

# Chapter 1

## NO<sub>x</sub> Emissions and Removal Techniques

### 1.1 The NO molecule

The NO molecule was first discovered by Joseph Priestley in 1772, the same person who previously had discovered the oxygen molecule [1]. Under atmospheric conditions, NO appears as a clear, colourless gas. NO is present in the atmosphere as a result of human activities such as the emission of waste gas from combustion processes using fossil fuels, burning biomass, but also from natural sources like soil emissions [2, 3]. NO plays an important role in the formation of photochemical smog and acid rain [4].

NO is not only a dangerous pollutant, but it is also an essential molecule for living species. NO is produced in nature by animal and plant cells from the amino acid, L-arginine [5]. In 1992, NO was named molecule of the year by the journal Science and in 1998, the Nobel Prize in Medicine was awarded for the discovery of the effects of NO in living organisms. Due to its small dimensions, the molecule is able to pass through cell membranes and it can serve as a signalling agent [6]. For example, in mammals, NO helps to maintain blood pressure within certain limits by dilating blood vessels and it plays a role in the regulation of the immune system. It also plays a role in controlling the penile erection, by taking part in the enzymatic pathway responsible for the relaxation of blood vessels. As a matter of fact, Viagra® amplifies the NO effect in this process [7]. Inside the brain, NO can contribute to the formation of memory and it plays a role in the communication between neurones [8]. Recently, it has been discovered that NO is able to block a protein involved in Parkinson's disease providing new pathways for treatment methodologies [9].

### 1.2 Environmental impact of NO<sub>x</sub>

The nitrogen monoxide molecule belongs to the family of NO<sub>x</sub> compounds, which includes nitrogen dioxide (NO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O). NO<sub>x</sub> can cause severe health problems and have strong environmental impacts. The main effects are:

- formation of ground-level ozone;
- formation of acid aerosols;
- formation of acid rain;
- deterioration of water quality;
- formation of toxic chemicals;
- global warming.

Below 100 µg/m<sup>3</sup>, plants and vegetable growth are not negatively affected by NO. For human beings, the critical short-term exposure level (24 hours) to NO is around 75 µg/m<sup>3</sup>. For long term exposure (one year), the critical level is around 30 µg/m<sup>3</sup> [10, 11].

#### 1.2.1 Ground level ozone

Ozone is naturally present in the stratosphere and protects life on earth against damage by UV radiation. At ground level, ozone is one of the main ingredients of

smog. The formation of ground level ozone takes place in the lower atmosphere, especially during hot weather. It is formed when NO<sub>x</sub> and volatile organic compounds (VOCs) react in the presence of heat and sunlight [12]. In presence of peroxide radicals, NO can be oxidised to NO<sub>2</sub> in the following way [13]:



NO<sub>2</sub> decomposition takes place photo-chemically and ozone is formed:



When inhaled, even at very low concentrations, ozone can cause acute respiratory problems. High concentrations of ground level ozone, in downwind rural areas may also result in reduced agricultural production [14 - 16].

### 1.2.2 Acid Rain

Rain is normally slightly acidic with a pH between 5 and 6. In case of acid rain, this value may decrease to 4 [17]. The primary responsible agents for the acidification of rain are sulphur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) [14, 18]. Acid rain is formed when these gases react in the atmosphere with water, oxygen, and other chemicals in presence of sunlight to form acidic compounds, like HNO<sub>3</sub>. A more precise term to indicate acid rain is *acid deposition*, which may be distinguished in wet and dry deposition. Wet deposition includes acid rain, fog, and snow. Dry deposition refers to acidic gases and particles which are deposited on surfaces. They can be washed away by rainstorms, increasing in this way the acidity of rain [19].

### 1.2.3 Acid particles

Particles can be directly emitted in the air from different sources like motor vehicles, chemical plants and power stations. Particles are, in combination with other pollutants, dangerous to the health of human beings and animals due to their ability to be transported into the lower parts of the lungs. Diesel fuel used for road transportation is a significant source of particles. The emissions can reach up to 510 mg of particulate per km. In order to decrease these emissions, new fuels for diesel engines have been tested and soot filters have been developed. Positive results were obtained for low sulphur fuel (200 mg/km) [20].

However, particles can also be formed in the air by chemical reactions between gases. For instance, NO<sub>x</sub> can react with ammonia, moisture, and other compounds to form fine particles of nitric acid (smaller than 2.5 micrometer in diameter) and acid aerosols. The fine particles may remain suspended in the air and travel long distances with the wind. [4].

### 1.2.4 Water Quality Deterioration

Water quality can be deteriorated by fertilizers and NO<sub>x</sub> emissions [21]. An increase in the amount of nitrogen compounds in water bodies can disturb the nutrient balance. Additional nitrogen can cause eutrophication, which leads to oxygen depletion and fish kills [4, 18]. Emissions of NO<sub>x</sub> may also change the pH of water, with the effect of lowering the buffering capacity leading to higher levels of dissolved metals [22].

### 1.2.5 Global Warming

Nitrous oxide ( $\text{N}_2\text{O}$ ) is considered a greenhouse gas. It may be emitted to the atmosphere from various sources or it can be formed from the oxidation of nitrogen monoxide. It accumulates in the atmosphere with other greenhouse gases, like carbon dioxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride ( $\text{SF}_6$ ). It is expected that this accumulation causes a gradual rise in the earth's temperature (1.5 - 4.5 °C if the  $\text{CO}_2$  concentration in the atmosphere doubles in the next 100 years [23]), resulting in a rising of the sea level (45 cm in 2100 [24]), expansion of desert lands, and changes in the rain patterns and in the local climate conditions.

### 1.2.6 Toxic Chemicals derived from $\text{NO}_x$

In the air,  $\text{NO}_x$  can react with organic chemicals, to form a wide variety of toxic products, some of which may cause biological mutations. Examples of these chemicals include the nitrate radical, nitroarenes, and nitrosamines [14]. Moreover, ground level ozone can be involved in a series of reactions with hydrocarbons to form aldehydes, various free radicals and other intermediates, which can react further to produce undesired pollutants [13].

## 1.3 $\text{NO}_x$ sources

The main source of  $\text{NO}_x$  emission is road transportation (61%), while industrial activities are responsible for 32% of the total emissions, see Fig. 1 for details. Typically, 90 – 95 % by volume of nitrogen oxides is emitted as  $\text{NO}$  and 5 - 10 % as  $\text{NO}_2$ , although substantial variations between various sources are possible. In 1990, the annual total  $\text{NO}_x$ -emissions in Europe were estimated to be 13.5 million ton. In 2002 the  $\text{NO}_x$  emissions decreased to 9.5 million ton. The relative contribution of each European country is reported in Fig. 2 [25]. The  $\text{NO}_x$  emissions in United States in 1998 were estimated at around 24 million ton [26].

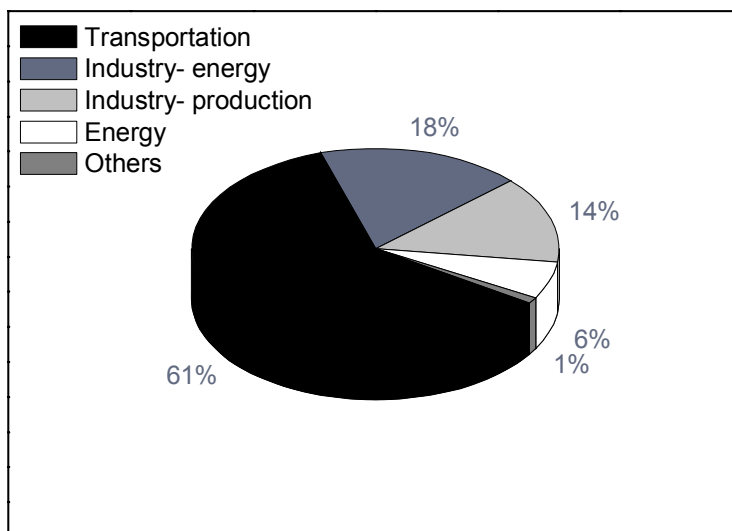


Figure 1. Main sources of  $\text{NO}_x$  emissions in the European Union, 2001. Data from the European Environment Agency, EEA.

According to the Gothenburg protocol, the NO<sub>x</sub> emissions should be reduced to 6 million ton before 2010 [25]. This target will be difficult to meet and significant activities will have to be undertaken.

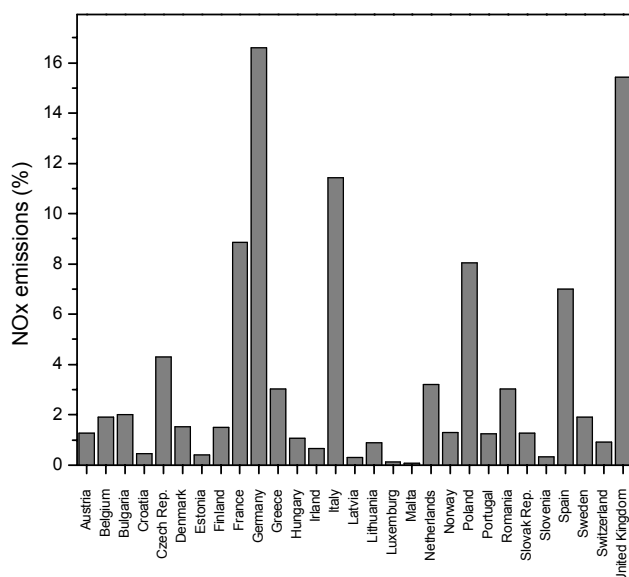


Figure 2. Contribution of each European country to the total NO<sub>x</sub> emission. Data from the European Environment Agency, EEA.

## 1.4 Emission limits for NO<sub>x</sub>

The existing regulations for NO emissions are usually specific for the different emission sources. For example, industrial gas emissions are regulated differently than vehicle emissions.

In the Netherlands, the industrial NO<sub>x</sub> emissions in the atmosphere are regulated according to the general emission standards approved on January 1<sup>st</sup> 2003. Before that time, NO<sub>x</sub> were classified as an inorganic gas with relatively low toxicity (category gA.4). The maximum emission concentration was 200 mg/Nm<sup>3</sup>, for a gas flow above 5 kg/h, and no limits were set for lower flow rates. With the new regulation, NO<sub>x</sub> have been placed in a different category (gA.5), and the emission limits are different for the various applications. For combustion modification treatments, the limit values range up to 500 mg/Nm<sup>3</sup>. For SCR (selective catalytic reduction) the maximum concentration allowed varies, according to the different installations, from 50 to 100 mg/Nm<sup>3</sup> (NH<sub>3</sub> max 5 mg/Nm<sup>3</sup>) and for SNCR (selective non catalytic reduction) from 50 to 200 mg/Nm<sup>3</sup> [27].

## 1.5. Removal techniques

For the reasons given above, it is evident that NO<sub>x</sub> emissions from both stationary and mobile sources need to be reduced considerably in the near future. For stationary sources, two different approaches are applied:

- prevention of NO<sub>x</sub> formation during the combustion process;

- removal of NO<sub>x</sub> in the flue gas (end-of-pipe).

### 1.5.1 NO<sub>x</sub> prevention

There are three main mechanisms to form NO by burning fossil fuels.

#### 1.5.1.1 Thermal NO

During combustion, NO is formed according to the following mechanism:



High thermal NO concentrations (> 2000 vppm) may be reached in case of high operating temperatures (above 1400 °C) using a low excess of air and long residence times.

#### 1.5.1.2 Prompt NO

Very fast chemical reactions taking place at the border of the flame generate prompt NO. The amount of prompt NO formed in a common burner is around 0 - 30 vppm.

#### 1.5.1.3 Fuel NO

Fuel NO originates from the organic nitrogen components present in the fuel. Its formation is not strongly temperature dependent like in the case of thermal NO. Typical conversion values of fuel-bound nitrogen to NO<sub>x</sub> range between 15 and 35% and are dependent on the type of burner used [28 – 30].

A well-known solution used for the prevention of NO<sub>x</sub> is to reduce the flame temperature. This may be achieved by applying an optimal air/fuel ratio. Low NO<sub>x</sub> burners are dedicated burners which regulate the air and fuel ratio continuously to reduce the flame temperature. In this case, the combustion chamber consists of two zones. In the first, the oxygen concentration is maintained at a low level to prevent NO<sub>x</sub> formation. In the second zone, complete combustion at lower temperature occurs [30]. A low NO<sub>x</sub> burner may result in NO<sub>x</sub> reductions up to 40 - 60%. Advanced technologies in combination with low NO<sub>x</sub> burners achieve even better results. Examples are the application of External Flue Gas Recirculation (EFGR) or Induced Flue Gas Recirculation (IFGR), used to decrease the excess of air present during the combustion. In EFGR, a controlled amount of the outgoing flue gas is recirculated to the burner in order to reduce the concentration of oxygen present and consequently the NO formation. The maximum NO<sub>x</sub> removal level is limited by the recirculation rate, which in turn is limited by the flame stability and the amount of air in excess. In IFGR, a part of the outgoing flue gas is mixed with air and then recirculated to the burner. The recirculated flow is limited by the flame stability and the combined air/flue gas temperature [31]. The EFGR and IFGR concept are schematically represented in Fig. 3. The EFGR concept has shown to lead to reductions in the NO<sub>x</sub> emissions of 50 to 75%, the IFGR is even better and reductions up to 70 to 80% were achieved [32].

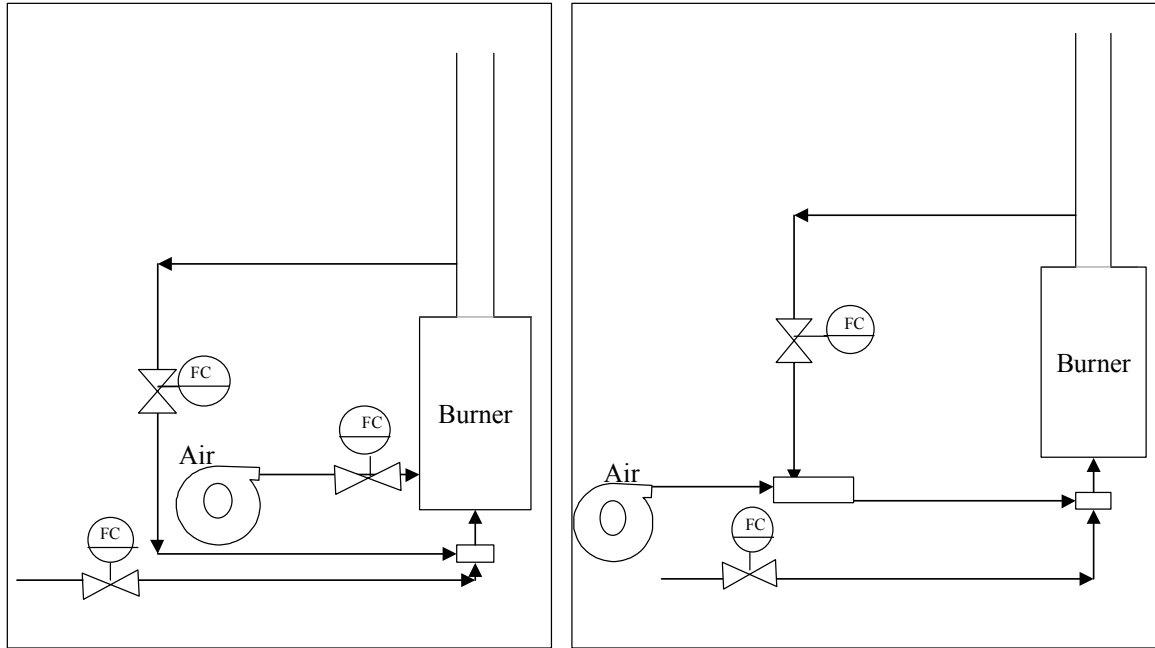
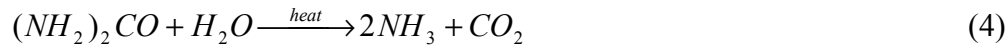


Figure 3. Representation of the EFGR (left) and IFGR (right) systems for prevention of NO<sub>x</sub> formation.

### 1.5.2 End of pipe NO<sub>x</sub> removal technologies: SCR and SNCR

Selective Catalytic Reduction (SCR) and Selective Non Catalytic Reduction (SNCR) are end-of-pipe removal techniques. Both techniques apply ammonia or urea to convert NO<sub>x</sub> to nitrogen and water. A schematic representation of the SCR process is given in Fig. 4. The basic chemistry of the process is the following:



Both technologies are based on the concept of injecting the ammonia/urea into the flue gas stream downstream of the combustion zone. In addition, SCR uses a catalyst to increase the reaction rate. Common catalysts are based on titanium, vanadium, tungsten, and regenerable zeolites. A coal-fired boiler, ranging in power size from 100 to 850 MW, equipped with a SCR system is able to reach a removal efficiency of up to 85 - 90%. The removal efficiency is strongly influenced by the oxygen content, the urea/ammonia content, the temperature, the mixing pattern in the reactor, and the NO<sub>x</sub> concentration. The SCR process is operated at around 400°C while, for a SNCR, the process temperature is considerably higher (800 - 1200°C) [33, 34]. Some important features of the SCR and SNCR are:

- the SCR system is quite sensitive to volumetric flow rate changes and to the gas composition. Some components (like SO<sub>2</sub> or dust) may decrease the catalyst stability;
- SCR and SNCR are designed for a specific NO<sub>x</sub> inlet concentration. If the concentration exceeds the design values, the conversion may be reduced dramatically;
- the presence of CO interferes with the process, consuming the oxygen to form CO<sub>2</sub>;

- excess of ammonia can lead to ammonium chloride particles formation, which can deposit on the fly ash. This phenomenon does hardly occur in case of SCR (few vppm), while it may be considerable in case of SNCR.

The cost for a SCR system varies with the type of catalyst used. The catalyst cost can be rather high and may be up to 40 - 60% of the operational costs [35]. Typically, the capital costs for such a unit are between 55 and 140 \$/KW of electrical power output [36]. The SNCR process is economically more attractive because it does not involve the use of a catalyst. Removal efficiencies of up to 60 – 70 % are achievable under ideal conditions. Higher NO<sub>x</sub> reductions are limited due to high levels of ammonia slip when aiming for high NO conversions. Capital costs are typically around 4 - 5 \$/KW in case of large installations and 12 – 14 \$/KW for smaller industrial installations [37].

High NO removal efficiencies are always associated with high costs. For this reason, research on NO removal technologies in the last decades has focused especially on the development of cheaper alternatives. A number of novel process concepts have been proposed and these will be provided in the following sections.

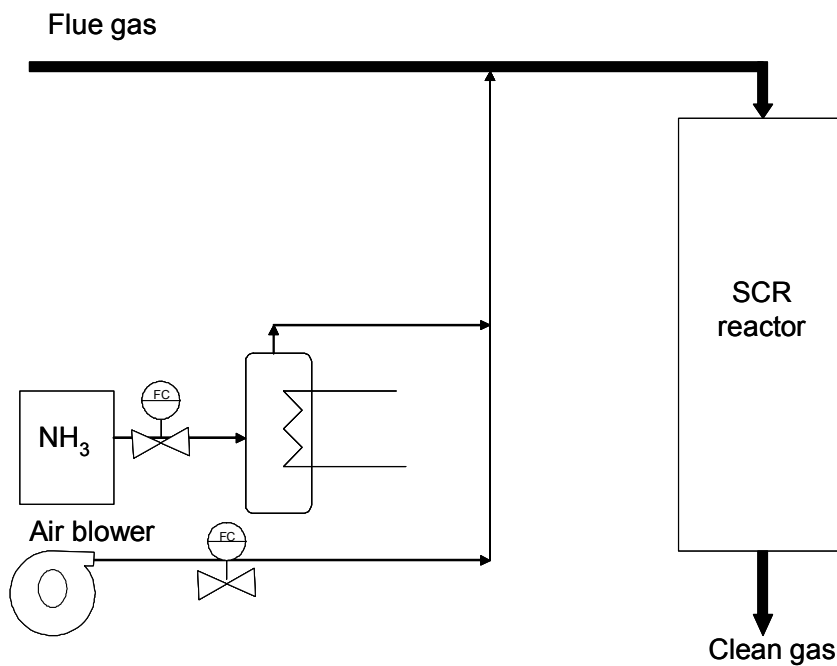


Figure 4. Schematic representation of the SCR process. NH<sub>3</sub> liquid is vaporized before being mixed with the flue gas.

### 1.5.3 NO removal using micro-organisms

In the last decade, biofiltration techniques, commonly used to control odour and VOC's emissions, have been tested to remove NO<sub>x</sub> from flue gas. Lab scale biofilters, filled with wood materials and/or compost, maintained at a pH between 6 and 7 at room temperature have shown to remove NO with efficiencies up to 90% ( $C_{NOin} = 100 - 500 \mu\text{l/l}$ ) [38]. Further studies, using lab scale trickle bed biofilters maintained under aerobic conditions have shown that the removal of NO and N<sub>2</sub>O is the result of the action of various micro organisms. These results imply that aerobic micro-organisms are able to remove NO directly [39, 40]. The concept needs further research and development before it can be commercialised. The identification of the biologically active species and testing of larger reactors are at the moment under investigation.

### 1.5.4 NO removal using wet absorption with metal chelates

The wet absorption concept consists of the absorption of a gas phase component in a liquid which contains a suitable reactant. The reactant should react with the gas-phase component to enhance the absorption rate. This concept is especially very convenient for gas-phase components which are poorly soluble in the liquid phase. NO is poorly soluble in water. The solubility of nitrogen oxide in water is  $5.33 \cdot 10^4 \text{ Pa} \cdot \text{mol}^{-1} \cdot \text{m}^3$  at  $T = 25 \text{ }^\circ\text{C}$  [41]. To enhance the absorption rates of NO in an aqueous solution, metal salts capable of reacting with NO may be added to the liquid phase. Particularly, divalent iron chelate complexes are very suitable for reactive NO absorption. Well known chelates able to form stable metal complexes are: EDTA (ethylenediaminetetraacetic acid, see Fig. 5), NTA (nitrilotriacetic acid), MIDA (methyliminodiacetic acid), HEDTA (hydroxy-ethylenediaminetriacetic acid) and DMPS (dimercaptopropanesulfonic acid).

Within the family of iron chelates,  $\text{Fe}^{\text{II}}(\text{EDTA})$  shows a high reactivity towards NO. The complex is highly sensitive to oxygen, which leads to the formation of ferric chelate,  $\text{Fe}^{\text{III}}(\text{EDTA})$ . The latter is not capable of binding NO [42 - 45]. However,  $\text{Fe}^{\text{II}}(\text{EDTA})$  is often preferred for its very high complex stability [46].

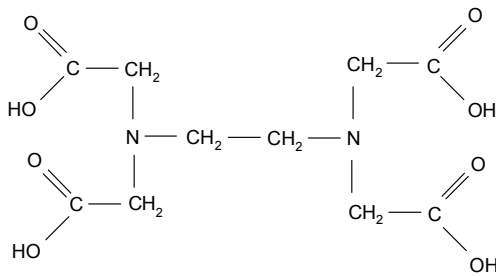


Figure 5. Molecular representation of EDTA.

To be cost effective, the loaded metal chelate solutions need to be regenerated. A number of regeneration techniques have been proposed.

#### 1.5.4.1 Regeneration with $\text{SO}_3^{2-}$

In presence of  $\text{SO}_3^{2-}$ , the ferric ion can be reduced to the ferrous form and dithionite. The following reaction occurs:



Unfortunately, the reaction is quite slow at temperatures below  $65^\circ\text{C}$  [42, 47, 48]. No indications about possible collateral effects due to the presence of the dithionite in solutions are reported.

#### 1.5.4.2 Regeneration using polyphenolic compound

This method of regeneration consists of the addition of organic polyphenolic compounds like tannic acid, pyrogallol, and gallic acid during the reactive absorption process. These compounds rapidly reduce the ferric ions back to the ferrous species and are able to inhibit the rate of the oxidation of ferrous ions. However, to reduce the oxidation rates sufficiently, constant addition of chemicals with a consequent increase of the costs is required [49, 50].

#### 1.5.4.3 Electrochemical regeneration

Electrochemical regeneration utilises electrochemical cells separated by membranes. The cathode compartment contains the ferrous and ferric chelate, while the anode compartment contains an electrolyte solution. When the current is applied, the ferric chelate is reduced to ferrous chelate and the water at the anode is electrolysed to oxygen and hydrogen ions. The electrochemical cell can effectively maintain the iron chelate in the active form. However the electrical usage is proportional to the gas flow rate, the required level of NO removal and the oxidation rate. Consequently, the method does not represent a convenient solution for industrial scale installations [51, 52].

#### 1.5.4.4 Biological regeneration

Denitrifying bacteria have shown to be able to reduce the ferric chelate as well as the nitrosyl complex back to the ferrous form. The process requires an electron donor like ethanol [53]. Preliminary economic evaluations for this regeneration procedure indicate that the process may be cost effective compared to other removal techniques. In 1993, Biostar, a joint venture between Paques B.V. (the Netherlands) and Corus Consulting and Technical Services B.V., has initiated the development of a biological NO removal method, called BiodeNOx.

## 1.6 The BiodeNOx process

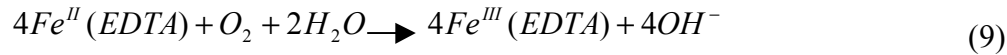
The BiodeNOx process consists of two parts: the reactive absorption of NO in an aqueous  $Fe^{II}(EDTA)$  solution followed by the biological regeneration of the iron chelate solution using denitrifying bacteria [54, 55].

### 1.6.1 Absorption

In this step, the flue gas containing NO is contacted with an aqueous  $Fe^{II}(EDTA)$  solution. The iron chelate binds the NO and forms a stable nitrosyl complex. The reaction that takes place is:



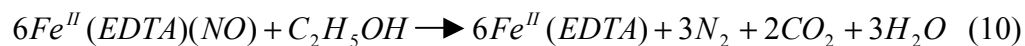
Flue gases contain also oxygen and part of the  $Fe^{II}(EDTA)$  complex is oxidised:



In contrast to  $Fe^{II}(EDTA)$ ,  $Fe^{III}(EDTA)$  is not capable of binding NO. Therefore, this reaction is highly undesired because it lowers the efficiency of the process. Moreover, oxygen is suspected to be responsible for the chemical degradation of the chelate complex [56, 58].

### 1.6.2 Regeneration

The regeneration takes place in the presence of denitrifying micro-organisms. The regeneration reaction proceeds according to:



and:



Both the nitrosyl complex  $Fe^{II}(EDTA)(NO)$  and  $Fe^{III}(EDTA)$  are regenerated to  $Fe^{II}(EDTA)$ . Ethanol can be used as an electron donor. However, other electron donors like methanol might be suitable as well.

Overall, NO and ethanol are converted to nitrogen, water and  $CO_2$ . The “catalytic” role of the metal chelate in the process is shown in Fig. 6.

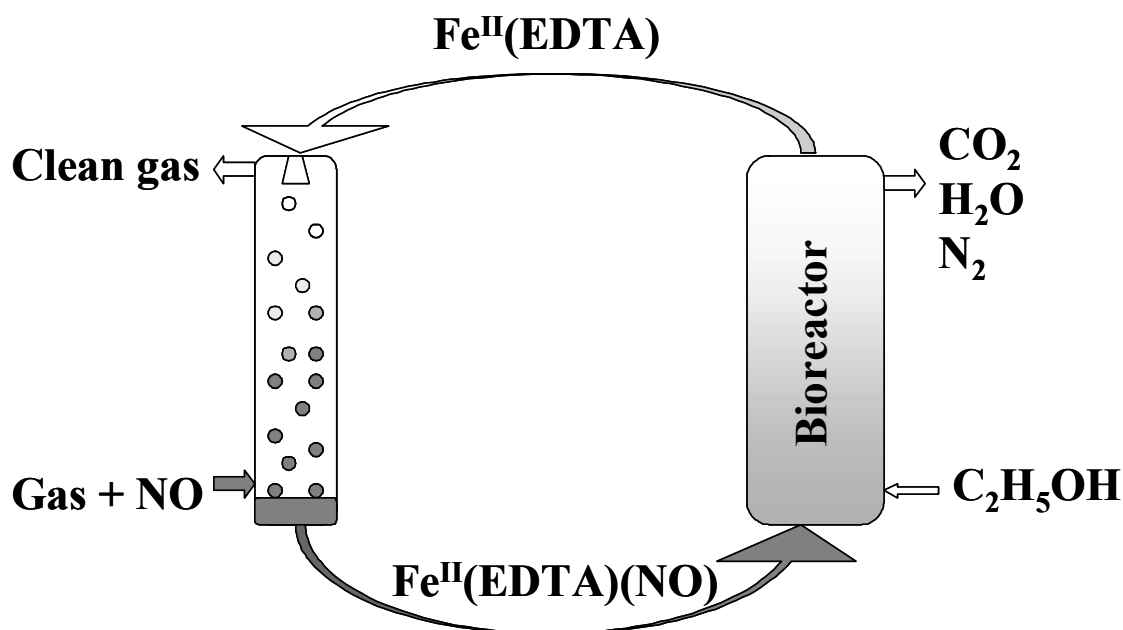


Figure 6. Schematic representation of the BiodeNOx process.

### 1.6.3 BiodeNOx process characteristics

The schematic representation of the BiodeNOx process given in Fig. 6 shows a concept with a separate scrubber and bioreactor. A combined scrubber- bioreactor is a possible alternative [53] and may be particularly interesting when the presence of microorganisms in the scrubber unit does not negatively affect the absorption process. A combined unit is more process intensified and is therefore expected to be less capital intensive. However, the concept of two separate reactors may be more suitable in case the necessary residence times for the two reactors differ significantly.

The major topic of this PhD thesis is the design of the reactive gas-liquid absorber unit. For a proper design of the absorber unit, it is essential to have knowledge on the possible window of process conditions. The temperature in the absorber will be determined mainly by the temperature of the flue gas and the gas-liquid ratio in the column. On the basis of preliminary estimations, the temperature in the absorber is estimated to be about 40 – 60 °C [59]. When applying flue gas cooling, lower temperatures are possible although this will lead to enhanced capital costs and the requirement of heat integration. The temperature of the recycle liquid flow from the bioreactor will be determined by the optimum reaction temperature of the bio-reactor, which is estimated to be about 50 °C. In the experimental studies described in this work, a temperature between 25 and 55 °C has been applied.

An important design variable is the pH of the solution. The pH of the recycle liquid from the bioreactor will be in the range between 5 - 8. This pH range is also used in all experimental studies.

Finally, the concentration of the  $\text{Fe}^{\text{II}}(\text{EDTA})$  in the inlet of the absorber has to be taken into considerations. It is to be in the range of  $10 - 100 \text{ mol/m}^3$  to guarantee consistent gas absorption rates.

Furthermore, it is expected that the biological  $\text{DeNO}_x$  process can be combined with other gas treatment systems like the  $\text{SO}_2$  removal with biological limestone gypsum process [60].

## 1.7 BiodeNO<sub>x</sub> research activities

The BiodeNO<sub>x</sub> process has been tested successfully in pilot applications showing NO removal efficiencies up to 60 – 65 %. For instance, a test unit was erected at the Pelletising plant of Hoogovens (Corus, The Netherlands). Using a  $\Phi_G$  of  $100 \text{ Nm}^3/\text{h}$ , a  $C_{\text{NOin}} = 250 \text{ vppm}$  and a  $C_{\text{O}_2}$  of 19%, a removal efficiency of 60% was obtained [61]. A fundamental understanding of the BiodeNO<sub>x</sub> process was considered necessary to optimise the process parameters to improve the NO removal efficiency and to reduce the costs.

A BiodeNO<sub>x</sub> research group has been instituted with the support of the Netherlands Technology Foundation (STW). The consortium consists of a number of universities (the University of Groningen, the University of Wageningen and the University of Delft) and a number of companies (Paques B.V, Corus, Akzo Nobel).

In this thesis, process research on the BiodeNO<sub>x</sub> absorber unit will be presented. In Chapter 2, investigations on the reaction of NO with  $\text{Fe}^{\text{II}}(\text{EDTA})$  in aqueous solutions are reported. The reaction is studied in a stirred cell reactor to obtain information on the intrinsic kinetics, the thermodynamics of the reaction, and the rate of absorption as a function of the process parameters.

In Chapter 3, the NO absorption process is investigated experimentally in a stirred cell reactor in the presence of denitrifying micro-organisms to determine the effects of micro-organisms on the rate of NO absorption. A reactive gas-liquid absorption model taking into account the effects of micro-organisms will be provided.

A study on the reaction between  $\text{Fe}^{\text{II}}(\text{EDTA})$  and oxygen which leads to the formation of ferric chelate that may limit the absorption efficiency of the BiodeNO<sub>x</sub> scrubber, is reported in Chapter 4. The oxidation reaction is studied at typical BiodeNO<sub>x</sub> process conditions. In particular, the effects of pH variation (5 - 8) and salinity are investigated.

In Chapter 5, an experimental investigation on the simultaneous absorption of NO and oxygen in aqueous  $\text{Fe}^{\text{II}}(\text{EDTA})$  solutions using a stirred cell reactor is reported. The NO and oxygen absorption rates are studied as a function of the process parameters. This investigation is of particular importance to get insights in the factors which affect the selectivity of the gas absorption process. Novel, explicit relations for the enhancement factors for the system of simultaneous absorption of two gases with a third reactant on the basis of the film theory will be reported.

In Chapter 6, experimental studies in a continuous bench scale model spray tower will be provided. In this novel reactor concept, the hydrodynamics are well defined by using single falling drops, eliminating wall and swarm effects. The absorption rates of NO are measured and the efficiency of the gas absorption is investigated as a function of the process conditions.

Chapter 7 presents an experimental study on EDTA ligand degradation. The EDTA

degradation rates are determined as a function of the process conditions. Chapter 8 describes a reactor model for a counter current packed column dimensioned to treat the flue gas of a  $600 \text{ Nm}^3/\text{s}$  to reduce the NO concentration in the outlet to 25 vppm. Here, the results of all experimental studies (reaction kinetics, thermodynamics, physical properties) described in the previous chapters are integrated. This model allows selection of the optimum process conditions to achieve the desired NO removal efficiencies. In addition, it gives the possibility to determine the sensitivity of the various process parameters.