Flue Gas Treatment – State of the Art

Margit Löschau und Rudi Karpf

Content   Page

1   Summary

For the removal of air pollutants from the flue gas, a flue gas treatment system is required downstream the boiler. Such treatment systems consist of a system of cleaning processes for the reduction of particulate, vapour and gaseous substances in the flue gas. There are special flue gas treatment components for removal of special pollutants, however, some components are able to remove more than one pollutant.

The selection of the appropriate flue gas treatment system depends in particular on the composition respectively pollution of the fuel, the resulting composition of the raw gas, the expected maximum concentrations of pollutants in the raw gas and their fluctuations and the required efficiency of the treatment process to meet the applicable emission limits. An overview of the flue gas treatment components for the removal of pollutants is shown in Table 1.

Table 1:   Overview of flue gas treatment components for removal of pollutants

Pollutant	Apparatus/Process	Principle
Particle and Particle Bounded Heavy Metals	Cyclone	Centrifugal Force, Inertia
	Fabric Filter	Filtration
	Electrostatic Precipitator	Electrical Attraction
	Wet Separator	Heterocoagulation
NO_x	Selective Non-Catalytic Reduction (SNCR)	Gas Phase Reaction
	Selective Catalytic Reduction (SCR)	Heterogeneous Catalysis (Chemical Adsorption)
HCl, HF, SO_2, SO_3	Wet Flue Gas Treatment	Absorption
	Semi-Dry Flue Gas Treatment	Absorption and Adsorption
	Dry Flue Gas Treatment	Chemical Adsorption
Organic Pollutants and Heavy Metals	Entrained Flow Absorber	Physical Adsorption
	Fixed or Moving Bed Adsorber	

2   Flue Gas Treatment Options

2.1   Removal of Particles and Particle-Bounded Heavy Metals

For removal of particles, the following components were usually used in flue gas treatment systems downstream the waste incineration:

- Centrifugal Separator
- Electrostatic Separator
- Filtering Separator
- Wet Separator
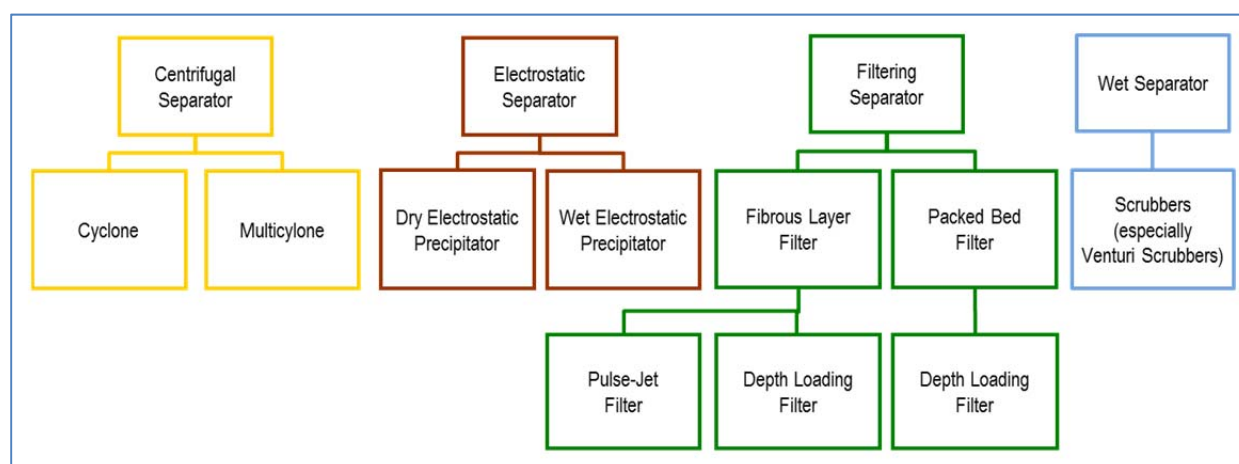
Figure 1: Flue gas treatment systems for the removal of particles

Due to their low separation efficiency, cyclones can only be used for pre-dedustig. Wet scrubbers intend to remove acidic compounds of the flue gas, the separation of dust is just a side effect (exception: venture scrubbers which are appropriate for fine dust separation). Electrostatic separators are often used in flue gas cleaning installations, mostly as pre-dedusting step upstream of a scrubber system. However, to achieve the emission limits of the European Industrial Emission Directive, fibrous layer filter with pulse jet cleaning are the most common installation for dust removal in flue gas cleaning.

2.1.1   Electrostatic Separators

Electrostatic Separators are used to capture particulate pollutants by means of the electrostatic attraction. There are

- Dry Electrostatic Precipitators, and
- Wet Electrostatic Precipitators.

Wet ESP are often used for cleaning gases saturated with water vapor in the flue gas purification of chemical processes. As part of the FGT of thermal waste treatment plants, they are rare-

ly used, and only in combination with wet scrubbers to achieve a downstream removal of aerosols and particulate matter.

Dry ESP are more often part of the flue gas cleaning concept but usually not as the only dedusting aggregate for waste-to-energy plants as the emission limit of 10 mg/Nm^3 can hardly be met. An exemplarily design of a dry ESP is shown in Figure 2:.
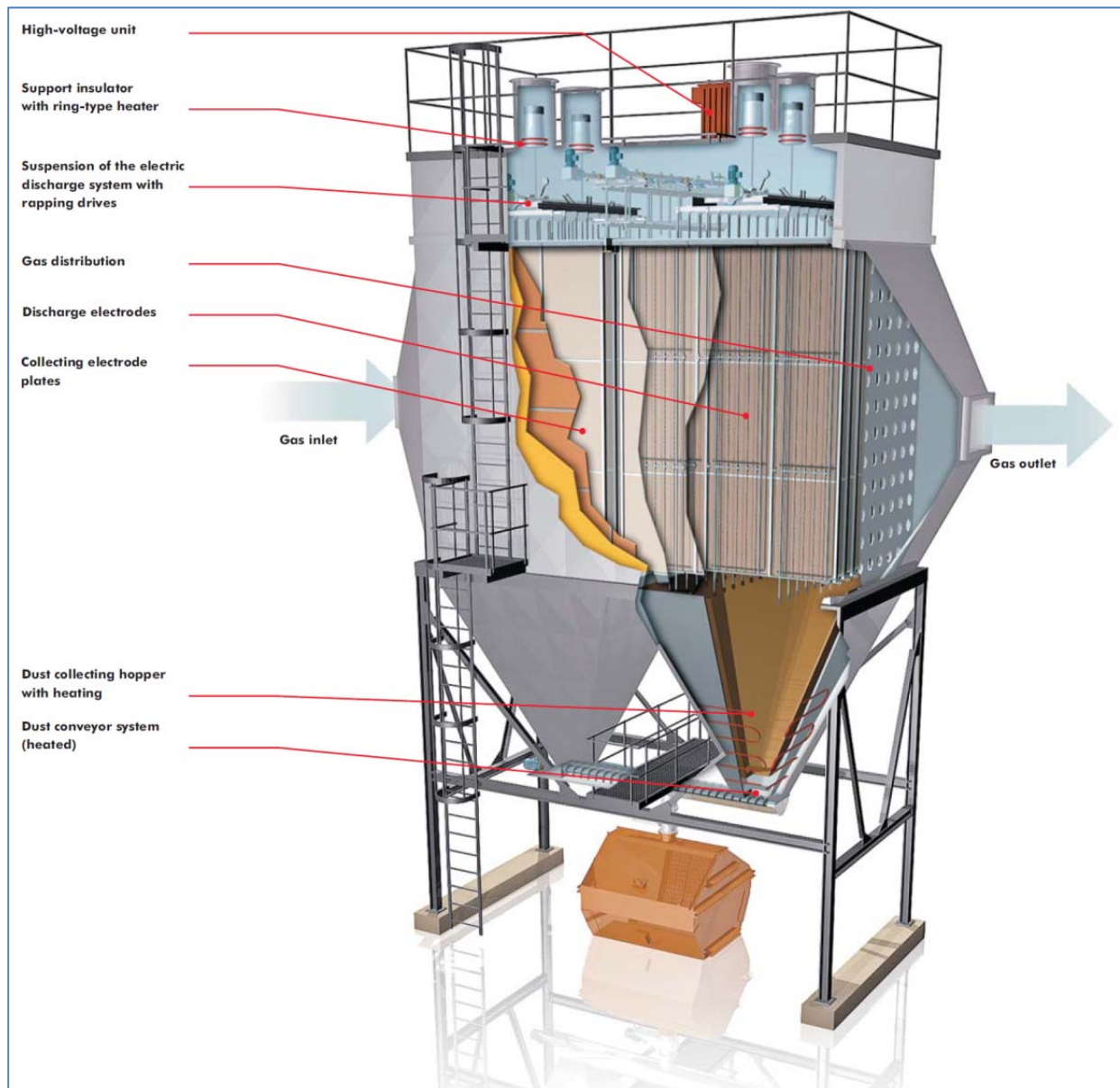
Figure 2: Example for a typical dry electrostatic precipitator

Source: BETH Filter GmbH: Dry Electrostatic Precipitator. Company Brochure, 2014

In the ESP, the particles are electrically charged in an electric field (20 and 100 kV) and disposed at the collecting electrode. The principle is shown in Figure 3.
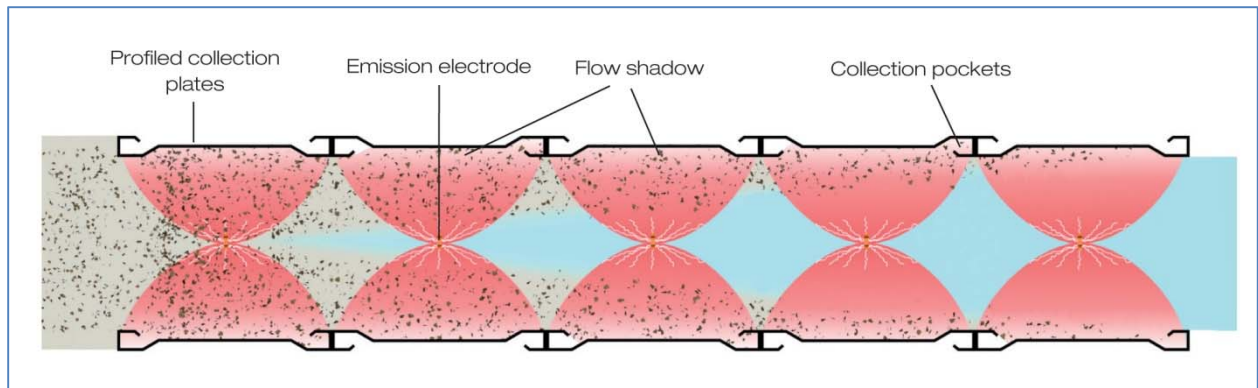
**Figure 3:** Removal of dust in an electrostatic precipitator

Source: Scheuch GmbH: Dry Electrostatic Precipitator. Company Brochure

2.1.2   Filtering Separators

Filtration is a mechanical process for separating mixture of substances. Both mixtures of liquid and solids (suspensions) and mixtures of gases and solids can be separated. For filtering, the mixture pass through a filter medium. Through the filter medium e.g. particles will be retained from the gas stream.

The filter effect depends on the particle size and can take place on the surface of the filter medium, but also in the filter medium itself. Accordingly, there are:

- Surface Filtration, and
- Depth-Loaded Filtration (Figure 4)
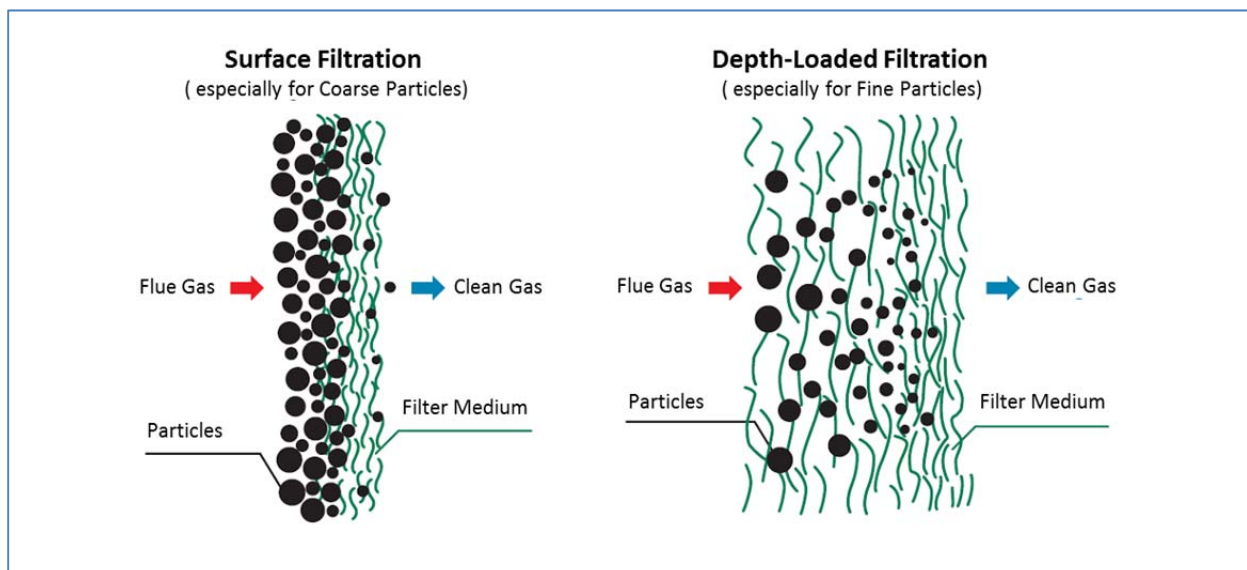
Figure 4: Principe of surface and depth-loaded filtration

Source: Liqui-Filter, company material. Im Internet: http://www.liqui-filter.info/know-how/absaugen-und-filtern-von-luft/wie-arbeiten-unsere-filter.html, extracted on 1st February 2012, edited

With respect to the filter medium one distinguishes between:

- Fibrous Layer Filter, and
- Packed Bed Filter.

For dust removal in the flue gas of waste-to-energy plants, only fibrous layer filters which can be cleaned on-line (during operation) can be used. Fabric filters with 4–8 chambers (mostly 6), vertical bags and pulse jet for cleaning the filter tubes are commonly installed in waste incineration plants (see Figure 5). Filter designs with horizontal bags also exists.
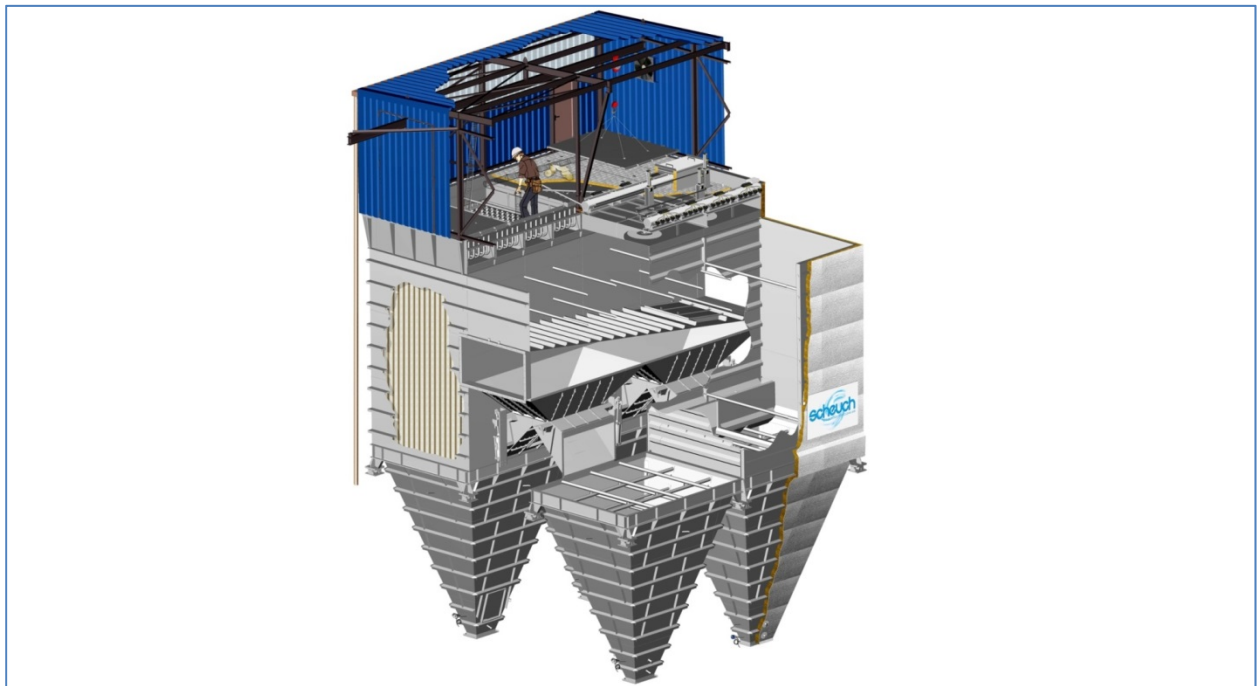
Figure 5: Typical design of a fabric filter with chambers and vertical tubes

Source: Scheuch GmbH: Bauformen Filter / Abscheider. In the Internet:
http://www.scheuch.com/de/filter_abscheider_impulsfilter_bauformen/, extracted April 2013

If the fabric filter operates not only as a dust collector but also as a sorption filter the filter medium should be always designed for a surface filtration.
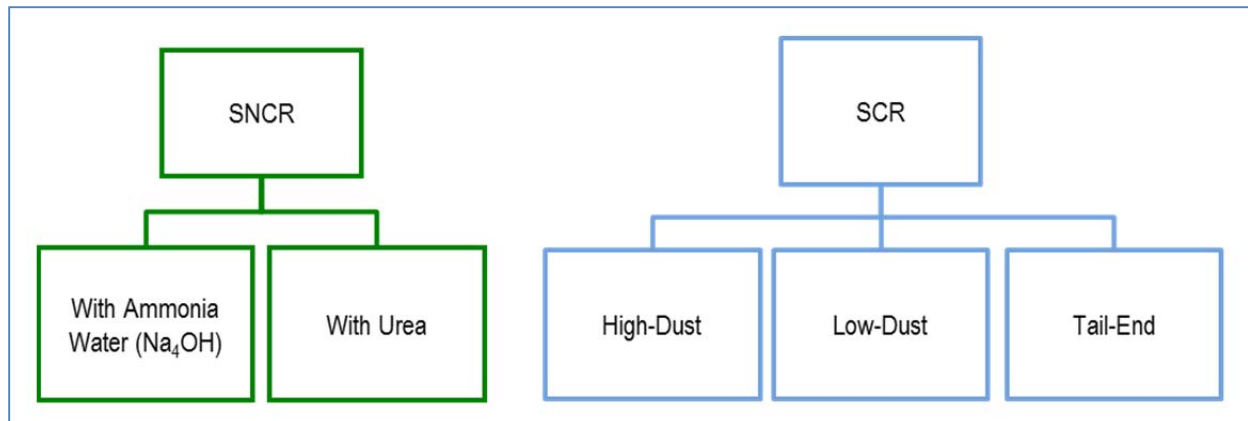
2.2 Removal of NO$_x$

For the removal of NOx two established processes exist:

- Selective Non-Catalytic Reduction (SNCR), and
- Selective Catalytic Reduction (SCR)

Both processes are able to remove NO$_x$ with the efficiency needed to meet an emission value of 100 mg/m^3 STP. Reagents and plant configurations are shown in Figure 6.

Figure 6: Flue gas treatment systems for the removal of NO$_x$

2.2.1   SNCR

In the selective non-catalytic reduction process (SNCR) nitrogen oxide (NO$_x$) in the flue gas is reduced by reaction with ammonia (NH$_3$) to elemental nitrogen (N$_2$). For this purpose, aqueous ammonia solution (NH$_4$OH) or urea solution (NH$_2$CONH$_2$) is injected into the hot flue gas in the first boiler pass. As a carrier medium for the reagent, pressurised air, steam or pressurised water can be used. A typical SNCR system is shown in Figure 7.
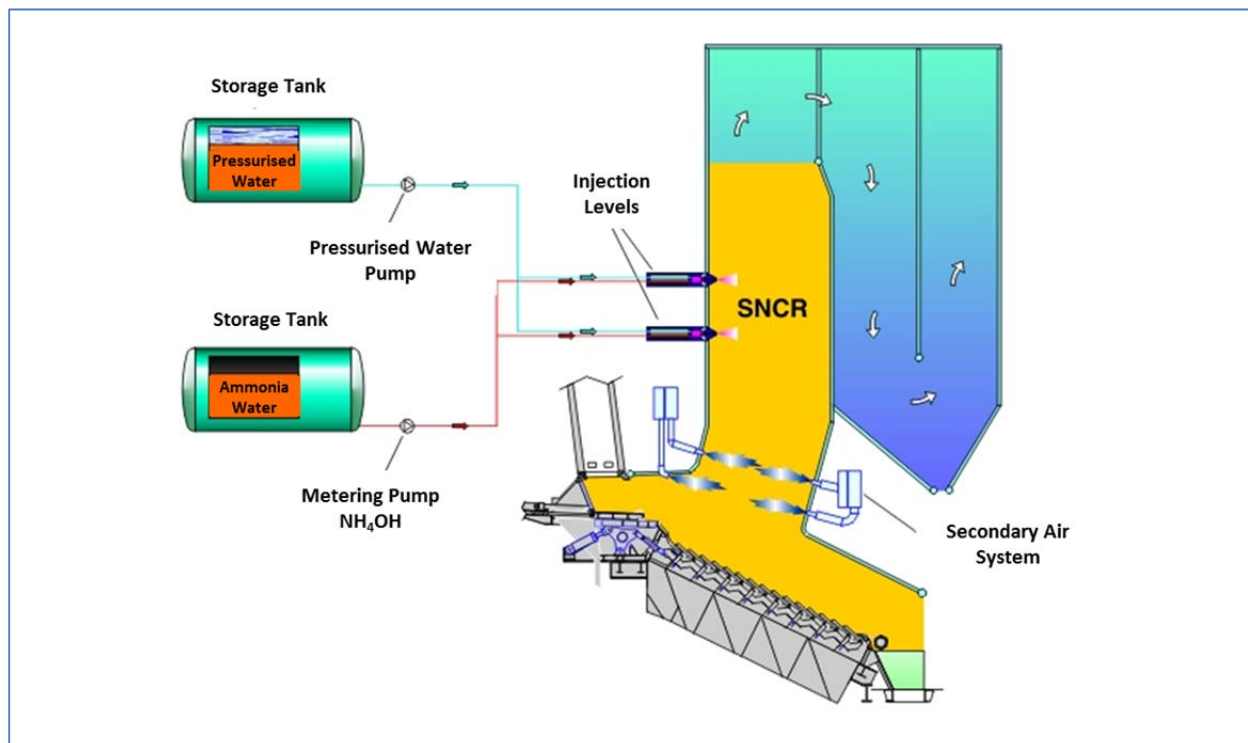
Figure 7: Example for a SNCR system

Source: Martin GmbH für Umwelt- und Energietechnik: Firmenbroschüre „Das Martin SNCR System"

$NH_4OH \rightarrow NH_3 + H_2O$

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

$2\ NO_2 + 4\ NH_3 + O_2 \rightarrow 3\ N_2 + 6\ H_2O$
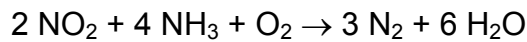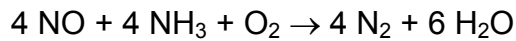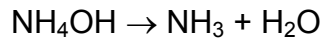
To avoid NH_3-slip, NH_3 oxidation and NO generation, the reduction reaction in the SNCR process takes place in a narrow temperature range from 850–1 100 °C, with an optimum at approximately 970 °C (Figure 8). For the optimisation of the injections of reagent in the right temperature zone an IR-pyrometer or an acoustical gas temperature measurement can be installed. The efficiency of SNCR can be increased by increasing the stoichiometric factor for ammonia water but is limited due to the inevitable NH_3-slip.
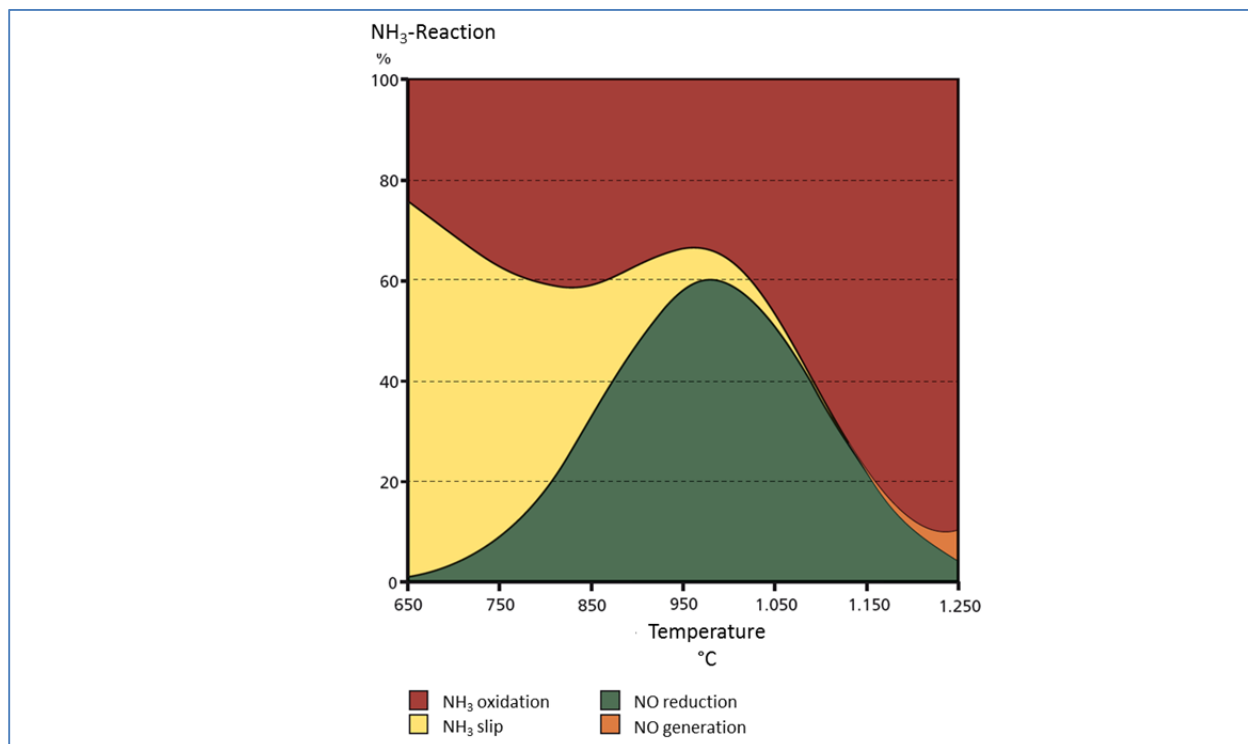

Figure 8: NH_3-reaction depending on temperature as a function of temperature

Source: Dittrich, R.; Nowag, R.: Vergleichende Beurteilung und Abscheideleistung von SNCR-/SCR-Technik. VDI-Wissensforum: BAT und preisorientierte Rauchgasreinigungstechniken, München, 2002, edited

2.2.2 SCR

In the selective catalytic reduction process (SCR), a catalyst is used to increase the efficiency of the reaction of nitrogen oxide (NO_x) in the flue gas with the reagent ammonia (NH_3). NH_3 is mostly provided by the injection of ammonia water. The reaction equations are the same as for the SNCR but the catalysed process takes place at lower temperatures (160–450 °C). As ammonia water is converted almost stoichiometrically there is hardly any NH_3-slip. With respect to the location of the SCR-catalyst there are four different plant configurations (Figure 9):

a. High-Dust-SCR

b. Low-Dust / High SO_x-SCR

c. Low-Dust / Low-SO_x-SCR

d. Tail-End-SCR
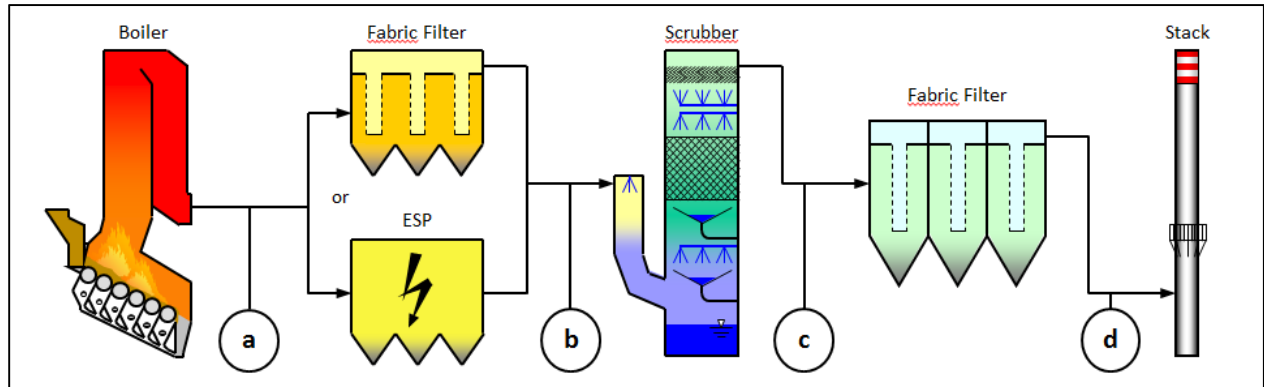
Figure 9: Plant configurations for SCR

Source: Karpf, R.; Basic features of the dry absorption process for flue gas treatment systems in waste incineration; Earth Engineering Center, Columbia University, New York, April 2015
Karpf, R.: Überblick zur Abgasreinigung. 10. Fachtagung Abgasreinigung von Feuerungsanlagen und thermische Prozesse; Haus der Technik, Essen, 25-26th June 2015

Most common for waste-to-energy installations is the Tail-End-SCR (Figure 10) which is located downstream the removal of particles and acid compounds in the flue gas and therefore ensures long lifetime of the catalyst. However, as the temperature of the flue gas after the fabric filter is usually too low for the catalytic reduction of NO_x, for this configuration a reheating of the flue gas is necessary, which requires steam or natural gas. Most common are catalysts consisting of TiO_2 as carrier material with V_2O_5 as active component and WO_3 as promoter.
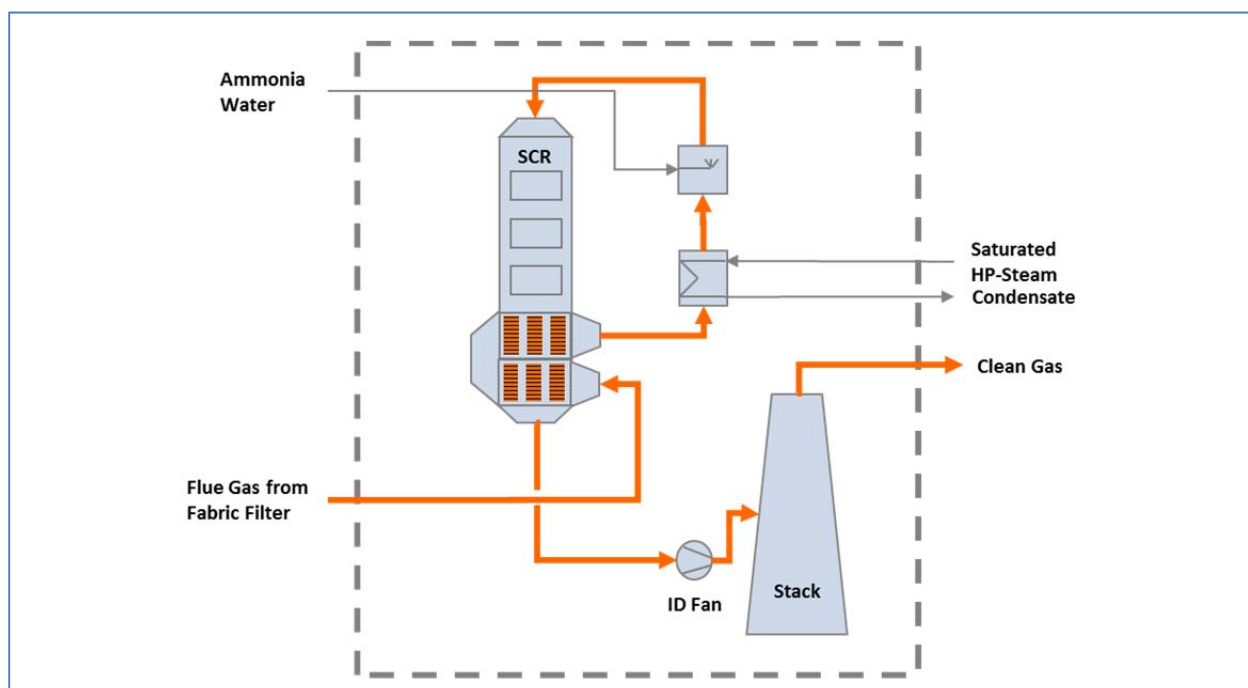
Figure 10: Typical Tail-End-SCR-Concept

2.3   Removal of Organic Pollutants and Vaporous Heavy Metals

For the removal of organic pollutants (mainly PCDD/F) and vapour forms of heavy metals (main-ly Hg), the following established processes exist:
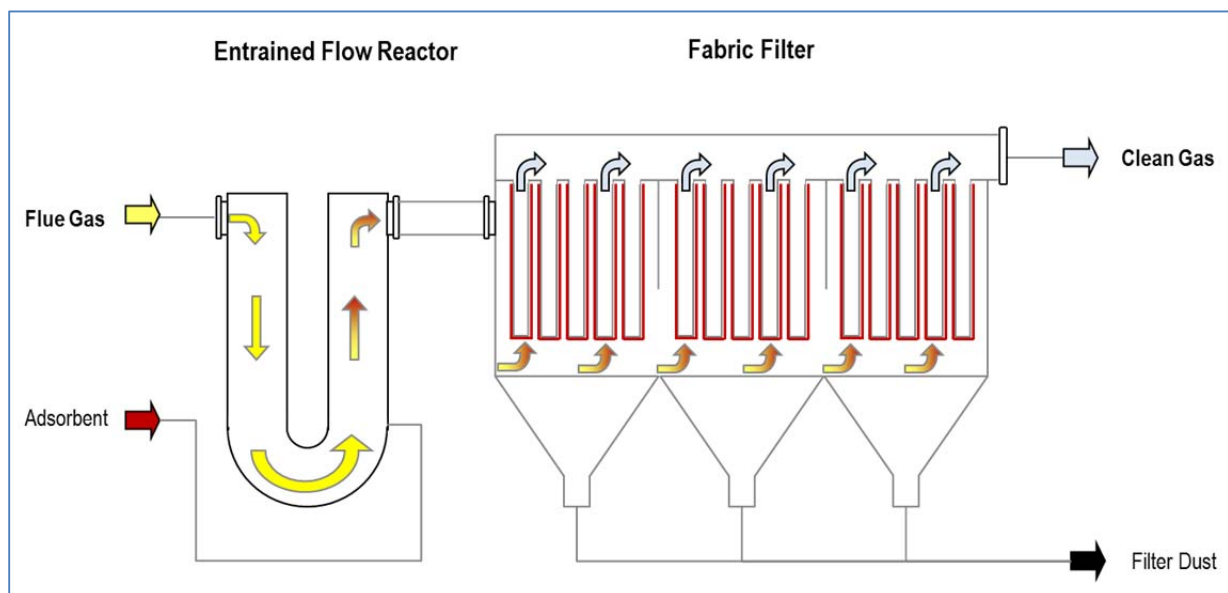
- Entrained Flow - Filter Layer Process
- Fixed or Moving Bed Adsorber

For organic pollutants, additionally an oxidation catalyst can be used.

2.3.1   Entrained Flow - Filter Layer Process

In an entrained flow adsorber, the adsorbent (mostly lignite active coke) is injected directly into the flue gas and carried away with this. Organic pollutants (such as PCDD/F) and heavy metals in vapour form (such as Hg) are adsorbed on the surface of the adsorbent and removed with the particles in the downstream fabric filter. On the filter bags of the fabric filter layer of dust and ad-sorbent is developed which contributes to the adsorption processes. In Figure 11 the basic prin-ciple of the entrained flow - filter layer process is shown.

Figure 11: Principle of an entrained flow - filter layer process

The advantage of this process is that it can be perfectly combined with conditioned-dry removal of acid compounds where usually a reactor and a fabric filter are part of the system too. So the technical equipment can be minimised.

2.3.2 Fixed or Moving Bed Adsorber

Fixed or moving bed adsorbers are usually located downstream of a wet FGT process (Figure 12). The flue gas flows through a granular bed of an adsorbent. For technical and economic reasons, mostly lignite coke is chosen. The separation of organic pollutants and vaporous heavy metals is based on the principle of physical adsorption.
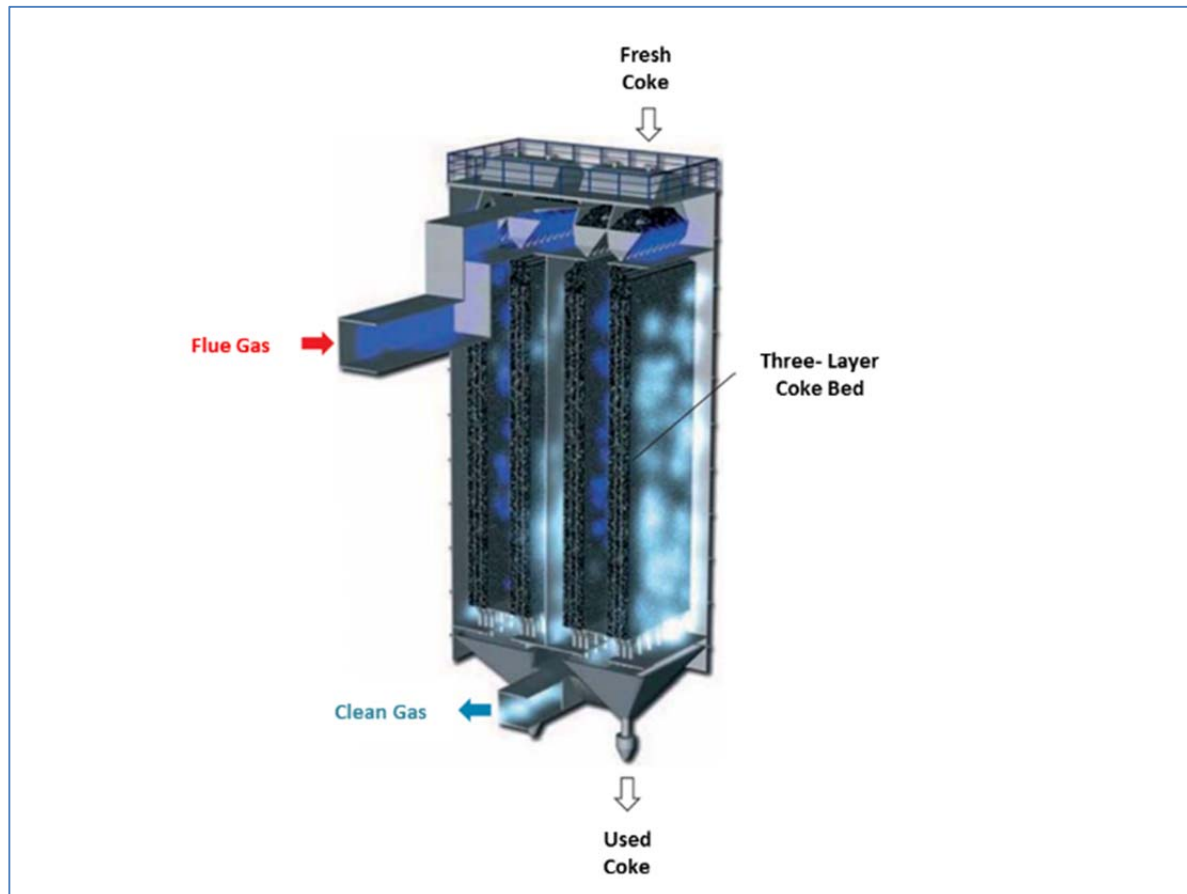
Figure 12: Example for a moving bed adsorber with four three-layer active coke bed

Source: Thermische Abfallbehandlung Lauta GmbH & Co. oHG: Aufbau und Funktion: Aktivkoksfilter. In the Internet: http://www.t-a-lauta.de/aufbau-funktion/aktivkoksfilter.html, extracted 23rd January 2012, edited

2.4 Removal of Acid Compounds

For the removal of acid compounds, mainly HCl and SO_2 downstream waste incineration, there are the following three established flue gas treatment systems in Europe:

- wet.
- semi-dry and
- dry

Usually, calcium or sodium based absorbent are used as reagent for the removal. In Figure 13, the further subdivision of the main systems is shown.
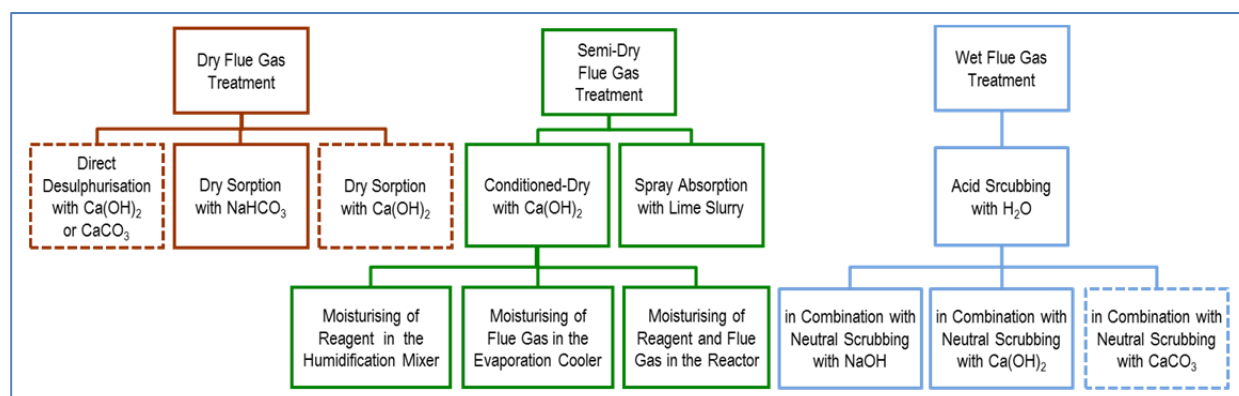
Figure 13: Flue gas treatment systems for the removal of acid compounds

2.4.1 Lime-Based Processes

The separation of the pollutants takes place via adsorption on the surface of calcium hydroxide particles. These particles are brought into contact with the flue gas in a variety of forms. The primary reactions take place according to the following equations:

$$SO_2 + Ca(OH)_2 \rightarrow CaSO_3 \text{ x } \tfrac{1}{2} H_2O + \tfrac{1}{2} H_2O$$
$$SO_3 + Ca(OH)_2 \rightarrow CaSO_4 + H_2O$$
$$2\,HF + Ca(OH)_2 \rightarrow CaF_2 + 2\,H_2O$$
$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$$
$$2\,HCl + Ca(OH)_2 \rightarrow CaCl_2 \text{ x } 2\,H_2O$$
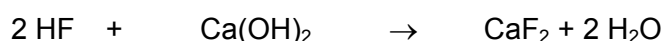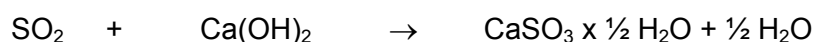
Reaction of lime with HCl in two steps:
$$Ca(OH)_2 + HCl \rightarrow Ca(OH)Cl + H_2O_{(l)}$$
$$Ca(OH)Cl + HCl \leftrightarrow CaCl_2 + H2O_{(l)}$$
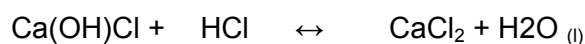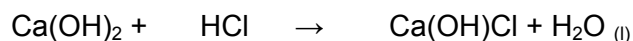
Reaction of lime with calcium chloride:
$$Ca(OH)_2 + CaCl_2 \leftrightarrow 2\,Ca(OH)Cl$$
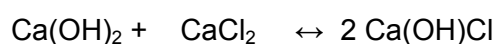
The reactivity sequence between calcium hydroxide and the pollutants can be set out as follows:

$$SO_3 > HF > HCl \gg SO_2 > CO_2$$

The most important calcium-hydroxide-based processes are described in below.

2.4.1.1 Conditioned-Dry Sorption with Hydrated Lime

In this process, separation of the pollutants via deposition on lime is ameliorated by a hydrate shell which is formed around (and inside the pores of) the lime particles and results from the H_2O contained in the flue gas. This means that the separation is governed by the dissolution rate of the pollutants in aqueous solution. The absorption and adsorption processes run parallel throughout the separation process.

An increased level of relative humidity is required for the capillary condensation and the formation of the hydrate shell on the surface. The flue gas is therefore first conditioned in order to optimize the downstream pollutant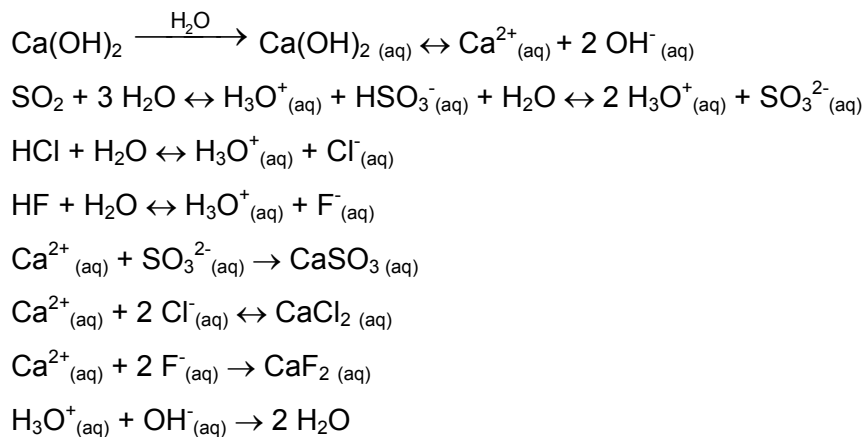 separation process. This conditioning consists primarily of a reduction of the gas temperature to approximately 130 – 150 °C in order to achieve a relative humidity of approximately 6 %. Flue gas temperatures below 130 °C should, however, be avoided, as, depending on surface temperature, the salts created during the reaction may increase the risk of corrosion to those parts of the facility in direct contact with the flue gas.

The presence of liquid water allows for the dissolution of the reaction partner (see the following reactions) and for an ionic reaction to take place, the fastest reaction rate at our disposal.

$$Ca(OH)_2 \xrightarrow{\ H_2O\ } Ca(OH)_{2\,(aq)} \leftrightarrow Ca^{2+}_{(aq)} + 2\ OH^-_{(aq)}$$

$$SO_2 + 3\ H_2O \leftrightarrow H_3O^+_{(aq)} + HSO_3^-_{(aq)} + H_2O \leftrightarrow 2\ H_3O^+_{(aq)} + SO_3^{2-}_{(aq)}$$

$$HCl + H_2O \leftrightarrow H_3O^+_{(aq)} + Cl^-_{(aq)}$$

$$HF + H_2O \leftrightarrow H_3O^+_{(aq)} + F^-_{(aq)}$$

$$Ca^{2+}_{(aq)} + SO_3^{2-}_{(aq)} \rightarrow CaSO_{3\,(aq)}$$

$$Ca^{2+}_{(aq)} + 2\ Cl^-_{(aq)} \leftrightarrow CaCl_{2\,(aq)}$$

$$Ca^{2+}_{(aq)} + 2\ F^-_{(aq)} \rightarrow CaF_{2\,(aq)}$$

$$H_3O^+_{(aq)} + OH^-_{(aq)} \rightarrow 2\ H_2O$$

Reducing the temperature or increasing the relative humidity can be effected via an economizer (ECO) or a cooling tower (CT). However, a combination (Combi) of both the gas cooling and humidifying processes is also possible. The cooling tower allows one to increase the absolute humidity in the system via the amount of injected water. The injected water promotes the separation of pollutants adhering to the hydrate lime particles.
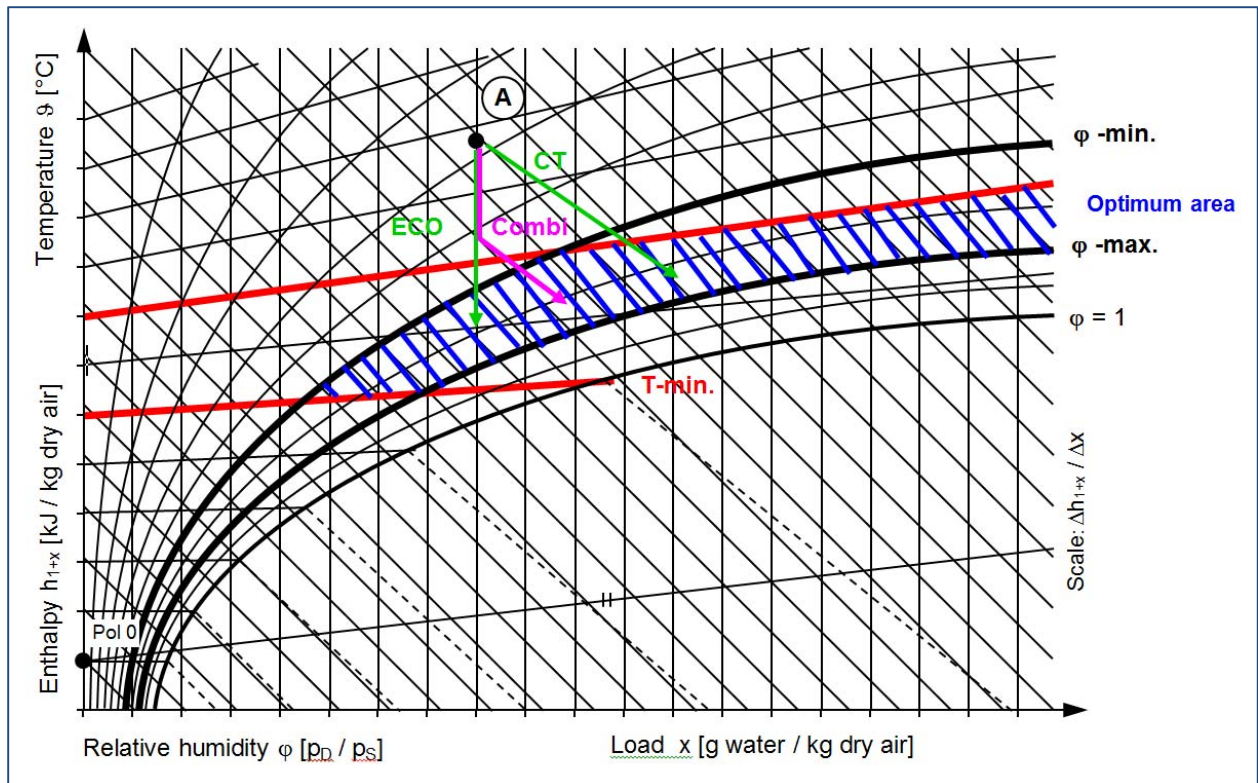
Figure 14: Mollier h-x diagram with optimum temperature-humidity range for conditioned dry absorption with calcium hydroxide (A = starting point)

Source: Karpf, R.; Basic features of the dry absorption process for flue gas treatment systems in waste incineration; Earth Engineering Center, Columbia University, New York, April 2015
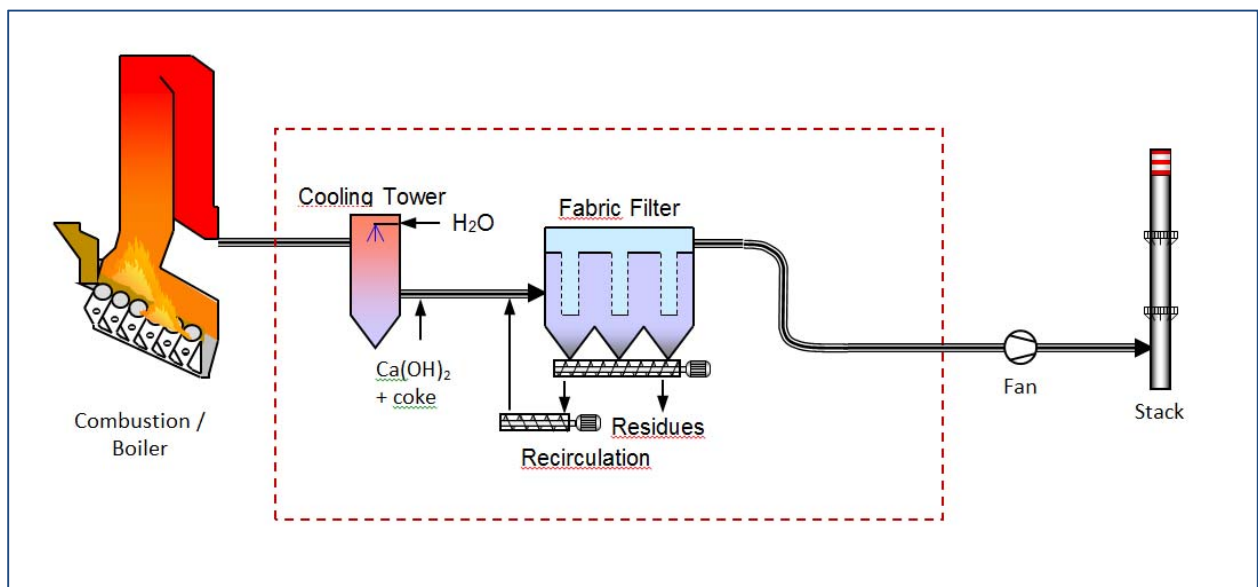
Figure 15: Conditioned dry process with hydrated lime

In order to increase the separation efficiency, a part of the residue of the reaction products in the fabric filter should be feed back into the flue gas. This permits the un-reacted contingent to be brought back into contact with the pollutants as well as providing a quantity of chloride to im-

prove separation efficiency, especially that of SO_2. Concerning the presence of calcium chloride, a quantity of $HCl/SO_2 > 1$ at the inlet of the flue gas treatment system is necessary.

The higher the fabric filter temperature, the less efficient the SO_2-separation due to the decrease in relative humidity.

2.4.1.2 Spray Absorption with Lime Slurry

The semi-dry spray absorption process is an alternative method. Here a spray dryer is used to inject a suspension of lime and water (lime slurry) into the flue gas stream.

The suspension is generally created from quicklime (CaO) and water via an on-site slaking process. The fact that this is conducted on-site is of additional benefit to the reactivity of the reagent. When the suspension is injected into the flue gas stream, the water component evaporates and only the solid lime particles remain in the flue gas. The liquid phase of this process has proven to be more efficient concerning HCl-removal than it is by applying slaked lime (calcium hydroxide) in dry form.
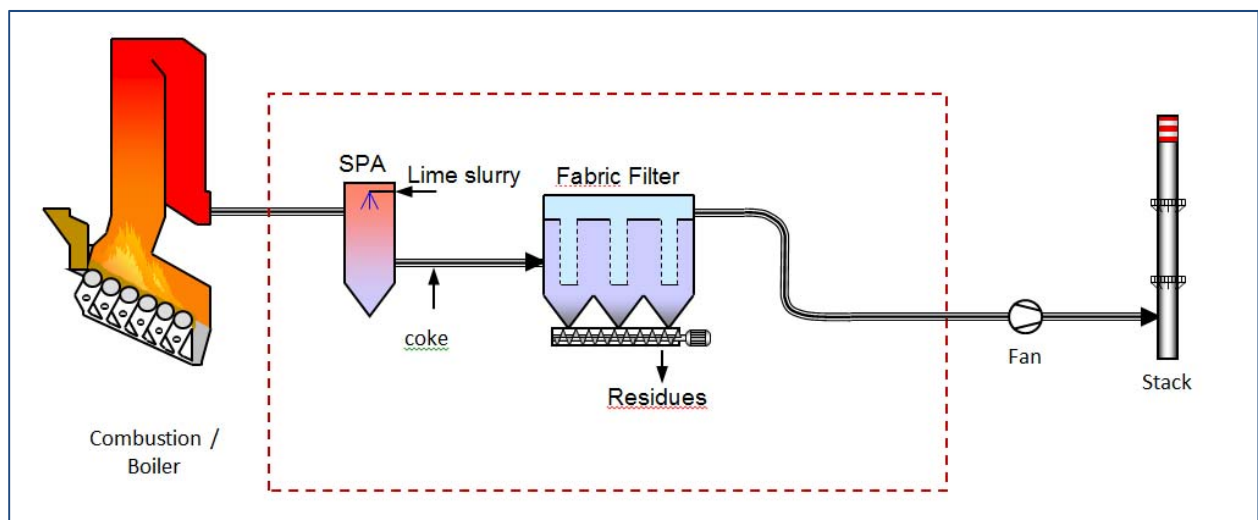
Figure 16: Spray absorption process with lime slurry (SPA = Spray Absorber)

Since CO_2 is also an acid gas component, the amount of CO_2-molecules compared to the amount of the other acid gas molecules such as HCl, HF, SO_2 is much higher. Consequently, the possibility of a reaction between CO_2 and a lime particle is much greater than that of a reaction between the other acid gas components and formed calcium carbonate ($CaCO_3$). For the liquid phase, an HCl- or SO_2-molecule can react with the already formed $CaCO_3$ and out through the CO_2-molecule again due to the higher acid state. However, this is only possible in the case of the liquid phase.

Therefore, the spray absorption process will operate with a higher lime consumption (higher stoichiometric ratio (SR)) compared to a conditioned dry absorption process with a dry lime injection. The dosage of lime slurry that is applied is generally too high in cases of a stoichiometric ratio of 2.3 < SR < 3.5. In order for sufficient drying of the particles, an inlet temperature of approx. 200 °C and a certain outlet temperature (mostly > 140 °C) prior to the spray absorber process is desirable, depending on the dimensions of the spray absorber (e.g. residence time). In some cases, the outlet temperature should be lower than 140 °C, especially for SO_2-removal, except where this is not possible. If a higher degree of separation efficiency is required, dry calcium hydroxide can be injected upstream of the fabric filter.

2.4.1.3 Lime Slurry Scrubber

In a wet flue gas treatment system the acid compounds of the raw gas are absorbed in a liquid in a scrubbing system. While semi-dry and dry flue gas treatment systems are always waste water free, in wet flue gas treatment systems the waste water from the scrubbers which is contaminated with salts and heavy metals has to be taken account to. This waste water must be treated in an appropriate manner, using either
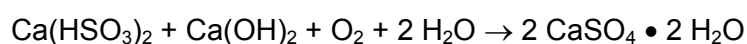
- waste water cleaning or
- an effluent evaporation.

Both variants cause high technical effort and herewith high investment cost. Because even after a cleaning process the discharge of saline effluent is in most countries critical, a wet flue gas system should be designed effluent-free which requires a spray dryer and a fabric filter upstream the scrubbing system. Most common for waste incineration plants are wet systems with water as absorbent for HCl and with lime milk as absorbent for SO_2 (Figure 17).
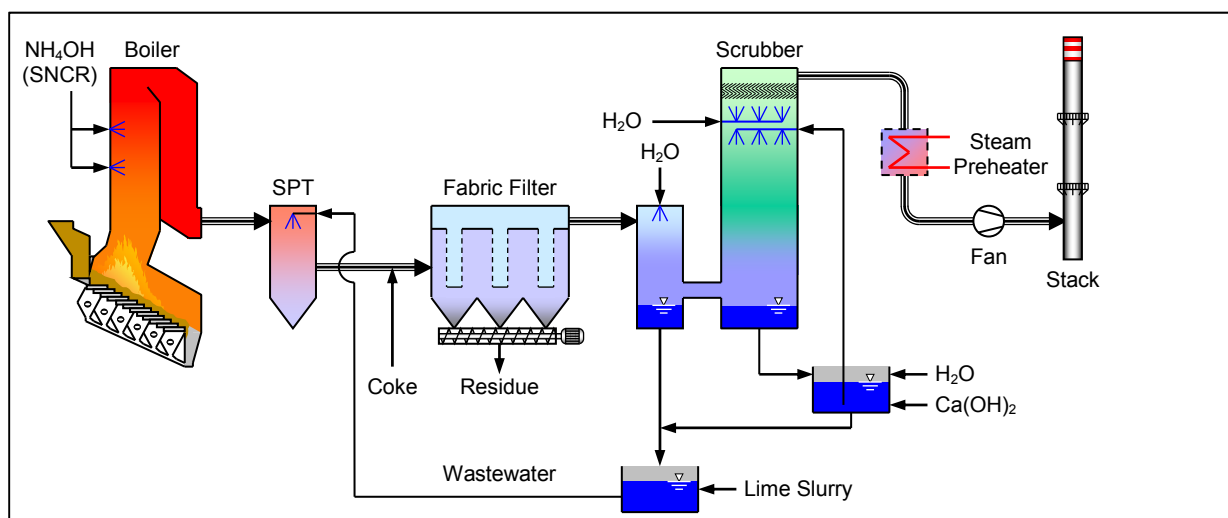
Figure 17:   Wet Flue gas cleaning system with lime slurry and spray absorber

Beside hydrated lime, sodium hydroxide or limestone solution as absorbent are possible to be used.

The typical wet system for waste incineration consists of two scrubbers, one for the removal of HCl in an acid environment and one for the removal of SO_2 in a neutral environment. The acid liquids are neutralised with hydrated lime.

$$HCl(g) + H_2O_{(l)} \rightarrow H_3O+ + Cl^-$$

$$SO_2(g) + H_2O_{(l)} \leftrightarrow H^+ + HSO_3^-$$
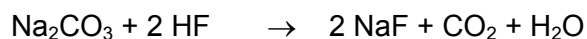
$$2\ HSO_3^- + Ca^2+ \rightarrow Ca(HSO_3)_2$$

$$Ca(HSO_3)_2 + Ca(OH)_2 + O_2 + 2\ H_2O \rightarrow 2\ CaSO_4 \bullet 2\ H_2O$$
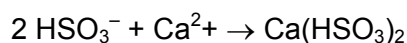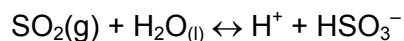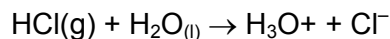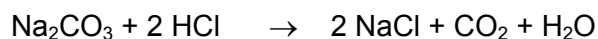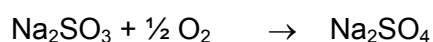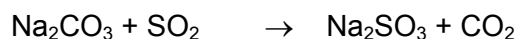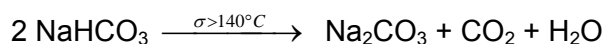
For the evaporation of the salt solution a spray dryer must be installed. The vaporised salts are removed in the downstream fabric filter. The higher the raw gas concentration, the higher is the amount of water which has to be evaporated in the spry dryer. Depending on raw gas concentration, relatively high raw gas temperatures after the boiler are required which can be adverse to energy efficiency of the boiler. Lignite activated coke can be used in addition to eliminate lightly volatile heavy metals (e.g. mercury) and hazardous organic pollutants (e. g. PCDD/F).

2.4.2 Sodium-Based Processes

2.4.2.1 Dry Sorption with Sodium Hydrogen Carbonate

Sodium hydrogen carbonate allows the implementation of a purely dry technique, as it enables a good dedusting result for HCl und SO_2 at comparatively high temperatures and regardless of the flue gas humidity.

As, in most cases, activated carbon is added to the sodium bicarbonate during the process in order to achieve a better dedusting result with regard to heavy metals and dioxins / furans in the flue gas, the flue gas temperature must be cooled to 140 – 180 °C in order to prevent desorption occurring in the activated carbon. At temperatures > 140 °C, the sodium hydrogen carbonate decomposes into sodium carbonate ($NaCO_3$), carbon dioxide (CO_2) and water (H_2O):

$$2\ NaHCO_3 \xrightarrow{\sigma > 140°C} Na_2CO_3 + CO_2 + H_2O$$
$$Na_2CO_3 + SO_2 \rightarrow Na_2SO_3 + CO_2$$
$$Na_2SO_3 + \tfrac{1}{2}\ O_2 \rightarrow Na_2SO_4$$
$$Na_2CO_3 + 2\ HCl \rightarrow 2\ NaCl + CO_2 + H_2O$$
$$Na_2CO_3 + 2\ HF \rightarrow 2\ NaF + CO_2 + H_2O$$

The reactivity sequence can be set out as follows:

$$SO_3 > HCl > SO_2 \gg HF > CO_2$$
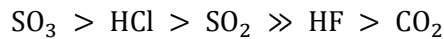
When compared to the application of lime, the chemical decomposition and transition of the gaseous reaction products into the flue gas stream reduces the quantity of residue requiring subsequent disposal.

This decomposition also leads to a greater specific surface. The greater the available reaction surface, the more efficient the separation performance of the sodium carbonate. The removal performance also generally increases in line with a rise in temperature. The temperature must, however, be confined to a specific corridor if activated carbon is also being used to separate mercury.
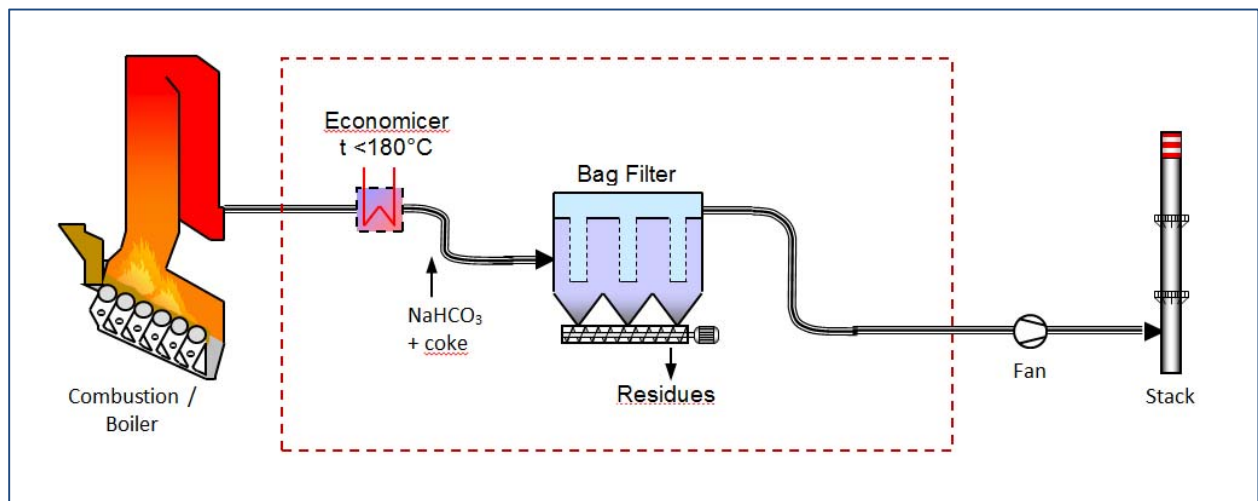
Figure 18: Dry FGT process with sodium hydrogen carbonate

Main Features of the Process:
- Very good reactivity of $NaHCO_3$ with HCl and SO_2
- The higher the temperature, the more efficient the separation of HCl and SO_2. However, limitation of the temperature is advisable due to mercury separation
- The desired temperature corridor should lie between 180 – 190 °C if activated carbon is being used
- Desired bicarbonate grind: the smaller the grain size, the better the separation performance
- No influence of HCl/SO_2 ratio on separation performance
- No influence of humidity on separation performance
- Poor reactivity with HF

- Stoichiometric values of 1.1 < SR < 1.4 are common. A slight improvement in the separation performance if recirculation is applied within the bicarbonate process
- Additives are very expensive
- Low amount of residual substances compared to lime-based process

2.4.2.2 Sodium Hydroxide Scrubber

Sodium-based reagents in form of sodium hydroxide are also used in wet flue gas cleaning systems to remove the acids from the flue gas:

$$NaOH_{(l)} + H_2O_{(l)} \rightarrow Na^+ + OH^- + H_2O_{(l)}$$

$$HSO_3^- + Na^+ \rightarrow NaHSO_{3(l)}$$

$$SO_4^{2-} + 2\,Na^+ \rightarrow Na_2SO_{4(l)}$$
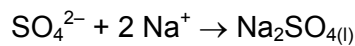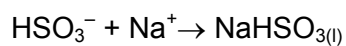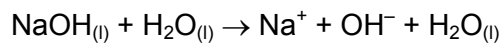
A typical plant configuration is shown in Figure 19.
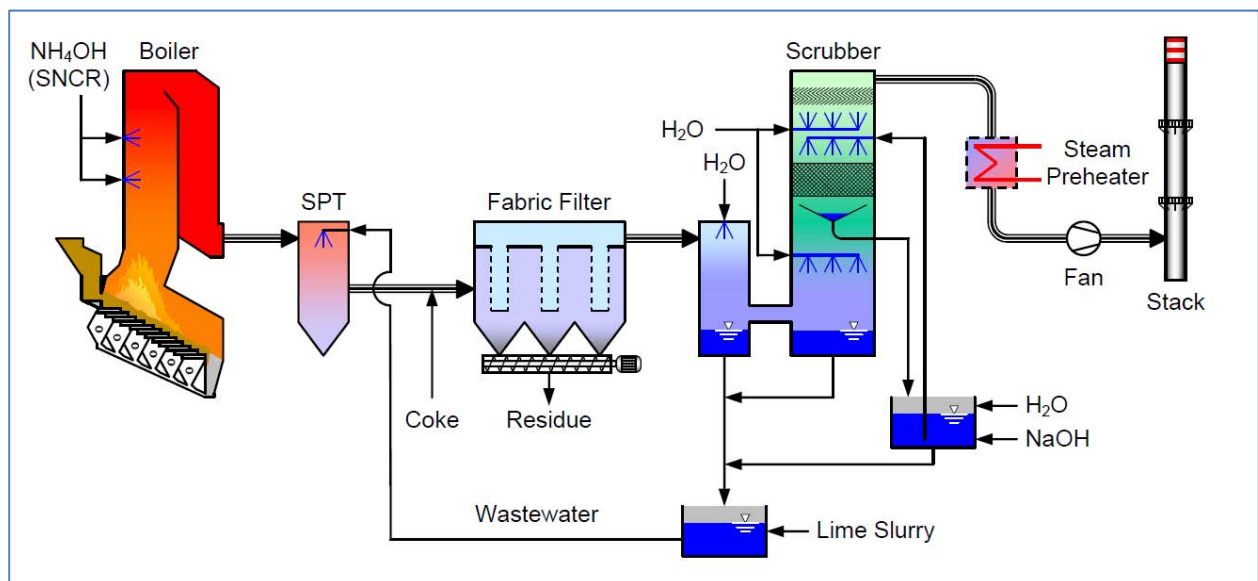
Figure 19: Wet FGT process with sodium hydroxide

3   Achievable Emission Values

3.1 Particles

The fractional efficiency of the different de-dusting technologies varies greatly (Figure 20).

Cyclones are only appropriate for pre-dedusting to remove coarse particles x_p >10 µm. E.g. a cyclone which is able to separate particles with a size of 10 µm with an efficiency of approx. 80 % (depending on the cyclone diameter) will separate particles with 5 µm only with an efficiency of 5 %.
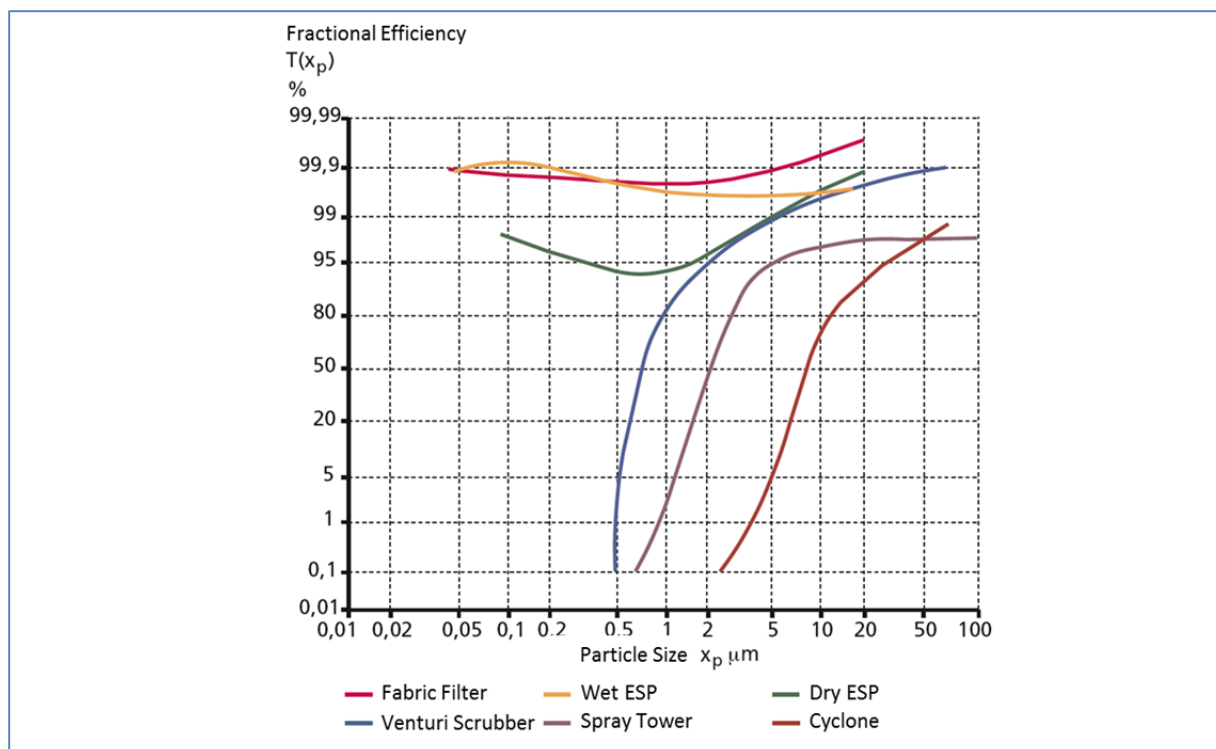
Figure 20: Fractional efficiency of different de-dusting technologies

Source: Müller, C. Stark, R.: Trends in der Abgasreinigung zur Beherrschung des Quecksilber- und Feinstaubprob-lems – Technische Lösungen. In: Thomé-Kozmiensky, K. J.; Beckmann, M. (Hrsg.): Energie aus Abfall, Band 2. Neu-ruppin: TK Verlag, 2007, edited

Electrostatic precipitators (ESP) as single dedusting aggregate do not reach the efficiency to be in accordance with the dust emission limit of 10 mg/m³STP for waste incineration. The main task of a scrubber is not to remove particles but to remove acid pollutants, even though particles will be separated in the scrubber. Venturi scrubbers are implemented to reduce fine particles and aerosols but are not able to handle the whole fly ash amount. Therefore it is most common to install another de-dusting technology upstream the scrubbers to reduce the dust load of inlet flues gas.

Only fabric filters are suitable for removal of particle sizes x_p < 10 μm with a sufficient efficiency needed to reach the emission limit of 10 mg/m³ STP.

3.2 Nitrogen Oxides

SNCR as well as SCR are state-of-the art technologies to comply with the emission limits for waste-to-energy plants. In Figure 21 an evaluation of the NOx emissions of 50 waste-to-energy plant in Germany considering the DeNO$_x$ system is shown. Basically, with the SCR lower emission values for NO$_x$ are possible.
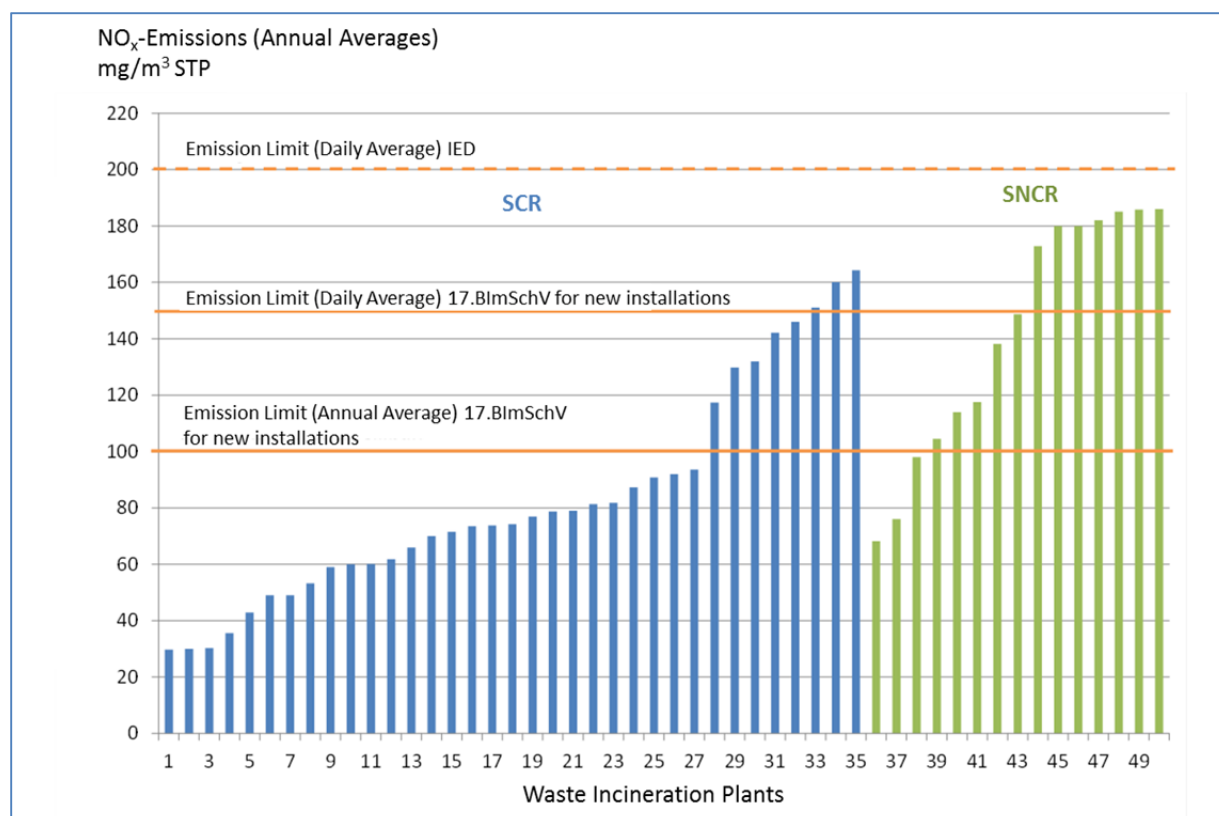
Figure 21: Emissions of NOₓ of municipal solid waste incineration plants in Germany consider-ing flue gas treatment system SNCR and SCR (number of plants = 50)

3.3 Acid Pollutants

The dry flue gas treatment system with sodium hydrogen carbonate is flexible if variations of the raw gas concentration of acid compounds occur. The stoichiometric ratio varies between 1.1-1.3, even if there are very high concentrations of HCl und SO_2. It is possible to go app. 50 % be-low the limits of the European Directive on Industrial Emissions with just slightly increased amount of $NaHCO_3$.

The semi-/conditioned dry flue gas treatment systems have to operate with a higher stoichio-metric ratio (approx. 2) to be able to buffer away raw gas peaks and ensure the compliance of the limits. In wet and effluent-free flue gas treatment systems the gas temperature difference between boiler exit and fabric filter defines the amount of vaporisable salt solution. Therefore, the wet flue gas treatment has to operate with higher raw gas temperatures in case of high raw gas concentrations of HCl and SO_2 (much higher than at present design point). The scrubbers are designed for a fixed efficiency (height of scrubber, number of levels with nozzles). Almost zero emissions of HCl are possible. Absorbent consumption is stoichiometric and therefore most efficient.

3.4 Dust and Heavy Metals

For dry and semi-dry flue gas cleaning systems, the removal of heavy metals depends on dust removal efficiency because most heavy metals are condensed at the surface of dust particles. Therefore, the efficiency of removal of particle bounded heavy metals such as Cd, Tl, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V und Sn cannot be higher than the efficiency of dust removal. Removal of mercury as a vaporous heavy metal can be controlled by the application of activated carbon. Please keep in mind that the adsorption efficiency is a function of the adsorption temperature!

For effluent free wet flue gas treatment systems, the efficiency of fine dust removal and herewith the particle bounded heavy metals is determined also by the efficiency of the fabric filter. An additional removal can be reached by the use of a venturi step, which, however, causes an additional pressure loss and therefore higher electricity consumption. However, the wet system allows higher separation of mercury present as chloride which is soluble in the scrubber water.

3.5 Overview for Germany

In Figure 22, the annual average emissions of municipal solid waste incineration plants in Germany are shown. In average operation, all emissions are much below the legal standard, for dust, heavy metals and dioxins actually below 10 % of the limit. There are no appreciable differences in the efficiency of wet and semi-dry/conditioned-dry flue gas cleaning concepts except for HCl, where wet flue gas treatment reaches very low emission values.
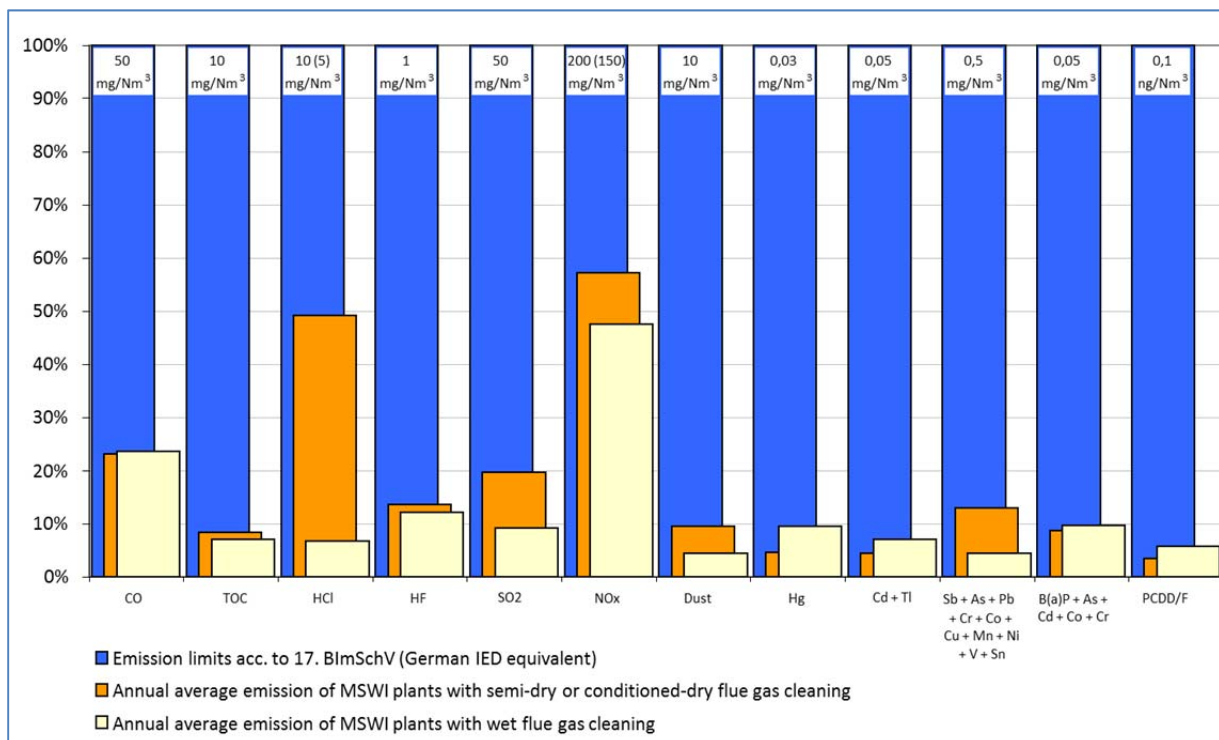
Figure 22: Emissions of municipal solid waste incineration plants in Germany for different flue gas treatment systems (number of plants = 50)

For further details please refer to Löschau, M.: Reinigung von Abgasen – unter besonderer Berücksichtigung der thermischen Abfallbehandlung. Text and practical handbook, 496 pages. Neuruppin: TK Verlag, 2014

4   Examples for Concepts for Retrofit and New Installations

The following examples give an impression about the potential of optimisation and ideas / concepts for new installations.

4.1   Changing from a Wet to a Dry System

Many wet flue gas treatment systems of waste incineration plants are at the end of their lifetime, which makes a retrofit necessary. However, more and more frequently plant operators decide to substitute the wet system (an example is shown in Figure 23) by a dry (an example is shown in Figure 24) or conditioned-dry system. The following changing from a wet to a dry system is based on an optimisation of the operating costs with the same emission limits.
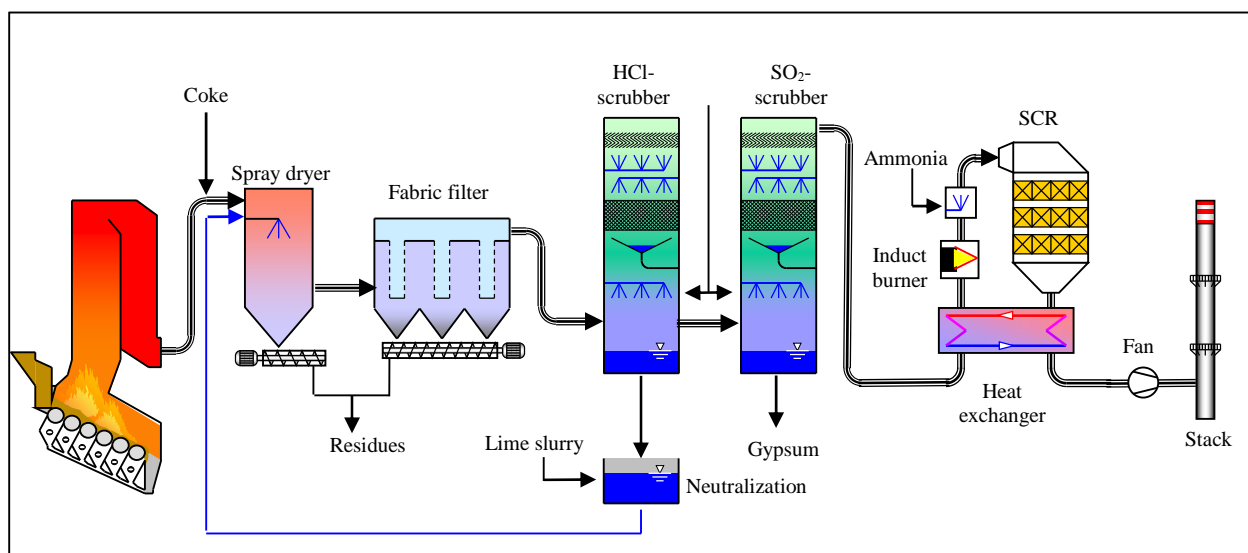
Figure 23: Formerly flow sheet of the wet system
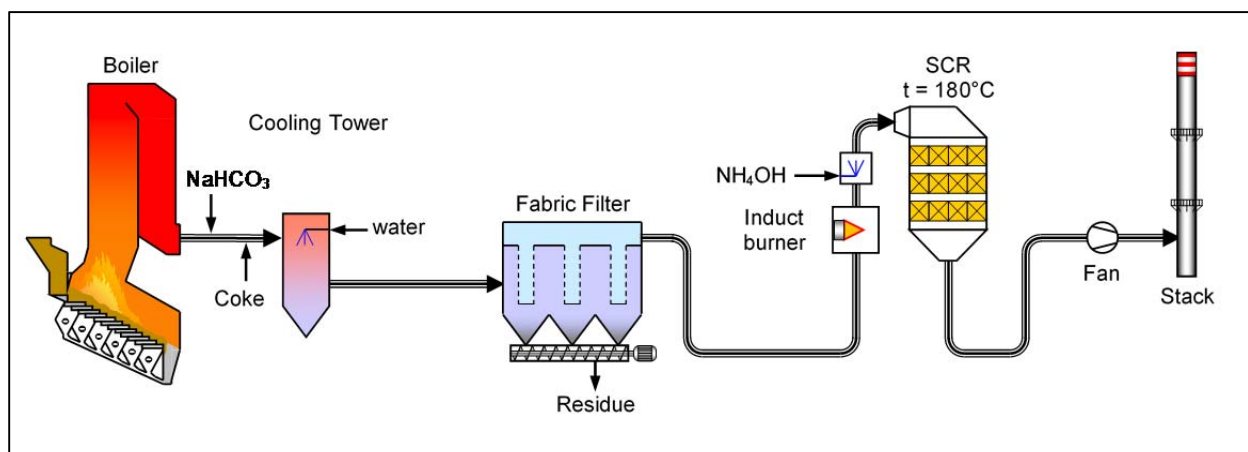
Figure 24: Afterwards flow sheet of installed dry system

The change results in savings by

- loss of natural gas consumption by the loss reheating in the SCR-system
- loss of the gas-gas-heat exchanger instead
- using the enthalpies of the flue gas for the preheat of the turbine condensate by a heat exchanger upstream of the stack
- reduction of the electrical energy consumption because of loss scrubber operation (reduction of pressure loss, loss of the pumps, loss of the gas-gas-heat exchanger)

In Table 2 the main results from the concept evaluation are summarised.

Table 2   Results from the concept evaluation

Parameter	Saving in MWh	Saving in %
Electrical energy consumption	15000	48
Natural gas consumption	54000	97
Steam consumption/heat recovery	31000	84

For further details of the concept please refer to Karpf, R.; Krüger, T., Berliner Abfallwirtschafts- und Energiekonferenz, 25.-26. January 2011.

4.2   Retrofit to an Energy Optimised Concept

In the recent years, energetic optimisation of waste-to-energy plants is focused more. The main goal for the following optimisation (Figure 25) is the realisation of an energy recovery nearly with the existing equipment.
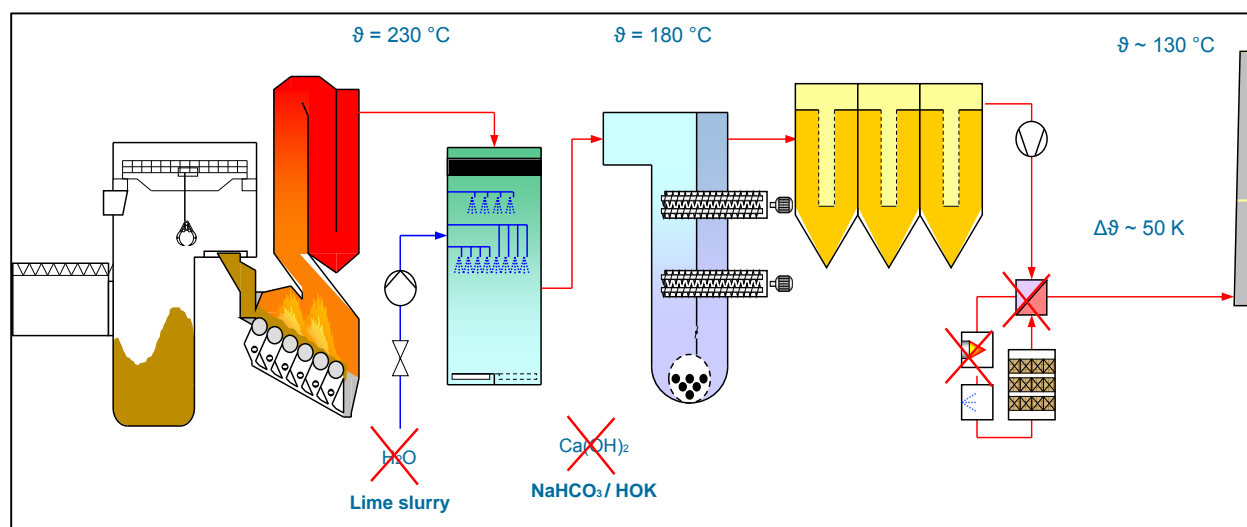
Figure 25: Flow sheet from an energy optimised dry absorption system

The advantages of this concept are as follows:
- Separation of the main pollutant HCl with the cheap CaO (lime slurry)
- Keep the requested emission levels of HCl, SO_2 with sodium bicarbonate ($NaHCO_3$) also with various waste compositions
- Operate the existing catalysts as a low temperature catalyst at ~ 180 °C
- Loss natural gas (unless for start-up or thermal regeneration)
- Loss of the gas/gas- heat exchanger (~ 20 mbar)
- Heat recovery (~ 1 MWh/line with 50 K temperature reduction for the calculated system, but depends on the size of the plant)
- Reduction of corrosion problems

4.3   Change from Spray Absorption to Conditioned-Dry Sorption

Also the replacement of a spray absorption system by a conditioned-dry system could have significant advantages and can reduce the plant`s operation costs (Table 3). Furthermore the cooling effect can be increased with the pure water injection instead of lime milk injection so that the SO_2-reduction can be significantly increased too.

Table 3:   Exemplarily comparison of operation costs for substitution of spray absorption by conditioned-dry system with cooling tower

Operation Costs	unit	Cond. dry absorption	Spray absorption
Lignite coke	€/h	3,048	3,048
Activated coke	€/h	0	0
Lime Ca(OH)$_2$	€/h	21,15	26,741
Lime CaO	€/h	-	10,71
Water	€/h	2,49	2,21
Compressed air (8 bar)	€/h	54,4	54,4
Electrical energy	€/h	16,24	18,56
Residual products	€/h	61,56	73,32
Sum operation costs	€/h	158,89	188,99
Difference	€/h	0	30,11
Difference	%	0	18,95
Annual costs at 8000 h/a	€/a	1.271.084	1.511.928
Difference	€/a	-	240.844

For further details please refer to Karpf, R.; Pohl, M., International VDI Workshop CHALLENGES OF FLUE GAS TREATMENT IN THE FUTURE – INTELLIGENT CONCEPTS, 5th May 2015, Düsseldorf

4.4 Concept for a New Installation

In the following example, a two staged dry flue gas treatment system with sodium bicarbonate and lime in combination with a SCR was implemented as optimal solution (Figure 26). The reasons for that concept for a new installation was to realise for all pollutants 50 % of EU emission limits and for NO_x emission even values < 70 mg/m³. Furthermore it was a requisition on an optimised energy efficiency and heat recovery.
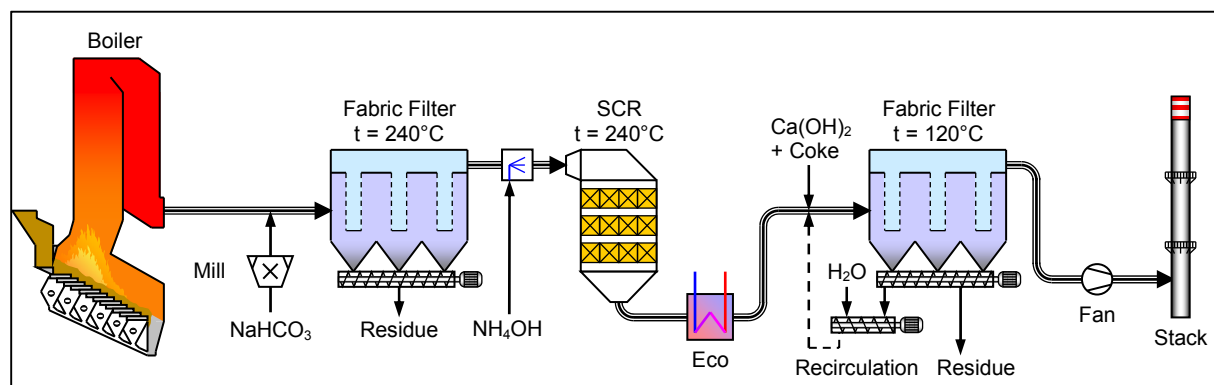
Figure 26: Flow sheet for a flue gas treatment combination of sodium bicarbonate and lime (Waste-to-Energy Plant Delfzijl (NL)

In Table 4 the consumptions of this concept are shown.

Table 4:   Consumptions of WtE plant Delfzijl (NL)

Electrical Energy	kWh/t	20
Lime Ca(OH)$_2$	kg/t	0.8
Sodium bicarbonate NaHCO$_3$	kg/t	20
Active coke	kg/t	0.1
Pressurised air	m³/t	15
Ammonia	kg/t	2.2
Residues	kg/t	35
Waste water	kg/t	0
Energy recovery	kW/t waste	230

For further details to the concept please refer to Bieber, H.; Karpf, R., 25. VDI-Fachkonferenz Thermische Abfallbehandlung, Würzburg 10-11th October 2013.

5 References

[1] BETH Filter GmbH: Dry Electrostatic Precipitator. Company Brochure, 2014

[2] Bieber, H.; Karpf, R., 25. VDI-Fachkonferenz Thermische Abfallbehandlung, Würzburg 10-11th October 2013

[3] Brauer, H. (Hrsg.): Additiver Umweltschutz: Behandlung von Abluft und Abgasen. Handbuch des Umweltschutzes und der Umweltschutztechnik – Band 3. Berlin, Heidelberg: Springer Verlag, 1996

[4] Dittrich, R.; Nowag, R.: Vergleichende Beurteilung und Abscheideleistung von SNCR-/SCR-Technik. VDI-Wissensforum: BAT und preisorientierte Rauchgasreinigungstechniken, München, 2002

[5] Hitachi Zosen Inova: Funktionsprinzip Ringjet. Company Brochure

[6] Karpf, R.; Basic features of the dry absorption process for flue gas treatment systems in waste incineration; Earth Engineering Center, Columbia University, New York, April 2015

[7] Karpf, R.: Überblick zur Abgasreinigung. 10. Fachtagung Abgasreinigung von Feuerungsanlagen und thermische Prozesse; Haus der Technik, Essen, 25-26th June 2015

[8] Karpf, R.; Krüger, T., Berliner Abfallwirtschafts- und Energiekonferenz, 25.-26. January 2011

[9] Karpf, R.; Pohl, M., International VDI Workshop CHALLENGES OF FLUE GAS TREATMENT IN THE FUTURE – INTELLIGENT CONCEPTS, 5th May 2015, Düsseldorf

[10] Liqui-Filter, company material. Im Internet: http://www.liqui-filter.info/know-how/absaugen-und-filtern-von-luft/wie-arbeiten-unsere-filter.html, extracted on 1st February 2012

[11] Löschau, M.: Reinigung von Abgasen – unter besonderer Berücksichtigung der thermischen Abfallbehandlung. Text and practical handbook, 496 pages. Neuruppin: TK Verlag, 2014

[12] Martin GmbH für Umwelt- und Energietechnik: Firmenbroschüre „Das Martin SNCR System"

[13] Müller, C. Stark, R.: Trends in der Abgasreinigung zur Beherrschung des Quecksilber- und Feinstaubproblems – Technische Lösungen. In: Thomé-Kozmiensky, K. J.; Beckmann, M. (Hrsg.): Energie aus Abfall, Band 2. Neuruppin: TK Verlag, 2007

[14] Scheuch GmbH: Bauformen Filter / Abscheider. In the Internet: http://www.scheuch.com/de/filter_abscheider_impulsfilter_bauformen/, extracted April 2013

[15] Scheuch GmbH: Dry Electrostatic Precipitator. Company Brochure

[16] Thermische Abfallbehandlung Lauta GmbH & Co. oHG: Aufbau und Funktion: Aktivkoksfilter. In the Internet: http://www.t-a-lauta.de/aufbau-funktion/aktivkoksfilter.html, extracted 23rd January 2012