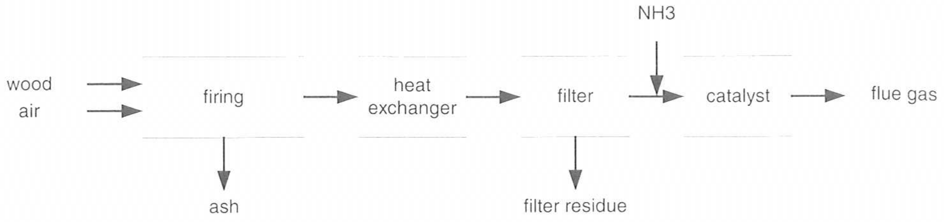

Figure 8.17: *Wood-firing system with NO_x reduction by SCR low dust process [249].*

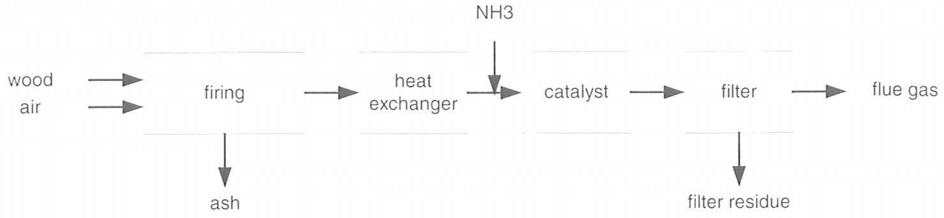

Figure 8.18: *Wood-firing system with NO_x reduction by SCR high dust process [249].*

Selective Non-Catalytic Reduction (SNCR)
Because of the requirements and demands of catalysts, SNCR processes have been developed which do not require a catalyst for activation of the reaction. Instead, the reaction is run at higher temperatures. In the SNCR process, ammonia or urea is injected into the flue gas at a temperature usually between 850 and 950°C. In a wood-firing system, a temperature between 840 and 920°C proved optimal [279]. Because of the high temperature, this process does not need a catalyst to initiate the reactions. Ammonia is injected at a rate of between 1:1 to 2:1 mole ammonia to mole of NO_x reduced. About 60-90% NO_x reduction can be reached with SNCR. The SNCR process requires an accurate temperature control to achieve optimum NO_x reduction conditions. If the temperature is too high, ammonia is oxidised to NO and if the temperature is too low, ammonia does not react at all and is emitted together with the NO_x. Hence, there exists an optimum temperature window for the SNCR process. Ammonia must be added to the flue gas in a quantity that is proportional to the NO_x content in the flue gas. Good mixing is very important to achieve optimum NO_x reduction conditions. Most SNCR processes have an ammonia slip of about 1 to 2 ppm in the flue gas leaving the stack. Figure 8.19 shows a schematic view of an SNCR process for a wood-firing system.

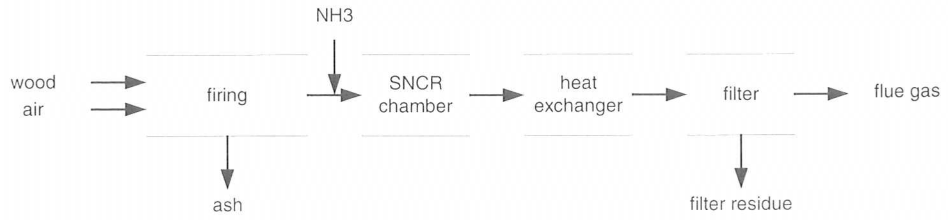

Figure 8.19: *Wood-firing system with NO_X reduction by SNCR [249].*

In Figure 8.20 the NO_x reduction potential of SCR and SNCR is illustrated as a function of the fuel nitrogen content and compared to the NO_x reduction potential of staged-air combustion with a separate reduction chamber and also to conventional combustion.

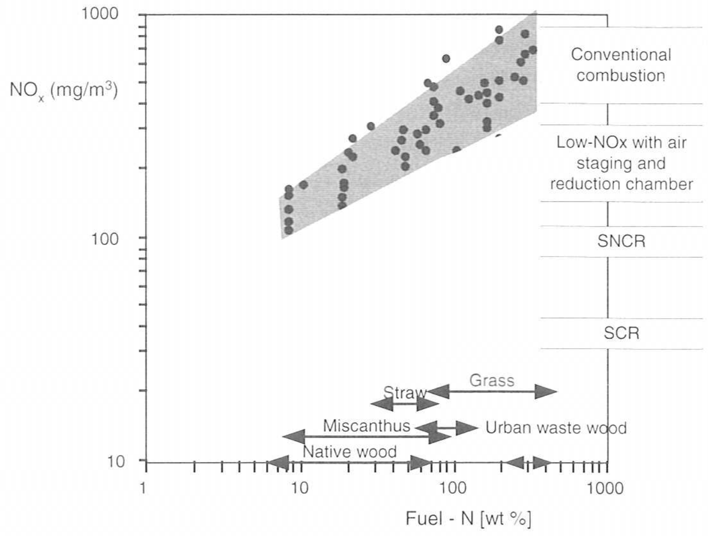

Figure 8.20: *Comparison of NO_X reduction potential for various NO_X reduction measures [230].*

8.2.4.3 SO_x control technologies
SO_x emission levels from biomass combustion applications are generally low. Mainly SO_2 (> 95%) is formed. Emissions of SO_2 are usually not significant for wood combustion applications, due to the low sulphur content in wood. However, for biomass fuels such as miscanthus, grass, and straw, emissions of SO_2 may be significant and SO_2 emission reduction measures must be applied.

Several measures have been developed for removal of SO_2 from gases. However, for flue gases from combustion applications, in which the SO_2 concentration is usually below 1000 ppm, the common measure is scrubbing the flue gas with water containing finely ground limestone in limestone wet scrubbers, as shown in Figure 8.21. The flue gas, from which the solid fly-ash particles have been removed, passes through a tower where it passes countercurrent to a scrubbing slurry containing water and limestone particles. Figure 8.21 shows the scrubber vessel as a spray tower with multiple sprays and a mist eliminator; some other designs use a packing with a very high open area in the tower or specialised bubbler designs.

In the tower, the SO_2 dissolves in the slurry and reacts with limestone, producing CO_2, which enters the gas stream, and $CaSO_3$. The latter is almost entirely oxidised to $CaSO_4$, partly by the excess oxygen in the flue gases in the tower, partly in the effluent hold tank, or the thickener, or in an additional oxidising vessel, sparged with air. The slurry is recirculated from the hold tank. A side-stream is taken to a thickener (also called a settler) and a filter to remove solids; ultimately the captured SO_2 must leave the system as $CaSO_4$ or $CaSO_3$ in this waste solid. Finely ground fresh limestone is added to the effluent hold tank. The scrubber operates at or near the adiabatic saturation temperature of the entering flue gas, which is about 125°F (52°C). The cleaned flue gas is normally reheated to about 175°F (80°C) to restore plume buoyancy and to prevent acid corrosion of the ducts and stack downstream of the reheater, and then released to the stack. The moisture content of the waste slurry is reduced by thickening and then vacuum filtration. The filter cake is often mixed with dry fly ash from the same plant to make a solid waste stream that has a still lower moisture content. The resultant mixture is easier to handle and store as it goes to its ultimate destination, a landfill.

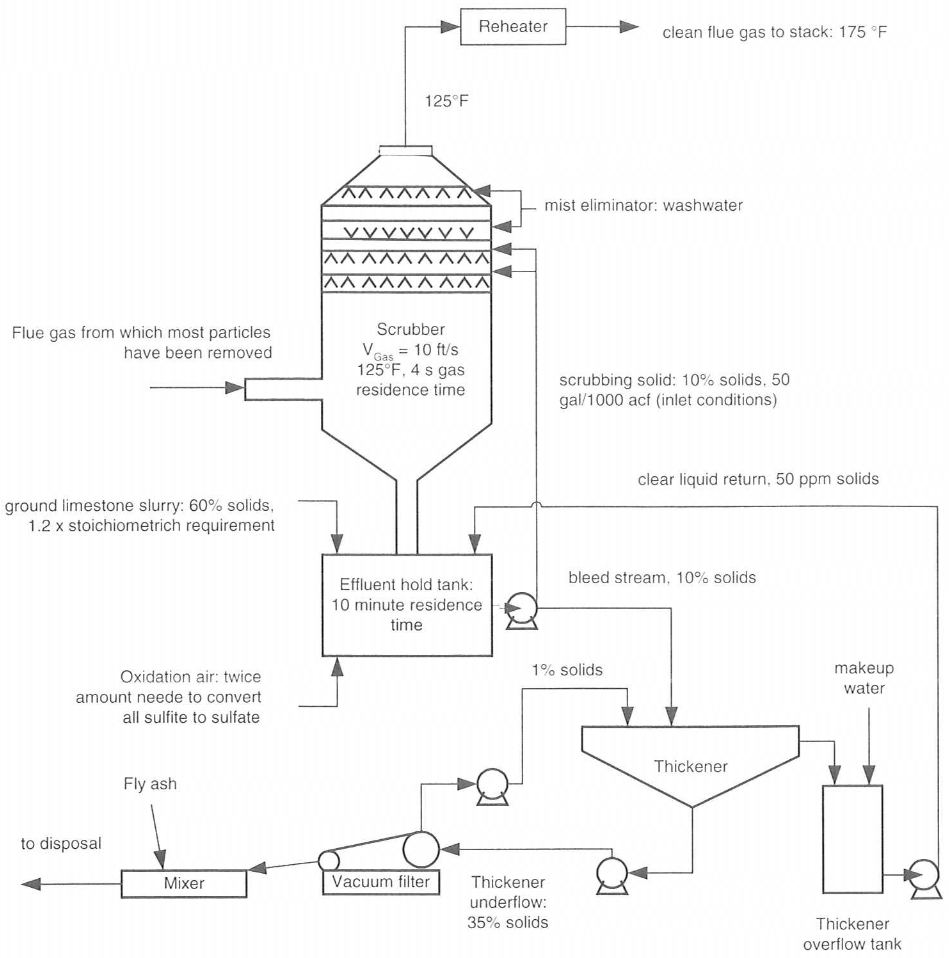

Figure 8.21: *Flow diagram of a typical limestone wet scrubber [199].*

The wet limestone scrubber is a wet throwaway process. However, dry throwaway processes have also been developed to avoid the solids handling and wet sludge disposal difficulties that come with wet throwaway processes. Dry throwaway processes have less corrosion and scaling difficulties and produce a waste product much easier to handle and

dispose of. All of these systems inject dry alkaline particles (limestone, hydrated lime, sodium carbonate, or sodium bicarbonate) into the gas stream, where they react with the gas to remove SO_2. The SO_2-containing particles are then captured in the particle collection device that the plant must have to collect fly ash. With limestone or lime, high SO_2 collection efficiencies can only be reached by putting a large excess of lime or limestone into the system, thus increasing reagent costs, increasing the load on the particle collector, and increasing the volume of solid wastes to be disposed of. However, if one uses more reactive (and much more expensive) sodium carbonate or sodium bicarbonate, the collection efficiency is much better, mostly because of the much higher reactivity of these salts.

Wet-dry systems have also been developed, combining some features of the preceding two kinds of systems. The most widely used wet-dry systems are spray dryers.

Simultaneous gas (SO_2, NO_2, HCl) absorption and particle removal can be achieved in scrubbers. However, scrubbers are too expensive for most smaller biomass combustion applications and are not widely applied. Limestone injection is commonly applied in large-scale fluidised bed reactors burning coal. However, fluidised bed combustion is not yet commonly applied for combustion of biomass fuels.

8.2.5 Emission limits in selected IEA member countries

For selected IEA countries, the maximum emissions allowed for biomass combustion plants are listed in this chapter. The overview was produced by Heikki Oravainen of VTT [296]. The figures vary significantly from country to country, which has a large influence on the technology selected. Furthermore, the various units used make comparison difficult; therefore standardisation is desirable. The term m^3_0 used in this chapter designates volume at standard reference condition; pressure 101.3 kPa and temperature 273 K.

8.2.5.1 European Union

In EU member countries, new emission legislation will be derived from the recently issued guidelines for Large Combustion Plants (2001/80/EG, PB L 309) as well as the Waste Incineration Directive (2000/76/EG, PB L 332). Guideline 2001/80/EG applies for biomass, defined as products from agriculture and forestry, vegetable waste from agriculture, forestry and from the food production industry, untreated wood waste and cork waste). Guideline 2000/76/EG applies to the incineration of all other types of waste. The emission guidelines are listed in Table 8.15.