Air Pollution Control Technologies

Fact Sheets

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Appendix 1 Suppliers who contributed to the update

Abbreviations

Abm	Activities Decree (Environmental Management Act)
Bal	Activities Decree (Environment and Planning Act)
BAT	Best available techniques
BREF	BAT Reference Document, see https://eippcb.jrc.ec.europa.eu/reference/
CO	Carbon monoxide
COS	Carbonyl sulphide
EMIS	Energy and Environmental Information System
DeNOx	NOx abatement technology by converting nitrogen oxides (NOx) chemically into atmospheric nitrogen (N_2)
ESP	Electrostatic precipitation
EU	European Union
H2S	Hydrogen sulphide
HCl	Hydrogen chloride
HCN	Hydrogen cyanide
HEPA	High Efficiency Particle Air Filter
HF	Hydrogen fluoride
Hg	Mercury
IR	Infrared light
LUSS	Air treatment selection system, see https://emis.vito.be/nl/bbt/bbt-tools/selectiesystemen/luss
NaOCl	Sodium hypochlorite
NH_3	Ammonia
NOx	Nitrogen oxides, sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) expressed as NO_2
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyl
PCDD/F	Polychlorinated dibenzodioxins and dibenzofurans (dioxins)
pH	Acidity
PM	Particulate matter; PM10 and PM2.5 for particle sizes up to 10 µm and 2.5 µm respectively
PTFE	Polytetrafluoroethylene (Teflon)
RTO	Regenerative incinerator (regenerative thermal oxidation unit)
RWS	Rijkswaterstaat, Agency of the Dutch Ministry of Infrastructure and Water Management
SCR	Selective Catalytic Reduction
SLA	Clean Air Agreement, see www.schoneluchtakkoord.nl
SNCR	Selective Non-Catalytic Reduction
SOx	Sulphur oxides, sum of sulphur dioxide (SO_2) and sulphur trioxide (SO_3) expressed as SO_2
TOC	Total Organic Carbon
UV	Ultraviolet light
VITO	Flemish Institution for Technological Research, see www.vito.be
VOC	Volatile organic compounds
SVHC	Substances of Very High Concern

1 Introduction

1.1 Background

Many industrial processes require end-of-pipe technologies in order to meet current emission limits. Given the importance of good air quality for public health, emission requirements are becoming increasingly stringent, leading further to the development of end-of-pipe technologies. Reliable information on abatement technologies is essential when choosing appropriate measures.

The Dutch reference document titled 'Handreiking Luchtemissiebeperkende technieken' ('Guide to Air Pollution Control Technologies') from 2009 (reference [1]) is no longer up-to-date in all respects. The Agency of the Dutch Ministry of Infrastructure and Water Management, Rijkswaterstaat (RWS), has decided to update the information sheets on abatement technologies as part of the Clean Air Agreement (SLA). The SLA aims to achieve permanent improvements in air quality and is aimed at all aspects of society, including industry. Therefore up-to-date information on abatement technologies is very important.

1.2 Target Audience

The Guide to Air Pollution Control Technologies provides insight into the operation and the environmental and financial aspects of the current technologies. For each technology, an information sheet has been drawn up, which has also been made available on the website of IPLO, https://iplo.nl'. These are known as 'fact sheets'.

The information is also used internationally, for example as Dutch input for the European reference documents for best available techniques (BREF). Conversely, the BREF documents also have an impact on the fact sheets. There is also an active exchange of information with the Flemish Knowledge Centre for Best Available Techniques, which is part of VITO. VITO makes the fact sheets on abatement technologies, called 'technique sheets', available on its EMIS website in Dutch and English. Both web pages on abatement technologies are frequently consulted by industry and government professionals. Together the webpages were consulted approximately 110,000 times in 2020.

1.3 Objective

The objective of this Guide to Air Pollution Control Technologies is to provide all parties involved with reliable, elementary information on the choice of available end-of-pipe emission control technologies. The information concerns the operation and the environmental and financial aspects. The parties involved are companies, the competent authority, consultants and suppliers.

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[1] Guidance document on air emission control technologies; dossier: B8176.01.001 registration number: MD-MV20081123 version: 3, Infomil; DHV B.V.; 15 April 2009

In a general sense the information is intended to enable a first selection of suitable technologies. After the first selection a further elaboration of the concrete situation is necessary, for which additional, situation specific information will be required.

1.4 Scope

The fact sheets provide an overview of the most important characteristics of general air pollution control technologies that have been proven in practice. These include the operating principle, the area of application, the performance (final concentration and efficiency) and financial aspects. This research is limited to technologies that are applied on an industrial scale. Technologies that are only applied on a laboratory or experimental scale are not described in this research.

The technologies are limited to end-of-pipe technologies for point sources in industry. The technologies are primarily aimed at treating emissions. The legal requirements relate to residual concentrations and removal efficiency.

1.5 Document Structure

The context and application of emission control technologies are explained in Chapter 2. The usual technologies for treating the most common air pollutants are discussed. The chapter concludes with an overview table. Chapter 3 explains the use and format of the fact sheets. Chapter 4 contains the fact sheets. The layout of the fact sheets is based on the operating principle. The fact sheets explain the most important forms of implementation for each operating principle. Chapter 5 discusses a number of related subjects.

1.6 Document History

The basis of the document was laid in 1993, when it was intended as an internal document to support RWS (at that time the staff office of the Dutch Emission Guidelines, NeR) in providing information to permit providers on the technical, legal and procedural aspects of environmental policy. This report was thoroughly updated in 1999, when it was also made accessible to third parties, publication L26 'Factsheets afgasbehandelingstechnieken' (2000).

The revision of the BAT Reference Document (BREF) on Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector in 2003 prompted a review of the relevance of the fact sheets. Commissioned by RWS, DHV has reviewed the actuality of the fact sheets in 2009 and updated them where necessary.

In Flanders, VITO (since 2004) makes available similar information as the fact sheets through 'LUSS'. LUSS is a system that can help with a first screening of and decision on possible technologies to solve an air pollution problem. This system is available digitally via: http://www.emis.vito.be/Luss/.

1.7 Recent Developments

After 2009 there have been a number of developments that are of importance to the application of abatement technologies. The most important developments in legislation since 2009 with consequences for current emission requirements are:

- Tightening of emission requirements in BAT conclusions (16 sectors)
- Publication of the BREF document for Waste Gas Treatment in the Chemical Industry (draft, 2019)
- Normative part of the Dutch Emission Guidelines (NeR) included in the Activities Decree
- Implementation of the European Directive 2015/2193/EC on Medium-sized Combustion Plants and Implementing Decision (EU) 2017/1442 on BAT Conclusions for Large Combustion Plants in the Activities Decree and Activities Regulation
- Transition from the Activities Decree (Abm) of the environmental Management Act to the Activities Decree (Bal) of the Environment and Planning Act
- Intended tightening of general emission limits in the revision of the ‘Bal’

The main recent policy developments are:

- The Clean Air Agreement (SLA) with the aim of achieving a permanent improvement in air quality
- More attention to substances of very high concern (SVHC)
- Need for very low emissions of nitrogen compounds, due to the nitrogen problem in the Netherlands and Flanders

In addition, new European policies are being developed, such as:

- European Green Deal [2] on reducing air, water and soil pollution to a level that is no longer considered harmful to health and natural ecosystems ('zero pollution')
- Review of air quality standards
- New emission limit values for 29 air pollutants in the chemical industry

In practice, this leads to more combinations of technologies and optimisation of existing technologies. The question therefore shifts more from 'what' (which technique) to 'how' (meeting emission requirements). The updating of the fact sheets focuses on both the content of the information and the form in which this information is provided.

1.8 Approach

Rijkswaterstaat set up a guidance committee to supervise the updating project. The guidance committee included representatives of RWS, competent authority, industry, suppliers and VITO. The actualisation was carried out by TAUW.

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[2] Route to a healthy planet for all, EU Action Plan: Pollution of air, water and soil to zero; Communication of 12.05.2021

The update included:

- Incorporating changes to the Best Available Techniques Reference (BREF) documents and other reference documents, in particular:
    - BREF CWW 2016: BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector' of 2016
    - BREF WGC D1 2019: BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
    - LUSS technique sheets (https://emis.vito.be/nl/node/204)
    - BVT 2016:
        - Festlegung von besten verfügbaren Techniken (BVT) in Europa: BVT zur Minderung von Emissionen in die Luft im Bereich der chemischen Industrie in Deutschland from October 2016
        - Definition of Best Available Techniques (BAT) in Europe: BAT for Air Emission Reduction in the Chemical Industry Sector in Germany; Final Report; ÖKOPOL GmbH - Institut für Ökologie und Politik; Project number: FKZ 3714 43 312 4; October 2016
    - Previously used literature references
- Consideration of recent studies conducted for RWS:
    - RWS, Follow-up study on tightening emission limit values under section 2.3 of the Activities Decree', 2020: analysis of measurement results
    - RWS, Actualisation of reference values for cost effectiveness, 2020: cost indexation
- Surveys of suppliers of end-of-pipe technologies
- Interviews with suppliers, industry and competent authorities
- Updating financial information to the year 2021
- Consistent structure and grouping of technologies

The surveys completed by suppliers of end-of-pipe technologies were essential for the supply of new information. Appendix 1 shows which suppliers were approached for a response and which of these parties provided a substantive response.

2 Application of Pollution Control Technologies

2.1 Strategy to prevent or reduce emissions

End-of-pipe technologies should be seen as part of the strategy to reduce air emissions. The strategy starts by identifying the business processes, the operations and the emission requirements. This indicates the processes for which measures are required.

The general preference for action from an environmental perspective is as follows:

1. Avoidance (inherently cleaner)
2. Restriction by means of a process-integrated measure
3. Treatment with end-of-pipe technology [3]
    - 3.1 Product recovery or formation of valuable by-products
    - 3.2 Using the energy content (heat of the waste gas or through incineration)
    - 3.3 Minimize environmental impacts (destruction of the pollution with no or limited emissions of other environmentally harmful substances, formation of effluent and/or waste, energy and raw material consumption).

Process-integrated measures can prevent or reduce the environmental impact, for example by switching to other raw materials or recycling emission flows. Obvious measures are, for example:

- Modification of the process in such a way that an emission no longer occurs
- *Example: optimising an incineration process so that harmful dioxins are no longer produced. Then they no longer need to be captured*
- The use of other raw materials
- *Example: the use of low-sulphur oil as fuel, so that sulphur dioxide is no longer produced as a waste or by product*

If this is not feasible, end-of-pipe technologies are considered. The analysis of the production processes and the operational management leads to the preconditions needed to choose an end-of-pipe technology. This report is limited to end-of-pipe technologies.

2.2 Selection of technologies

This paragraph indicates which parameters are decisive in the selection process of an end-of-pipe technology or a combination of technologies. The process consists of three steps that are followed to choose a technology or a combination of technologies. A combination of technologies is often necessary to achieve the desired results. Several technologies can be placed in series to reduce emission concentrations to meet emissions thresholds, for example when treating waste gases containing SVHC.

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[3] Possibly prior concentration which makes an end-of-pipe technology more cost-effective.

2.2.1 Gas and particles characteristics

As a first step, the characteristics of a waste gas stream must be determined, for example with calculations and measurements. The characteristics of the waste gas flow determine the boundary conditions within which an end-of-pipe technology must be able to operate. The most important variables in this regard are:

- Process management: continuous or discontinuous, fluctuations in supply, disruptions, et cetera
- Waste gas parameters: flow rate, pressure, temperature
- Composition of waste gases: oxygen content, moisture, dust, type of pollutants

The most important substance characteristics are given below:

1. Chemical composition of the pollutants:
    - Organic (for example aliphatics, aromatics, alcohols, halogenated)
    - Inorganic (for example acids, bases, metals)
   - Physical composition of the pollutants:
     - Particulate matter
     - Gases and vapours
2. Particulate pollutants
   - Concentration
   - Particle size distribution
   - Shape of the particles
   - Stickiness/viscosity/hygroscopic properties
   - Electrostatic charge
3. Gaseous and vaporous pollutants
   - Concentration,
   - (water) solubility
   - Vapour pressure
   - Boiling point
   - Dew point
   - Explosion limits
   - Reactive / corrosive properties
   - Biodegradability

2.2.2 Technology and company characteristics

In a second step, technology and operating characteristics are considered. The applicable technologies are analysed in terms of reliability, efficiency and how it can be implemented. The operating situation must be analysed in terms of required/available facilities and available space.

The main technology characteristics are:

- Variation in application types
- Efficiency and/or achievable residual concentration, whether or not in combination with other technologies
- Operational reliability

- Operation manpower
- Maintenance requirements and maintenance sensitivity
- Space requirements
- Required process connections (pipework, control)

The main facility characteristics are:

- Integration into existing process
- Available space (surface and height)
- Foundation and building structures
- Required/available facilities (energy/electricity, steam, compressed air, wastewater treatment)
- Zoning plan
- Available environmental space (CO_2 emission allowance; existing nitrogen deposition in Natura 2000 areas, air quality, odour and noise pollution)
- Visual pollution

2.2.3 Environment and economy

In a third step, environmental and economic characteristics of the selected technologies are considered. The occurrence of by-products, waste streams and financial costs, among others, eventually lead to a choice of a feasible technology.

The most important environmental characteristics are listed below:

- Performance: residual emission and reduction efficiency
- By-products
- Waste streams (solid, liquid, slurry)
- Energy consumption
- Consumption of auxiliary substances such as water

The main economic characteristics are shown below:

- Investment costs
- Operational costs (personnel, energy/electricity, water, steam, compressed air, consumables, insurance)
- Maintenance costs
- Savings and yield of recovered product
- Waste processing costs

2.3 Commonly applied technologies

This section describes commonly applied technologies per substance group per waste gas temperature. This overview is intended as a general overview to be used when considering current technologies. To determine BAT, reference is made to the sector-specific BAT reference documents.

2.3.1 Sources of low temperature

The usual pollutants to be removed from waste gases produced at low temperatures (process gases) are particles (solid particles), VOC and inorganic compounds (HCl, SO_2, NO_x, et cetera).

2.3.1.1 Particulate matter

The usual technique is to separate particles from waste gas streams, either as final treatment or as pre-treatment to protect subsequent installations, while recovering material where possible. The energy and water consumption associated with the treatment technologies should be taken into account. Suitable technologies are

- Pre-treatment technologies with potential recovery:
  - Separator
  - Cyclone
  - Mist filter (also as an aftertreatment filter for aerosols and droplets)
- Final treatment technologies
  - Wet scrubber
  - Electrostatic filter
  - Fabric filter
  - Various high-efficiency filters, depending on the type of solid particles

2.3.1.2 Volatile organic compounds

The usual technique is to remove volatile organic compounds (VOCs) from waste gas streams as products or possibly to destroy them (for example by incineration). The appropriate abatement technology strongly depends on the process causing the emissions and the emission requirement. The general preference from an environmental perspective is as follows:

Choice 1: product recovery technologies. These may involve the product itself, for example gasoline, or an excipient (for example solvent). Suitable technologies include:

- Wet scrubbing (absorption)
- (Cryo)condensation
- Membrane filtration
- Adsorption or
- Combination of them for example condensation / adsorption

Choice 2: Abatement technologies when recovery is not (technically or economically) feasible, with preference being given to energy-efficient technologies such as biological treatment.

Choice 3: thermal or catalytic oxidation, when other equally efficient technologies are not available. Preferably, a technology should be selected with low energy consumption (efficient) and (if technically and economically feasible) the maximum possible recovery of energy. It should also be checked whether there is a suitable purpose for the recovered energy.

2.3.1.3 Inorganic gases and vapours

The usual technique is removing inorganic gases and vapours or to convert chemically. Suitable technologies are:

- Wet scrubbing (absorption/chemisorption with water, acid or alkali solution) for hydrogen halides, Cl_2, SO_2, H_2S, NH_3
- Scrubbing (absorption) with a non-aqueous solvent for CS_2, COS

- Adsorption for CS_2, COS, Hg
- Biological gas treatment for NH_3, H_2S, CS_2
- Combustion for H_2S, CS_2, COS, HCN, CO
- SCR/SNCR for NO_x

Where feasible, recovery technologies are preferred over other emission control techniques, for example:

- Recovery of hydrochloric acid if water is used as the scrubbing liquid in the first scrubbing step, producing a hydrochloric acid solution
- Recovery of NH_3

2.3.2 Sources of high temperature

The usual pollutants to be controlled in waste gases originating from high temperature processes (combustion or process gases) are particles, halogen compounds, carbon monoxide, sulphur oxides, nitrogen oxides and possibly dioxins.

2.3.2.1 Dust (particulate matter)

The usual technique is to separate particulate matter from waste gas streams. Suitable technologies are:

- Electrostatic filter
- Ceramic filter
- After cooling to approximately 120-150 °C: fabric filter or wet scrubber

2.3.2.2 Dioxins

The usual technique is to oxidise or possibly remove dioxins from the waste gas. Suitable technologies are:

- Thermal oxidation
- After cooling: adsorption

2.3.2.3 Inorganic gases and vapours

The usual technique is inorganic gases and vapours is to remove, possibly chemically convert. Suitable technologies are:

- HCl, HF and SO2
  - recovery by wet scrubbing
  - removal by dry, semi-dry or wet injection of absorbent (for example lime)
- NOx
  - SCR
  - SNCR

2.4 Overview of technologies

The first following table gives an insight in the occurrence of common technologies to treat waste gases in the German chemical industry [reference: Table 12 of BVT 2016] and in the EU [reference: section 3.3.2 of BREF WGC (D1, 2019)]. The picture is expected to be similar in the Netherlands and Flanders.

Table 2.1 Share of abatement technologies in the German chemical industry (2016)

Technology	Share (total = 3035)	Mentioned in BREF WGC (D1, 2019), para 3.3.2: (application in the chemical industry)
Gas scrubber	40 %	Absorption is widely used, for example, in the production of organic and inorganic substances, pharmaceuticals, crop protection agents, biocides and explosives.
Fabric filter	26 %	Fabric filters are widely used, for example, in the production of plastics such as polymers, synthetic fibres and cellulose-based fibres and in the production of non-metals, metal oxides or other inorganic compounds. Absolute filters are is widely used, for example, in the production of pharmaceuticals and in the production of non-metals, metal oxides or other inorganic compounds.
Thermal oxidizer (incinerator)	16 %	Thermal oxidation is widely used in the chemical sector, for example in central waste gas treatment as well as in the production of organic substances, plant protection products, biocides and pharmaceuticals. The use was also reported in the production of inorganic compounds such as metal oxides and non-metals.
Condenser	5,0 %	Condensation is widely used, for example, in the production of organic and inorganic substances, as well as plant protection products and biocides.
Activated carbon filter	3,9 %	Adsorption is widely used in the chemical sector, for example in the production of organic and inorganic substances, pharmaceuticals, plant protection products, biocides and explosives, also for odour reduction.
Cyclone	3,6 %	Cyclones are widely used, for example, in the production of polymers and inorganic compounds such as metal oxides and non-metals.
Catalytic oxidizer	2,5 %	Catalytic oxidation is sometimes used, for example, in the production of organic substances, plant protection products, biocides and pharmaceuticals.
SCR	2,3 %	SCR is used in some parts of the chemical industry, for example in the production of non-metals, metal oxides and other inorganic compounds and in the production of nitrogenous hydrocarbons.
SNCR	0,7 %	SNCR is rarely used, for example, in the production of nitrogenous hydrocarbons and inorganic gases.
Adsorption filter other than activated carbon filter	0,8 %	*(Activated carbon is usually used as an adsorbent)*
Electrostatic filter (ESP)	0,2 %	ESP is sometimes used in the production of non-metals, metal oxides or other inorganic compounds.

Table 2.2 provides an overview of all the technologies included in the fact sheets. For each abatement technology, the table indicates which substances can be removed and what the environmental performance is. Where known, the column 'final concentration' shows the median and the 10 and 90 percentile values. These were calculated using Tables 25-76 in BVT 2016. The median and percentile value are statistical concepts where the median (P50) indicates the most common value and is therefore characteristic of the technique. P10 is the value for 10 % of the numbers (final concentration in this case) is lower and thus 90 % is higher.

P10 is therefore a measure of what maximum can be achieved with the technique. P90 indicates the minimum that can be achieved with the technique.

If the technology is not primarily intended for a particular pollutant, but the pollutant is (partly) removed by the technology, this is indicated by a '+' instead of a '♦'.

The operating principles and technologies are elaborated in chapter 4, where also synonyms of the technologies, implementation forms and variations of the technology are considered.

Table 2.2 Technology with components removed and environmental performance (♦ for main effect, + for side effect)

Operating principle	Technology	Removed pollutants								Perfor-mance		
		Dry particles	Wet particles	VOC	SO_2	NO_x	NH_3	Inorganic gases	Odour	Final concentration [mg/Nm^3]	Efficiency [%]	Flow rate [Nm/h]^3
Absorption	Gas scrubber	+	+	♦	♦		♦	♦	♦	NH_3 P10: 0,05 P50: 0,9 P90: 7	30 - 99	50 - 500.000
	Filter with lime injection				♦			♦			10 - 95	10.000 - 1.000.000
Adsorption	Adsorption filter			♦			♦	♦	♦	VOC P10: 1 P50: 10 P90: 465	80 - 99	100 - 1.000.000
Biological treatment	Biofilter			♦			♦		♦		70 - 95	100 - 100.000
	Biotrickling			♦			♦	♦	♦		70 - 99	1.000 - 500.000
	Biological scrubber			♦			♦	♦	♦		70 - 95	
Chemical reduction	SCR					♦		♦			80 - 99	<1.000.000
	SNCR					♦		♦			25 - 80	<200.000
Condensation	Condenser			+			+	+	♦		60 - 90	100 - 100.000
	Cryocondensation			♦			+	+	♦		>99	<5.000
Electric Field	Electrostatic filter	♦	♦							P10: 0,2 P50: 4 P90: 9	97 - >99,9	1.800 - 2.000.000
Filtration	Dust filter	♦								P10: 0,1	99,95	300 - 1.800.000

Operating principle	Technology	Removed pollutants								Perfor-mance		
										P50: 0,4 P90: 4,8		
	Mist filter (droplets)		♦					+	+		<99	<150.000
Gravitation	Settling room	♦										
	Cyclone	♦								P10: 0,2 P50: 4 P90: 8		
Cold oxidation	Ionization			+				+	♦		80 - 99,9	20 - 200.000
Dust scrubbing	Dust scrubber	♦	♦	+	♦		♦	+	+	PM P10: 0,2 P50: 0,9 P90: 8,0	99	720 - 170.000
	Spray scrubber	♦	♦	+				+	+		70 - 99	1.000 - 50.000
	Venturi scrubber	♦	♦	+			♦	+	+		50 - 99	720 - 100.000
Thermal Oxidation	Thermal incinerator	+	+	♦			+		♦	VOC P10: 0,3 P50: 1 P90: 10	98 - 99,9	90 - 86.000
	Catalytic incinerator			♦					♦	VOC P10: 0,3 P50: 1,1 P90: 10,2	80 - 99	90 - 90.000

Table 2.3 provides an overview of all the technologies included in the fact sheets. The table shows the main characteristics of each abatement technology. The table is intended to allow comparison between technologies and does not show all variations within a technique. These variations are discussed in Chapter 4.

The following characteristics of the off-gas were compared qualitatively:

- Input concentration: 'low' indicates that the technique is suitable for treating a waste gas with a concentration of the component to be removed that is higher by a factor of 2 than the general emission limit value; 'high' indicates a concentration that is considerably higher
- Particulate matter in waste gas: 'low' indicates that the technique has limitations on the level of particles in the waste gas to be treated; 'high' indicates that there are no limitations on the particles content of common waste gases
- Waste gas temperature: 'low' indicates that the technique is suitable for treating a waste gas with a temperature of up to approximately 40ºC; 'high' indicates a temperature that is considerably higher
- Variable load: 'low' indicates that the technique is not or less suitable for treating waste gases characterised by rapid changes in flow rate and concentrations; 'high' indicates that the technique can cope better with rapid changes without making any significant loss of efficiency and effectiveness
- Moisture: 'no' indicates that the technique has limitations with regard to the moisture content of the waste gas to be treated; 'yes' indicates that there are no limitations to the moisture content of standard waste gases
- Sensitivity to pollutants: 'yes' indicates that the technique has limitations with regard to the content of certain pollutants in the waste gas to be treated; 'no' indicates no limitations with regard to the content of pollutants in standard waste gases. Pollutants' refers to substances for which the technique is not intended, for example low concentrations of toxic substances

The following characteristics of the technology were compared qualitatively:

- Operation and maintenance: 'low' indicates that the equipment is easy to operate or requires little maintenance; 'high' indicates that the process control of the technology is complex or requires a lot of supervision and/or maintenance; 'medium' indicates a situation that is neither 'low' nor 'high'
- Side effects: the main side effects are indicated, being other forms of emissions to air, wastewater or waste
- Suitable for SVHC: 'yes' indicates that the technology is suitable for achieving low residual concentrations with which the emission limit values of substances of very high concern can be achieved; with 'no' the technology is not suitable for this. Size of the appliance: 'compact' indicates that the appliance can usually be integrated into an existing installation; 'large' indicates that the appliance requires considerable floor space so that it can often not be integrated into an existing situation without incurring significant costs (often higher than those of the appliance itself); 'medium' indicates a size which is neither 'compact' nor 'large'

Table 2.3 Technology with key characteristics

Operating principle	Technology	Waste gas						Other	
		Input concentration	Dust particles in waste gas	Discharge temperature	Alternating load	Moisture in the waste gas	Sensitive to impurities	Operation and maintenance	Side effects
Absorption	Gas scrubber	High Low	Low	Low	High	Yes	No	Medium	Wastewater
Adsorption	Adsorption (physical)	Low	Low	Low	High	No	Yes	Medium	(Waste)
	Adsorption (chemical)	High Low	High Low	High Low	High	Yes	No	High	Waste (or recovery)
Biological treatment	Biofilter	High	Low	Low	Low	Yes	Yes	Medium	Wastewater
	Biotrickling	High	Low	Low	Low	Yes	Yes	High	Wastewater
	Biological scrubber	High	Low	Low	High	Yes	Yes	Medium	Wastewater
Chemical reduction	SCR	High	Low	High	High	Yes	Yes	High	Ammonia, nitrous oxide
	SNCR	High	Low High	High	High	Yes	No	Medium	Ammonia
Condensation	Condenser	High	Low	Low	High	No	No	Low	-
	Cryocondensation	High	Low	Low	High	No	No	Medium	-
Electric Field	Electrostatic filter	High Low	High Low	High Low	High	No	No	High	-
Filtration	Dust filter	Low	Low	High Low	High	No	No	Medium	-
	Mist filter (droplets)	High	Low	Low	High	No	No	Low	-
Gravitation	Settling room	High	High	High Low	High	Yes	No	Low	-
	Cyclone	High	High	High Low	Low	Yes	No	Low	-
Cold oxidation	Ionization	Low	Low	Low High	High	Yes	No	Medium	(Ozone)
Dust scrubbing	Dust scrubber	High Low	High Low	Low	High	Yes	No	Medium	Wastewater
	Spray scrubber	High Low	High Low	Low	High	Yes	No	Medium	Wastewater
	Venturi scrubber	High Low	High Low	Low	Low	Yes	No	Medium	Wastewater
Thermal Oxidation	Thermal incinerator	High	Low	Low	Low	Yes	No	Medium	CO_2, NOx, (SO_2, dioxin)

Operating principle	Technology	Waste gas						Other	
		Low							
	Catalytic incinerator	High Low	Low	Low	Low	Yes	Yes	Medium	CO_2, NOx, (SO_2)

3 Structure of the fact sheets

The structure of the fact sheets is uniform for all technologies, with the designation of air pollutants and units being kept the same wherever possible. This uniform structure allows the user to compare different technologies and make an assessment.

3.1 Operating principle/ technology name

In the title, first the operating principle is named. Then the name of the specific technology is given.

Next, the different variations of the technology of a technology are named, along with the common synonyms for these variations of the technology.

Finally, the substances that can be removed or reduced by the technology are mentioned.

3.2 Brief description

The description of the technology is given here in outline form. The principle on which the capture of the components is based, is clarified by means of a principle diagram.

3.3 Applicability

This heading describes the applications for which a technology is used in practice. This includes a description of:

- The substances that can be captured with the technology in question and variation of the technology that are used for this purpose
- The business sectors in which the technologies are frequently applied. The list is not always exhaustive and application of the technique in other sectors than mentioned is possible
- Usual combinations of different technologies
- Performance and preconditions. In table form, an indicative description is provided of the usual performances of a technology and the boundary conditions within which these performances are achieved. These are not hard limits; they are data derived from practical use. In a specific situation a different performance level is possible

The data provided was obtained under various conditions, at various companies and processes. Therefore the values provided should be considered as indicative and all parameters are given as ranges. The best performance can be expected for processes where the conditions are optimal, the upper bandwidth is intended for processes where treatment is technically more difficult. The measured values are half hour averages, unless stated otherwise.

Where known, the median and the 10 and 90 percentile values are given. These were calculated using tables 25-76 in BVT 2016. The median and percentile value are statistical concepts where the median (P50) indicates the most common value and is therefore characteristic of the technology.

P10 is the value for 10 % of the numbers (final concentration in this case) is lower and thus 90 % is higher. P10 is therefore a measure of what maximum can be achieved with the technology. P90 indicates the minimum that can be achieved with the technology.

3.4 Detailed description

In practice, various technologies have many different implementation variations of the technology. These cases are mentioned in the fact sheet as a variation of the technology and are not included in a separate fact sheet. In the detailed description, further explanation is given of the operation of the various implementation variations of the technology of a technology, and in particular the specific properties of the variation of the technology in question.

Qualitative criteria for installation, design and maintenance are described under this heading so that it is clear within what limits a technique can be used. Monitoring is also discussed in the detailed description.

3.5 Environmental aspects

The installation of an end-of-pipe technology may be the result of a strategy to limit emissions of pollutants into the air. In this decision-making process, several (environmental) considerations must be made. The benefit to air quality of emission reduction must be weighed against the drawbacks for other environmental aspects and operational management.

Under this heading, specific advantages and disadvantages are mentioned that are linked to the use of a technology. The '*cross-media* effects' are also discussed. These include the use of raw materials, water consumption, electricity, CO_2 and/or NO_x emissions and waste production. The aim is to provide an overview of the possibilities; not all of these effects need to occur in a specific situation.

3.6 Financial aspects

The ranges mentioned give an indication of the costs. The following topics are covered:

- Investments (in the case of new buildings; no retrofit)
- Operational costs (personnel, energy/electricity, water, steam, compressed air, auxiliary materials, insurance, waste disposal costs). In the fact sheets all operational costs are summarized under the heading ‘operational costs’. In some cases more detailed information is available for the costs of staff, materials or energy. These costs are part of the operational costs and should not be added to them when the cost figures are used as key figures for cost effectiveness analysis
- Material in so far as auxiliary materials is consumed or materials in a unit have to be replaced regularly
- Benefits if recovered product can be put to good use or energy is saved
- Cost-determining parameters
- Energy consumption of for example electricity and natural gas

3.7 Information source

Listed here are the main reference documents, suppliers and the competent authority used to review the existing information. Three primary sources are used in this study:

- The previous version of this guide (2009)
- New literature published after 2009, such as BREF WGC D1 2019
- Surveys and interviews with suppliers of end-of-pipe technologies

4 Fact sheets

4.1 Absorption: scrubber

Absorption: scrubber

Variations of the technology and synonyms

Gas scrubber, *scrubber, absorber, air scrubber*
Acid *scrubber*
Alkaline scrubber, *alkaline scrubber*
Alkaline-oxidizing gas scrubber, *alkaline-oxidizing gas scrubber*, *alkaline-oxidizing gas scrubber*

Removed pollutants

Mainly: Ammonia, Odour, H_2S, HCl and HF, SO_2, VOC
To a lesser extent: particles and droplets, NOx

1. Brief description

1.1 Description

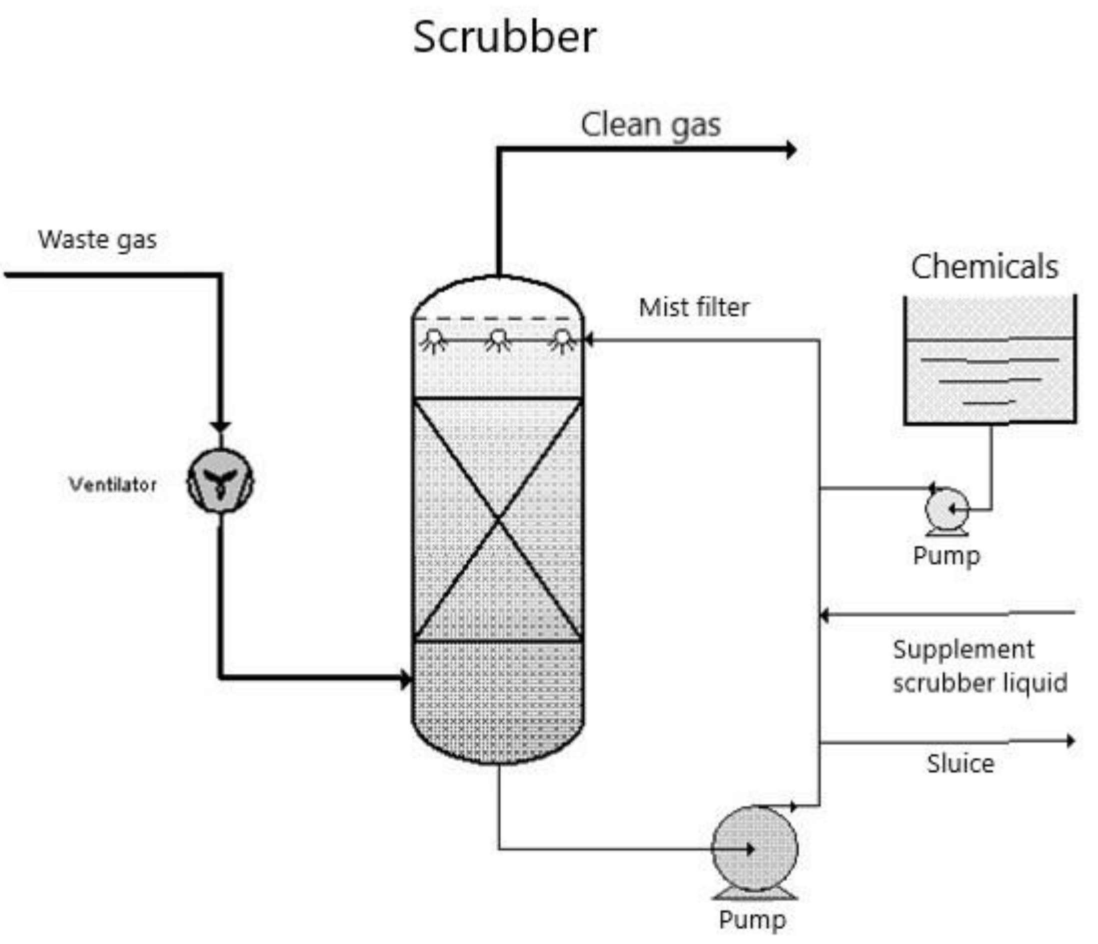
The operating principle of a gas scrubber is based on the dissolution of a gas or vapour in a liquid (absorption). The gas is intensively brought in contact with the scrubber liquid, often water (or aqueous solution).
Basically, a gas scrubber consists of three parts: an absorption section with scrubber liquid, a drip collector and a recirculation tank. The treatment efficiency of gas scrubbers is a combination of especially the residence time of the gas in the absorption section, the type of packing, the gas-liquid ratio (L/G), the exchange rate, the water temperature and the addition of chemicals (see acid and alkaline/basic gas scrubbers).

Absorption should not be confused with adsorption, in which molecules, atoms or ions of the substance to be removed attach themselves to the surface of a solid.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Absorption: scrubber



2. Applicability

2.1 Scope

(general)

Gas scrubbing is the most commonly used abatement technology in the chemical industry. Gas scrubbers are applied for water soluble substances like alcohols and acetone. There are also systems with organic scrubber liquids to scrub organic gasses. By adding chemicals to the scrubber liquid, like acids or bases, the effectiveness of a gas scrubber can be tuned to the chemical properties of a specific substance group. Recovery of raw materials is possible with this technique, but requires an additional separation technology. The technology can also be used for odour control.

(sectors)

Wide range of applications in the following sectors, among others:

- Waste incinerators
- Chemical Industry

Absorption: scrubber

- Pharmaceutical industry
- Storage and transhipment of chemicals
- Surface treatment
- Primary aluminium industry
- Livestock

Variation of the technology in which acids are added to the scrubbing liquid in order to capture alkaline gases from the waste gas are mainly applied in the sectors:

- Intensive livestock farming/Fertilizer processing (ammonia)
- Composting (ammonia)
- Waste treatment plants (ammonia, amines)
- Fertilizer production (ammonia)
- Pharmaceutical industry (esters)
- Chemical industry (esters)
- Foundries (amines)
- Production of fish feed (amines)

Variation of the technology in which bases are added to the scrubbing liquid in order to capture acidic gases from the waste gas are mainly applied in the sectors:

- Chemical Industry
- Galvanic industry
- Storage and transhipment of chemicals
- Waste incinerators
- Sludge treatment plants, sewage pumping stations, sewage treatment plants

The alkaline-oxidative scrubber is mainly applied for odour control in the sectors:

- Food industry
- Compound feed manufacturers
- Slaughterhouses
- Fragrance industry
- Textile industry
- Storage and transhipment of liquids

(SVHC)

The residual concentration from gas scrubbers is strongly dependent on the application and the substance to be removed. In most cases, it is possible to meet the emission requirements for specific pollutants with a gas scrubber. It may be possible to achieve lower residual concentrations that are complying with strict SVHC requirements. However, often a second end-of-pipe technology is needed after the gas scrubber in order to reduce SVHC emissions sufficiently.

Absorption: scrubber

2.2 Combination of technologies

Gas scrubbers can be part of complex combinations of technologies. On the one hand, these can be combinations with different variations of the technology of gas scrubbers, for example an acid and an alkaline scrubber connected one after the other to obtain both effects (two-stage scrubber). On the other hand, a gas scrubber can be part of a broader selection of technologies, whereby the gas scrubber is aimed at the removal of gasses. Other technologies are then added for the capture of dust particles. To reach low (<1 mg/Nm^3) output concentrations, a gas scrubber is usually not sufficient and a second end-of-pipe technology might be necessary.

2.3 Environmental performance

The environmental performance is shown in the following table. The values presented depend on the specific configuration and operating conditions. In principle, the values are based on half-hourly average values. In certain situations, deviating values may be justified.

The data is taken from the BREF CWW (2016), BVT 2016 and BREF WGC D1 (2019). NI stands for 'no information' and means that there are no sources from which a general value for that situation can be derived. NA stands for 'not applicable' and has been used for odour. No emission limits have been set for odours because acceptability is tested based on the odour concentration at sensitive receptors.

Pollutant	**Disposal efficiency, %**	**Concentration after treatment, mg/Nm^3**	**Scrubbing liquid**
Alcohols	30 - 99	<20 - 40	Water
Amines	>99	<1	Acid
Ammonia	>99	< 1-3 P10: 0,05 P50: 0,9 P90: 7	Acid
Chlorine	NI	P10: 0,05 P50: 0,4 P90: 2	NI
Chromic acid	99	<10	Water
Esters	80	<20 - 40	Acid
Ethylene oxide	99	P10: 0,02 P50: 0,07 P90: 1	Acid
Halogenated hydrocarbons (not SVHC)	NI	P10: 0,1 P50: 1 P90: 15	NI
Phenols	90	<20 - 40	Alkaline
formaldehyde	NI	P10: 0,04 P50: 0,2 P90: 12	Water
Odour	60 - 85	N/A	Water
Odour	80 - 90	N/A	Alkaline-oxidizing
HCl	99	<10	Alkaline + Water

Absorption: scrubber

		P10: 0,1 P50: 0,8 P90: 5	
HF	>99	< 10 P10: 0,015 P50: 0,1 P90: 0,5	Alkaline + water
Methanol	NI	P10: 0,4 P50: 2 P90: 150	Water
NOx	NI	< 100 P10: 1 P50: 6 P90: 66	Alkaline
H_2S	90 - 95	<15	Alkaline
SO_2	95 - 98	<10	Water
SO_2	>85 - 99	<10 P10: 0,1 P50: 1,5 P90: 20	Alkaline
VOC	50 - 99	<20 - 40	Water (if water-soluble VOC)

2.4 Preconditions

Flow rate [Nm^3/h]:

P10: 30

P50: 2.000

P90: 30.000

Temperature [°C]:

5 - 80

Pressure [bar]:

Atmospheric

Pressure drop [mbar]:

4 - 8

Moisture content:

No restrictions

Dust [g/Nm^3]:

<10; low particulate concentrations are desirable for proper operation. Scrubbers designed for particulate removal have been considered as a separate technique.

Input concentration [mg/Nm^3]:

Absorption: scrubber

200 - 5,000 (alcohols)

200 - 1,000 (ammonia)

10 - 1,000 (amines)

>100 (esters)

50 - 20,000 (HCl)

50 - 1.000 (HF)

<5.000 (phenols)

100 - 10.000 (SO_2)

1,500 - 15,000 (H_2S)

3. Detailed description

3.1 Variations of the technology

Gas scrubber without chemicals

The technique is mainly used for substances that are highly water soluble, such as alcohols and acetone. There are also systems with organic scrubber liquid . Many variations of the technology can be designed, all using the same basic principles. The variations of the flow direction of the gasses through the liquid are cocurrent, crosscurrent and countercurrent. The way the gas comes in contact with the scrubber liquid may vary, such as scrubbers with trays, packing material, and scrubbers without packing material built-in, such as venturi and jet scrubbers and spray towers.

Acid scrubber

An acid scrubber works at a low acidity level so that alkaline substances are captured better. Salts are formed in the process. Based on density and/or conductivity, part of the scrubber liquid is discharged. The discharge water can contain up to 15 % salts and is either discharged after treatment or evaporated for re-use. The acid dosage is done by means of a pH control. In most cases, the acidity is controlled between pH 3 and 6. For economic reasons, sulphuric acid (H_2SO_4) is usually used as the acid. For specific applications, such as the capture of NH_3, nitric acid (HNO_3) is also used. Ammonium nitrate is formed, which can be used as fertilizer. Due to their basic character, amines and esters can also be captured in an acid scrubber.

Alkaline scrubber / basic scrubber

In an alkaline scrubber, acidic substances are better removed by neutralisation with a base (lye) as scrubbing liquid. During this process, salts are formed which can be reprocessed if required.

The dosing of base is based on a pH control or a direct measurement in the outgoing air stream, for example an H_2S measurement. Usually, the pH of an alkaline scrubber is controlled between 8.5 and 9.5. One cannot make the acidity too high, in connection with absorption of CO_2 in the water. From a pH higher than 10, the dissolved CO_2 will be present in the water as carbonate, causing the consumption of lye to increase strongly. The calcium carbonate will also precipitate on the packing which will increase the pressure drop. To avoid this, it is also recommended to use softened water in an alkaline scrubber.

Absorption: scrubber

Alkaline-oxidizing scrubber

Alkaline-oxidizing gas scrubbing is mainly used for odour control. The organic odour components are oxidized in an alkaline environment at pH 7 - 10. Sodium hypochlorite (NaOCl), potassium permanganate ($KMnO_4$) or hydrogen peroxide (H_2O_2) are used as strong oxidizers. In the case of potassium permanganate, manganese oxide (MnO_2) is formed which must be periodically removed from the scrubber liquid. With hypochlorite, chlorides are formed and with hydrogen peroxide no by-products are formed. Hydrogen peroxide is a weaker oxidant than hypochlorite or potassium permanganate. Especially for odour removal, as this can be complex in terms of the composition of the odour components, it is recommended to first perform tests on a smaller scale to specifically determine the removal efficiency. If amines are present in the waste gases, it is recommended to first carry out acid scrubbing to prevent the formation of chloramines.

When using NaOCl at low pH toxic chlorine vapours can be generated. Therefore, when using NaOCl it is best to install an alkaline scrubber afterwards in order to capture the chlorine vapours.

3.2 Installation, design and maintenance

An optimal design of a low emission gas scrubber requires high reliability, full automation and a good maintenance regime. The capacity of the scrubber is in the order of 1-2 m^3 per 1,000 Nm^3/hour. The main design parameters are:

- Exhaust gas flow
- Operating temperature and maximum temperature
- Gasket composition
- Turndown ratio: a gas scrubber operates on the basis of contact time and is designed for this purpose (ratio between flow rate of vapour and flow rate of circulating fluid). If this ratio (due to an instantaneous decrease or increase of the vapour flow rate, the circulating liquid flow rate is generally fixed) changes, this can have a major influence on the removal efficiency

(monitoring)

In order to measure the efficiency of the scrubber, it is necessary to measure the incoming and outgoing gas concentration. Depending on the component, this can be determined with UV or IR light, or wet-chemically. Routine measurements should include the pressure drop, ‘make-up’ water flow, recycle flow, reagent flow and in some cases the pH, temperature and conductivity of the outgoing water flow.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Wide application range
- Suitable for low residual concentrations required for SVHC.
- Compact installation in relation to the processed gas flow rate
- Possibility of material recovery
- Treats flammable and/or explosive gases in a relatively safe way

4.2 Disadvantages

The main disadvantages are:

Absorption: scrubber

- Wastewater stream must be treated
- Consumption of water and reagents
- Sensitive to frost and corrosion

4.3 Resources and energy

Water:

Consumption of water depends on the temperature and humidity of the incoming gas stream, and also on the frequency with which the scrubber liquid is refreshed. The outgoing gas stream is usually completely saturated with water vapour. If the concentration of the to-be-removed substance in the scrubber liquid increases, the removal efficiency decreases. To achieve the minimum required efficiency, sufficient purging and refreshing is required.

Chemicals:

Acids, bases, oxidizing agents, depending on the chosen application.

Energy consumption:

Electricity to drive a pump and possibly a fan.

4.4 Environmental considerations

Recovery:

Recovery of product is possible in a number of cases. In some cases, the saturated scrubber liquid can be used as such, for example ammonia water. In certain cases, the drained liquid (bleed-off) can be evaporated and reprocessed for recovery of products such as salts. An important application is gypsum in the case of SO_2 removal. Dissolved gases can be 'stripped' from the saturated solution to create a concentrated waste gas stream, that in turn can be treated. An important application is the capture of hydrogen sulphide (H_2S) from the gas stream after the desulphurisation step of petroleum products. The concentrated waste gas flow containing H_2S can then be treated in a sulphur recovery plant, where elemental sulphur and water are created.

Air:

No other forms of air pollution are created. A cooled gas stream will, however, exhibit less plume rise, which is detrimental to the dispersion of emissions in the outside air (especially important for odour control and the associated effects at sensitive receptors).

Wastewater:

This creates a waste (water) stream that will have to be treated before it can be discharged. The spray stream from acid and alkaline scrubbers will often need to be neutralized before it can be treated.

Waste:

Waste occurs when precipitation is formed in the scrubber liquid and cannot be put to good use. This may be due to chemicals that are deliberately added to increase efficiency or to neutralise the saturated scrubber liquid.

Absorption: scrubber

Safety:

Use of strong oxidizers requires the necessary safety devices and special execution of the installation. In a scrubber with chlorine bleach lye (NaOCl), toxic chlorine vapours may be produced at low pH. On the other hand, flammable and/or explosive gases can be treated in a relatively safe manner.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

7,500 - 25,000 for standard versions.
10,000 - 50,000 for acidic, basic or basic-oxidative scrubber

Operational costs [EUR / 1.000 Nm^3 / hour /year]:

1.000 - 30.000

Staff [hours/week]:

4

Material:

The choice of material depends on the application. If oxidising or acid scrubbing liquids are used, plastic is the most important construction material. Gasket material normally lasts many years.

Energy consumption [kWh/1,000 Nm^3]:

0,2 - 1 (excluding energy consumption for processing the spray stream (wastewater or otherwise))

Benefits:

Cost savings on raw material if recycling is possible or market value of the saturated solution (for example ammonia water), formed salts such as ammonium nitrate or recovered product (for example sulphur).

Cost determining parameters:

Flow rate, wastewater treatment

6. Information source

1. Handreiking luchtemissiebeperkende technieken ['Guide to Air Pollution Control Technologies’]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. BVT 2016
5. VITO LUSS: alkaline/basic oxidative/acid scrubber
6. Supplier Clean All Air Industrial Air Scrubbing Systems

4.2 Absorption: filter with lime injection

Absorption: filter with lime injection

Variations of the technology and synonyms

Lime injection (dry, semi-dry/semi-dry, semi-wet, wet), *spray adsorption, cascade adsorption, chemical adsorption, wet lime scrubbing, limestone gypsum process, in-situ forced oxidation process (IFO)*

Removed pollutants

Mainly: HCl, HF, SO_2

1. Brief description

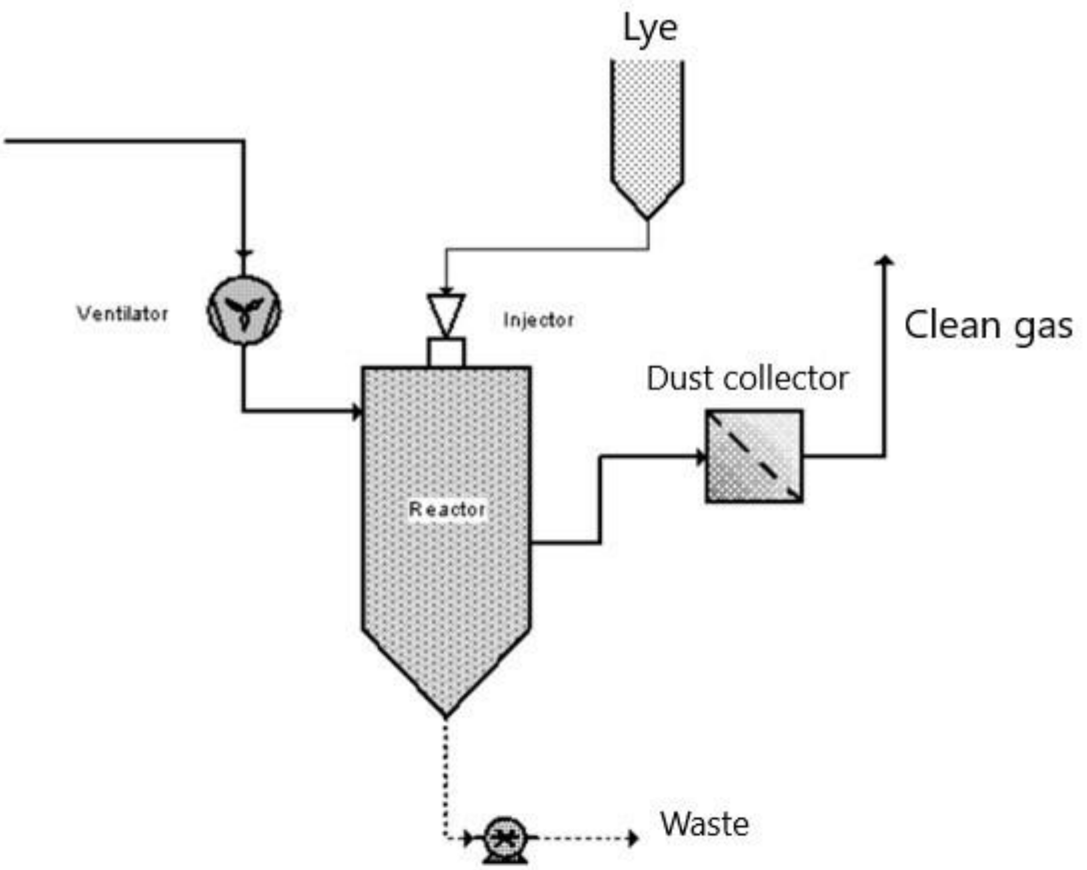
1.1 Description

The operating principle of a filter with lime injection is based on the chemical binding of substances in the waste gas. To this end, lime-containing powder or liquid is introduced into the waste gas. The lime binds acidic gaseous pollutants in solid compounds which can then be separated. In the case of SO_2, gypsum is produced, which can be used as a building material.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Absorption: filter with lime injection



2. Applicability

2.1 Scope

(general)

Lime injection is used to remove acidic gases, usually SO_x, HCl and HF from a waste gas stream.

(sectors)

Lime injection is mainly used in large combustion plants with liquid or solid fuels in the following sectors, among others:

- Glass industry
- Waste incinerators
- Ceramic industry
- Chemical Industry
- Power plants
- Aluminium smelters

Absorption: filter with lime injection

(SVHC)

The technique is aimed at capturing inorganic, acid gases, which are not SVHC. The residual concentration after dry lime injection is not low enough to meet the emission requirements for SVHC.

2.2 Combination of technologies

Lime injection is always applied in combination with a filter technique, a fabric filter or ESP. The unreacted powder forms a layer on the filter cloth with which the acid gases can react. This increases the removal efficiency.

Because lime injection usually takes place in hot waste gases (>140ºC), it is possible to install an SCR after the technique, without or with limited heating of the waste gas stream. This can be a reason to choose lime injection for SO_2 capture over the potentially higher efficiency of a scrubber.

Lime injection can also be combined with adsorption, by also injecting activated carbon. The activated carbon can capture heavy metals, dioxins and furans. Sorbalit is a brand name for a mixture of lime and activated carbon.

2.3 Environmental performance

The environmental performance is shown in the following table. The values presented depend on the specific configuration and operating conditions. In principle, the values are based on half-hourly average values. In certain situations, deviating values may be justified. The data is taken from the BREF CWW (2016), which in turn refers to the 2009 Fact Sheets, BVT 2016 and BREF WGC D1 (2019).

Pollutant	Dry Injection		Technology
	Disposal efficiency [%]	Concentration after treatment [mg/Nm^3]	
SO_X	10 - 70	<40	Dry lime injection
SOx	85 - 90	<40	Semi-dry injection
SOx	90 - 97	<40	Wet injection
SOx	90 - 95	<5	Dry injection with sodium bicarbonate
SO_2	75 - 98		Dry Injection
HCl	75 - 98	<2 - 10	Dry Injection
HCl	>90	<10	Semi-dry and wet injection
HF	75 - 98	<1	Dry Injection
HF	>85	<1	Semi-dry injection
Mercury	>95	<0,05	Dry injection with lime and activated carbon

Absorption: filter with lime injection

2.4 Preconditions

Flow rate [Nm^3/h]:

10,000 - 300,000 (dry injection)

<1,000,000 (semi-dry injection)

50 - 500,000 (wet injection)

Temperature [°C]:

The operating temperature strongly depends on the technique used and the adsorption material. Usually, the operating temperature lies between 140 - 400ºC.

Pressure [bar]:

Atmospheric

Pressure drop [mbar]:

25

Moisture content:

No restrictions

Dust content [g/Nm^3]:

No restrictions

Input concentration [mg/Nm^3]:

<10.000 (SO_x)

3. Detailed description

3.1 Variations of the technology

Dry Injection

In dry injection, a fine powder is sprayed in the waste gas. The reaction between the dry lime or limestone and the acidic components in the waste gas stream takes place in a reactor and partly in the downstream particulate separator, after the impurities in the lime have been absorbed. The reactor is necessary to ensure a sufficiently long reaction time, of a few seconds. The reaction occurs between the chemicals and the impurities in the waste gas stream. The injection of lime is sometimes carried out in the reactor. However, it is also possible to inject lime into the waste gas stream before it reaches the reactor.

When using a fabric filter for the removal of the reaction product, there is better contact between the lime and the gaseous pollutant than with an ESP filter. When dimensioning the reactor and also when determining the necessary excess of chemicals, the choice of the abatement technique for the removal of the particles is therefore very

Absorption: filter with lime injection

important. The reaction takes place after the absorption of the gaseous pollutant on the lime. Due to the small contact surface area, the necessary excess of chemicals is greater than with semi-dry scrubbing methods. Simultaneously with the separation of the dry reaction products and the excess chemicals, the particles contamination can also be separated. The chemicals used are partially recirculated with the separated pollutant. However, the chemical consumption and the amount of captured particles with dry scrubbing is considerably higher than with semi-dry scrubbing.

Further process control is possible via the temperature, particle size of the powder, molar ratio of sulphur to carbonate, turbulence in the reactor and the choice of adsorbent material. Different substances can be used for the adsorption material, but the most commonly used are lime (calcium carbonate) and sodium bicarbonate.

Dry cascade or bed reactor

In this process, lime is not sprayed in the but the flue gas is led through a bed of lime pellets. The pellets with the bound pollutants sink under the influence of gravity. The flue gases are led through the bed in countercurrent flow or crosscurrent flow. In order to make the reaction time and contact surface sufficiently large, obstacles are provided in these areas which slow down the falling speed of the granules and ensure efficient circulation and distribution of the flue gases in the reactor. The reacted calcium carbonate is collected at the bottom of the installation.

Because acid gases such as SO_2, HCl and HF mainly react on the outside of the calcium carbonate pellets, the adsorption efficiency of the pellets is fairly low. A peeling technique can be used to increase this efficiency. The softer outer layer consisting of calcium fluoride, calcium sulphite, calcium sulphate and calcium chloride is removed mechanically. The remaining pellet can then be added back to the top of the bed, as long as the size is sufficient.

Semi-dry injection

In semi-dry injection, the adsorbent material is atomized in droplet form as a suspension or solution. The moisture in the droplets evaporates during the reaction, the product is a dry solid powder. The efficiency of a semi-dry system is often higher than that of a dry system, because the contact surface between the waste gases and the powder particles is higher, so that the reaction can take place more efficiently.

Wet injection

Wet lime injection combines the advantages of gas scrubbers and (semi) dry lime injection. This waste gas treatment technology is mainly used for the desulphurization of waste gases while other acid forming components are also bound.

A slurry of limestone ($CaCO_3$) or slaked lime ($Ca(OH)_2$) is atomized in a spray column. In the presence of SO_2, calcium sulphite ($CaSO_3$) is mainly formed, after which it is further oxidised with the oxygen in the air to calcium sulphate in the form of gypsum ($CaSO_4.2H_2O$) (in-situ forced oxidation process - IFO). The gypsum is then dewatered. After desulphurisation, the cleaned waste gas passes a mist filter to capture the droplets.

The contact between the adsorbent and the acid gases is better than in the dry variations of the technology, allowing for higher removal efficiencies. Heating of the off-gases may be required to ensure that the temperature remains above the dew point.

Absorption: filter with lime injection

3.2 Installation, design and maintenance

Basic elements in the design include:

- A reactor space, that can be a pipe, a reactor vessel, or a tower
- Injection system for the powder/suspension, plus underlying storage of adsorbent material
- A particle filter (unless wet injection is used, in which case a droplet trap is required)

Regular inspection of the piping and moving parts is necessary to prevent clogging.

(monitoring)

Monitoring of the system is possible by measuring the concentration of acid gases in the cleaned gas. Adequate monitoring of the fabric filter is also necessary, see the relevant fact sheet.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Easy installation and operation
- No wastewater (except wet injection)
- Possibility to switch on an SCR without heating the waste gases.
- Possibility to use gypsum as raw material

4.2 Disadvantages

The main disadvantages are:

- Large installation (fabric filter)
- Relatively low efficiency, especially compared to a gas scrubber
- Water consumption (wet injection)
- Wastewater production (wet injection)
- Energy consumption for heating the waste gases (wet injection)

4.3 Resources and energy

Water:

Dry injection has no water consumption. Semi-dry injection 30-40 [litres / 1,000 Nm^3], wet injection 8,000 - 20,000 [litres / 1,000 Nm^3].

Chemicals:

Calcium carbonate, sodium bicarbonate or alternatives. The molar ratio Ca/S is about 3 for dry injection, 1.5 - 3 for semi-dry injection and 1.1 for wet injection.

Energy consumption:

Electricity for driving a fan, dosing system, possibly a pump and beating the cloth and the like.

Absorption: filter with lime injection

4.4 Environmental considerations

Recovery:

Product recovery is possible in a number of cases by processing the residue. When sodium bicarbonate is used, NaCl (salt) and sodium sulphate can be recovered. Wet lime injection produces gypsum, which may be of high purity and can be sold as a building material. The possibility of recovery depends on the presence of other substances such as heavy metals and/or dioxins/furans.

In contrast to the production of gypsum as a raw material for the construction industry, lime must be extracted and carbon dioxide is produced when lime reacts with acids.

Air:

A positive effect is that nitrogen oxides are also partially bound. The efficiency (in the order of 35-50%) depends on the SO_2/NOx ratio. The optimum performance lies at an operating temperature of 120 to 160ºC. No other forms of air pollution are created. Wet injection may give a visible plume if the saturated vapor is not hot enough.

Wastewater:

Wet injection results in a wastewater stream that must be treated.

Waste:

The spent lime (residue) must be disposed of and processed if it cannot be put to good use.

Safety:

No special safety measures are required.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour].

10,000 - 30,000 for dry injection
10,000 - 35,000 for semi-dry or wet injection
Numbers are exclusive of the fabric filter

Operational costs [EUR/year]:

Dry injection: 2,500 + 300 x (flow rate/1,000) + adsorbent
Semi-dry injection: 20,000 + 400 x (flow rate/1,000) + adsorption material
Wet Injection: N.B.

Staffing [hours/week]:

2 - 8 hours per week

Material:

Lime: EUR 100 - 250 per tonne.

Absorption: filter with lime injection

Energy [kWh / 1,000 Nm^3]:

1

Benefits:

None, unless material can be recovered and sold, such as gypsum.

Cost determining parameters:

Flow rate, pressure drop, concentration of pollutant, downstream filtration system.

6. Information source

1. Handreiking luchtemissiebeperkende technieken ['Guide to Air Pollution Control Technologies']; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. BVT 2016
5. VITO LUSS: dry/semi-dry/wet lime sorption

4.3 Adsorption: adsorption filter

Adsorption: adsorption filter

Variations of the technology and synonyms

Adsorption filter, *activated carbon filter, zeolite filter, polymer filter*

Removed pollutants

Especially: dioxins/furans, odour, mercury vapour, VOCs

To a lesser extent: halogenated hydrocarbons, H_2S, HCl and HF, SO_2

The principle of adsorption is based on the adhesion of substances in a waste gas to the surface of a solid (adsorbent). In principle, adsorption is a physical bonding based on Van der Waals forces and not on a chemical bond. In order to obtain a stronger bond with the substance to be removed, the adsorbent can be treated with chemicals so that a chemical bond is also possible. Adsorption should not be confused with absorption, where molecules, atoms or ions of the to-be-removed substance dissolve in the scrubber liquid.

Adsorption is a reversible process, i.e. the substance to be removed can either adhere to the surface of the adsorbent or be released from it. Adsorption is an exothermic process and therefore heat is released during adhesion, whilst desorption requires energy. The balance between the concentration on the surface adsorbed substance and the concentration of the substance in the gas or liquid depends among others on temperature and pressure. When the equilibrium is reached, the adsorbent is saturated. The adsorbent is no longer effective, but it is likely to become a source of emissions.

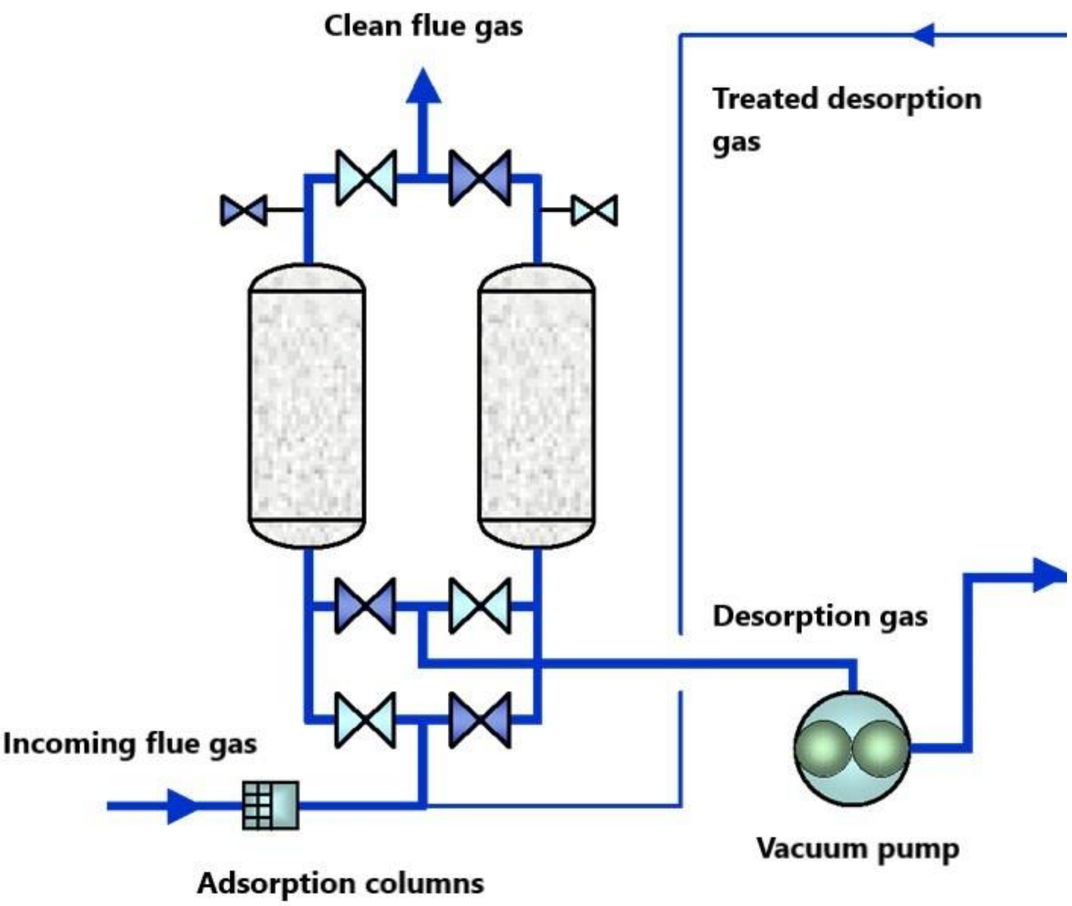
The saturated adsorbent can be destroyed or regenerated (desorption). During regeneration, the removed pollutants are released in a higher concentration and can therefore be recovered or destroyed. Desorption takes place by flushing with a gas, whether or not preheated or under vacuum.

There are different types of adsorbents, of which activated carbon is by far the most common. The systems are built in different versions. A distinction can be made between systems in which continuous regeneration of the adsorbents is integrated and systems in which regeneration/destruction takes place separately from the adsorption process.

1.2 Process flow diagram

The following is the principle scheme of adsorption with vacuum regeneration.

Adsorption: adsorption filter



2. Applicability

2.1 Scope

(general)
Adsorption filters have a wide application across the industrial sector in the capture of gaseous, usually organic, substances. In general, three primary applications can be distinguished:

- Recovering substances (raw material, solvent, product, etc.) from a waste gas stream
- Capturing hazardous substances that should not be recirculated but should instead be incinerated, such as dioxins
- As a '*police filter*', switched as a last treatment step in case one of the previous treatment steps fails

(SVHC)

Adsorption: adsorption filter

Adsorption filters may be suitable for capturing gaseous SVHC. Adsorption filters are effective at the low concentrations in which SVHC usually occur in a gas stream. It is also possible to meet the emission limit values that apply to SVHC. An additional advantage of adsorption filters is that the adsorption material can be incinerated as hazardous waste, which means that all pollutants are effectively removed.

2.2 Combination of technologies

An adsorption filter can be placed as a single technique, but can also be combined with a wide range of other technologies. Adsorption filters are often used as a second treatment step of a gas flow following another technique that has already removed the largest pollution load. The adsorption filter then serves to bring the emission concentration below the emission limit value.
If adsorption is used for recovery, a different technique is needed to treat the desorption gas. For example, the treatment of the captured pollution in the desorption may consist of condensation or absorption. If recovery is not possible, the treatment will often consist of combustion, of the desorption gas or of the saturated activated carbon.

2.3 Performance

The performance is shown in the following table. The values presented depend on the specific configuration and operating conditions. In principle, the values are based on half-hourly average values. In certain situations, deviating values may be justified.

The data is taken from the BREF CWW (2016), which in turn refers to the 2009 Fact Sheets, BVT 2016 and BREF WGC D1 (2019). NA stands for 'not applicable' and has been used for odour. No emission limit values have been set for odour as acceptability is assessed based on odour concentration at sensitive receptors.

For residual emissions, it should be noted that there is a clear difference between single use where lower residual concentrations are achievable and use with regeneration where this is not possible.

Pollutant	**Removal efficiency, %**	**Concentration after treatment, mg/Nm^3**	**Remarks**
VOC	90 - 99	P10: 1 P50: 10 P90: 465	Activated carbon, zeolites
	95 - 98	25 - 1.000	Polymer
Formaldehyde	NI	1 mg/Nm^3	Polymer
Dioxins / furans	>98	< 0,1 ng/Nm^{3}TEQ	Activated carbon
Odour	80 - 95	NA	Activated carbon
	80 - 95	NA	Zeolites
Mercury	>98	<0,05	Activated carbon
Hydrogen sulphide	95-99	1-10	Activated carbon

Adsorption: adsorption filter

2.4 Preconditions

Flow rate [Nm^3/h]:

P10: 20

P50: 1.000

P90: 35.000

Temperature [°C]:

5 - 80 (activated carbon);

< 250 (zeolites)

Pressure [bar]:

0.1 - 2 (activated carbon); atmospheric (zeolites); higher pressures for PSA

Pressure drop [mbar]:

5 - 20

Moisture content:

Humidity level lower than 70 %, in any case condensation must be avoided

Dust content:

Lower than 3-5 mg/Nm^3

Input concentration [mg/Nm^3]:

VOC: 30 - 5,000 (maximum 25 % of lower explosion limit except for regeneration with vacuum where this limit does not apply).

Dioxins (ng/Nm^3 TEQ): 10 - 100

Odour (ou_E /m^3): 5.000 - 100.000

Mercury: 1 - 10

H_2 S: 1,500 mg/Nm^3

3. Detailed description

3.1 Variations of the technology

Fixed bed

Adsorption: adsorption filter

A fixed bed adsorption filter is the simplest version of an adsorption filter and consists of a bed filled with adsorbent material through which waste gases are passed. The fixed bed can consist of pre-packed 1) cartridges or cassettes for low load systems or 2) of a column in which the adsorption material is filled for high load systems.

If the adsorbent material is saturated, it can be regenerated or destroyed. Regeneration can take place as a next step in the installation or externally by a specialised company. The disposal is usually carried out by specialised companies. Fixed-bed filters are often implemented with two or three adsorption beds which can be used interchangeably : while bed 1 is being regenerated, bed 2 can be operational and vice versa.

Pressure swing adsorption (PSA)

A pressure swing adsorption filter (PSA) consists of two or more adsorption filters connected in parallel with a fixed bed (usually activated carbon) to allow a continuous process of adsorption and desorption. Adsorption takes place at high pressure and desorption at low pressure, or in the case of vacuum regeneration, adsorption at almost atmospheric pressure and desorption under vacuum. The process consists of four steps: 1) pressure is built up by the waste gas flowing into the adsorption filter; 2) adsorption of air pollutants at high operating pressure or minimum overpressure; 3) pressure reduction or vacuum; 4) air pollutants are released at low pressure or vacuum. Due to their concentrated release, for example VOC vapours can be condensed or dissolved in a suitable product and solvent or petrol can thus be recovered.

PSA is not only used as an abatement technology but also for the separation of pure gases, such as hydrogen from synthesis gas or nitrogen from air.

Switching between the two parallel filters, PSA's (and to a lesser extent TSA's) results in fluctuating emission levels (zero just after bed change, then increasing to designed maximum and then again zero after bed change, etc.).

Activated carbon injection

For applications with high flow rates and lower concentrations, powdered activated carbon is sprayed into the waste gas stream, after which the activated carbon is filtered out of the treated waste gas with a fabric filter. The latter is often used for the removal of mercury or dioxins. If dry lime sorption is already present, a combination of lime and active carbon (Sorbalit®) is sometimes injected to capture both the acid components and the dioxins and VOCs.

Floating bed and continuous moving bed

In the case of an adsorption filter with a suspended bed and a continuously moving bed, the adsorbent material moves in countercurrent flow in relation to the waste gas in an adsorption column, after which the saturated adsorbent material is separated for regeneration. Regeneration usually takes place by heating, after which the adsorbent material is cooled and reintroduced to the top of the adsorption column. The vapours released during regeneration are extracted and, for example, condensed and recovered through cooling. The process consists of continuous adsorption and desorption. In a suspended bed, the regeneration step takes place in a single column with two heat exchangers at the bottom to first heat the adsorbent material for desorption and to cool it down after desorption. The regenerated adsorbent material is then pneumatically reintroduced into the top of the suspended bed. In the case of a continuously moving bed, the regeneration step takes place in another column.

Adsorption: adsorption filter

Impregnated activated carbon
For specific applications and to increase the removal efficiency, active carbon is chemically treated or impregnated. Impregnated activated carbon not only adsorbs through 'physical' Van der Waals forces but also through stronger chemical bonds (chemisorption). Impregnated activated carbon is specially designed to capture air pollutants that are difficult to adsorb on standard activated carbon. Known applications are:

- With oxidising agent, for example potassium permanganate ($KMnO_4$) for odour elimination by oxidation of organic substances or KI (potassium iodide) to increase the uptake capacity for hydrogen sulphide (H_2S) where H_2S is oxidised to sulphur dioxide (SO_2)
- With sulphur compounds for better removal of heavy metals such as mercury (Hg) through the formation of sulphides
- Impregnation with an acid such as sulphuric acid to capture alkaline substances such as ammonia (NH_3)
- Impregnation with alkali (for example caustic soda, NaOH) to capture acidic substances such as hydrogen sulphide (H_2S)

3.2 Installation, design and maintenance

The key design parameters are:

- Exhaust gas flow
- Composition of the waste gases
- Temperature
- Moisture content
- Pressure

High temperature and humidity lead to reduced adsorption capacity. Hot waste gases must be cooled to at least 80ºC for activated carbon, whereby condensation in the adsorption filter must be prevented. The humidity of waste gases must be reduced beforehand. High pressure will increase the adsorption capacity.

All adsorption processes are exothermic: heat is released to the bed during adsorption. In addition, the activated carbon or the metals on or in the active carbon can cause catalytic oxidation of the VOCs in the bed. This can result in strong local heating and even self-ignition of the bed. This is especially dangerous with certain hydrocarbons such as aldehydes, ketones, polymerising substances, some organic acids and turpentine. At higher concentrations of these components, activated carbon can cause hot spots (reduced adsorption efficiency) or bed fires, even with gases at room temperature. Self-ignition can be prevented by humidifying the air and strictly monitoring the bed temperature. In doing so, care must be taken not to reduce the efficiency of the activated carbon too much.

(monitoring)
The efficiency can be determined by measuring the VOC concentrations before and after the filter, odour emissions can be determined by olfactometry[4]. Determination of the pressure drop is important in order to be able to detect clogging of the filter by particles. Pressure across the bed should be approximately constant; an increase in

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[4] In olfactometry, the odour concentration of an air sample is determined using an olfactometer. The odour concentration is defined as the number of dilutions required to distinguish the diluted odour from odourless air by 50 % of a panel of trained observers after calibration

Adsorption: adsorption filter

pressure indicates either clogging by particles or disintegration of the activated carbon into dust. Temperature measurement of the filter is necessary to prevent fire.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Suitable for low residual concentrations required for SVHC
- Simple, robust technology
- Easy installation, also retrofit
- Suitable for discontinuous processes

4.2 Disadvantages

The main disadvantages are:

- Sensitive to clogging by dust
- Mixtures of different gases can lead to saturation of a certain component
- Less suitable for high input concentrations due to rapid saturation
- Not suitable for wet waste gases

4.3 Resources and energy

Water consumption:

Usually none, sometimes cooling water to control the temperature of the adsorption bed or for condensation to recover solvents or hydrocarbons such as gasoline.

Chemicals:

Not applicable.

Energy consumption:

Depending on the application, steam (for desorption) and nitrogen (as flushing gas). Electricity to drive a fan, heat for the desorption process, for example in the form of steam, or generation of vacuum and compression/condensation of the adsorbed VOCs.

4.4 Environmental considerations

Recovery

Depending on the design, recovery is possible.

Air

No other forms of air pollution are created.

Wastewater:

No

Waste:

The adsorbent material must be replaced periodically; regeneration can only take place in a limited number of cycles. If the adsorbent material is regenerated, the adsorbed substances must be collected, treated and/or disposed of.

Adsorption: adsorption filter

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:
10.000 - 50.000

Operating costs [EUR per 1,000 Nm^3/hour per year]:
2.500
Note: mobile filters on a rental basis also occur. Costs are between 10 - 100 euro per filter per day (costs to supplier).

Staffing [hours/week]:
A few days a year.

Material [EUR per kg adsorption material]:
0,8 - 6

Energy consumption [kWh/1,000 Nm^3]
PSA: 150 - 300 (recovery of VOCs in adsorbent).
Benefits:
Recovery of the captured substances.

Cost determining parameters:
Input concentration of pollutant, flow rate, lifetime of adsorbent material.

6. Information source

1. Handreiking luchtemissiebeperkende technieken ['Guide to Air Pollution Control Technologies']; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS

4.4 Biological treatment: biofilter

Biological treatment: biofilter

Variations of the technology and synonyms

Biofiltration, *biofilter, biological filter, biofilter, compost filter, biobed*

Removed pollutants

Especially: odour, H_2S, VOC

1. Brief description

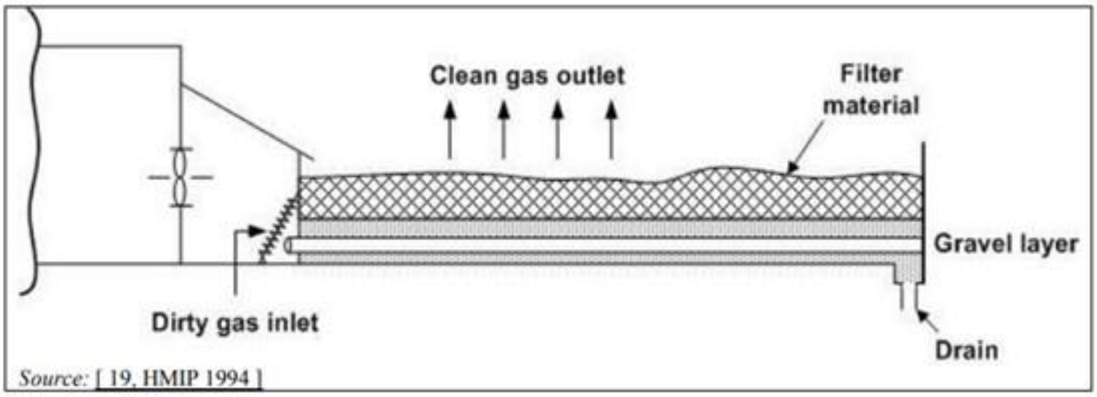
1.1 Description

The operating principle of a biofilter is based on the biological conversion of organic substances in a waste gas and oxygen (in air) into biomass, carbon dioxide (CO_2) and water. A biofilter consists of a fixed bed with microorganisms through which the waste gas to be treated is passed. The fixed bed consists of organic carrier material such as peat, compost, wood chips, tree bark or inorganic carrier material such as clay, activated carbon or polyurethane. On these carrier materials, microorganisms oxidise the pollutants in the waste gas with oxygen. The microbiological processes sustain the microorganisms allowing for their growth (biomass) and energy needs. To keep the biofilter active, moisture and nutrients usually need to be added, as well as acid or lye to stabilise the acidity.

Besides conversion into biomass, hydrocarbons are converted into water and carbon dioxide, and nitrogen- and sulphur-containing compounds into nitrate and sulphate respectively. The formed nitrate and sulphate are discharged as salts dissolved in water. Biofilters are operated in such a way that there is no net growth of microorganisms (biomass). This is possible because the microorganisms need energy for their survival and extract this energy from the (grown) biomass.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.



Source: [19, HMIP 1994]

2. Applicability

2.1 Scope

(general)
A biofilter is mainly used for the removal of odorants but is also applied for the treatment of low concentrations of water-soluble pollutants in cold waste gases. Wide application area in the following sectors:

Biological treatment: biofilter

- WWTPs and WTPs
- Composting plants (sludge, VGF, manure)
- Flavourings industry
- (Petro) chemical industry
- Plastics production
- Food industry
- Meat and fish processing industry
- Livestock

(SVHC)

Biofilters may be suitable for treatment air flows containing SVHC, but this will not happen often. The application is strongly dependent on the SVHC to be removed . The SVHC should be water soluble, biodegradable and not toxic for microorganisms. There are not many SVHC that meet these criteria. The initial concentration of a biofilter may be low enough to meet the emission limits for SVHC.

2.2 Combination of technologies

Depending on the previous processes, the waste gas must be pre-treated. This usually involves humidifying and cooling the waste gas to a suitable temperature, trapping particles and possibly buffering concentration peaks or removing substances that are toxic to the microorganisms. Fabric filters and gas scrubbers are often placed before the biofilter, to clean the air flow but also to humidify it and bring it to the right temperature for the biofilter. It is not common to place another technique after a biofilter.

2.3 Performance

The performance is shown in the following table. The values presented depend on the specific configuration and operating conditions. In principle, the values are based on half-hourly average values. In certain situations, deviating values may be justified.

NA' stands for 'not applicable' and has been used for odour. No emission limits have been set for odours, because acceptability will be tested based on the odour concentration at sensitive receptors.
In comparison with other technologies, biofilters are often able to remove odour substances cheaper. However, the treated air can never be completely odour-free, because a biofilter has its own specific odour (200-1,000 ou $_E$/m^3) (Huybrechts D. and Vrancken K., 2005; VITO, 2011b). Measurements in practice also show higher values for the specific odour (up to 2,500 ou $_E$/m^3).

Pollutant	**Removal efficiency, %**	**Concentration after treatment, mg/Nm^3**
VOC	75 - 95	5 - 50
Odour	70 - 99	200-2.500 ou $_E$/m^3

Biological treatment: biofilter

2.4 Preconditions

Flow rate [Nm^3/h]:
100 - 200.000

Temperature [°C]:
15 - 40

Pressure [bar]:
atmospheric

Pressure drop [mbar]:
10 - 30

Moisture content:
>95 % humidity

Dust content:
Adequate removal of particles is necessary before the airflow enters the biofilter. Clogging is a risk.

Input concentration [mg/Nm^3]:
200 - 2.000 (FOX)
5 - 20 (NH_3)
20.000 - 200.000 (odour, ou_E/m^3)
20 - 100 (toluene)
50 - 500 (styrene)
5 - 20 (H_2S)

3. Detailed description

3.1 Variations of the technology

Open biofilter

The simplest version of the biofilter is the open version. The bed consists of a layer of porous bio-material approximately 1 metre thick. Under the bed is a network of perforated pipes through which the contaminated air is blown, so that the air flow is evenly distributed over the bed. Larger flows can be handled by giving the biofilter a larger surface; the load of a biofilter lies between 100-500 Nm^3 air per m^2 per hour. As a result, a biofilter can be a large installation if large flows need to be processed. It is possible to apply extra layers of filter material, in which case the removal efficiency is increased. Typical installations are 2-3 layers of filter material, each 0.5 -1.5 meter thick. The microorganisms live on the biological filter material and the microorganisms degrade the contaminates. For optimal operation, the residence time must be long enough (5 - 60 seconds) and the living conditions must be suitable for microorganisms. This limits the biofilter in terms of pH value, temperature, humidity and type of substance that can be cleaned. once the biofilter material is dry, it is difficult to rehydrate and reactivate it.

Biological treatment: biofilter

Closed biofilter

A biofilter can also be executed in a closed version. This concerns the same principle as the open version, but in a closed housing. This gives the user more control over the (living) conditions in the biofilter, so that the removal efficiency of closed beds is often higher. The closed variation of the technology is more expensive than the open variation of the technology. A closed biofilter has an exhaust pipe and can therefore be considered as a point source to which emission limit values apply. This is in contrast to an open biofilter, which is regarded as a diffuse surface source.

Thermophilic biofilter

A thermophilic bed operates at higher temperatures (approximately 50 - 60ºC) than standard (mesothermal) beds (approximately 15 - 38ºC). It is mainly used when the waste gas flow temperature is higher. Thermophilic beds are more sensitive to temperature fluctuations, if the temperature exceeds 60ºC the biological activity in the bed will quickly deteriorate. A good temperature control is therefore necessary. Sometimes multiple layers are used to obtain different bacterial cultures.

3.2 Installation, design and maintenance

The key design parameters are:

- Exhaust gas flow rate, this is typically between 100 - 500 m^3/m^2/h
- Temperature, too hot air (>35ºC) must be cooled beforehand
- Carrier material, this must be well matched to the particles to be removed

The surface load of a biofilter is generally 50 - 500 m ^{3}/m^2/hr. When applying the packing, care must be taken that the filter material is distributed very uniformly and that there are no fixed and loose zones. These can cause short circuit currents so that the air is badly treated and the effective filter surface is reduced. Drying out of the filter during short-circuit currents will further reduce the effectiveness.
The high loads (500m^3 /m^2 /h) are limited by the bed height, which is necessary to guarantee the residence time. Generally accepted heights vary between 1 and 2 metres.

Cooling is required for application in warm air flows (> 38°C). This can be achieved by mixing with outside air, a water scrubber or a heat exchanger/condenser.

Periodically, every 0.5 - 5 years, the filter material must be replaced. This strongly depends on the type of filling material and the composition of the waste gases.

(monitoring)
Biofilters require little mechanical maintenance; the moving parts are limited to a ventilator. However, good monitoring is necessary. The removal efficiency can decrease sharply when the circumstances in the biofilter change, for example due to food shortage, shifted humidity balance or deterioration of the filter material. This must therefore be noticed and remedied in time. Monitoring takes place on the basis of air humidity and pH value of the discharged water, amongst other factors.

Biological treatment: biofilter

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Little waste production and side effects compared to other odour removal technologies.
- Treats flammable and/or explosive gases in a relatively safe way

4.2 Disadvantages

The main disadvantages are:

- Large installation
- Sensitive to variations in concentration and flow rate, and also sensitive to desiccation, acidification and poisoning of the microorganisms. This makes process control difficult.

4.3 Resources and energy

Water consumption:

5 [litres/1,000 Nm^3]

Chemicals:

Often it is necessary to add nutrients. The airflow usually needs to be actively humidified, for which a pre-heater can be used.

Energy consumption:

Electricity for pump and possibly fan; heating or cooling of the waste gas may also be required.

4.4 Environmental considerations

Recovery:

Product recovery is not possible. The sulphate or nitrate formed can sometimes be utilized, but this is uncommon.

Air:

No other forms of air pollution are created. However, a cooled gas stream will show less plume rise, which is detrimental to the dispersion of emissions in the outside air.

Wastewater:

A small amount of wastewater is produced to counteract acidification of the bed and to remove the salts formed (leachate water).

Waste:

Organic carrier material if it is 'digested' or clogged inorganic carrier material (dust or fouling). The carrier material should be replaced periodically. The frequency is highly dependent on local conditions but is usually once every 0.5 - 5 years.

Biological treatment: biofilter

Safety:

There are no special safety aspects other than the danger characteristics of any acids or bases used to stabilise the acidity. Flammable and/or explosive gases can be handled with relative safety due to the favourable conditions in biological processes.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

8.000 - 14.000

Operating costs [EUR per 1,000 Nm^3/hour per year]:

Approximately 10.000 - 20.000

Staffing [hours/week]:

1

Material [EUR per 1,000 Nm^3/hour]:

<200 (carrier material)

Energy consumption [kWh/1,000 Nm^3]:

<1

Benefits:

No

Cost determining parameters:

Flow rate, concentration and type of contamination, required efficiency, type of filter material.

6. Information source

1. Handreiking luchtemissiebeperkende technieken ['Guide to Air Pollution Control Technologies']; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS
5. Supplier: Azzuro
6. D. Huybrechts and K. Vrancken; Best Available Techniques for composting and digestion plants; Ghent, Academia Press; 2005; ISBN 90 382 0819 7 (https://emis.vito.be/nl/node/71626)

4.5 Biological treatment: biotrickling filter

Biological treatment: biotrickling filter

Variations of the technology and synonyms

Biotrickling (BTF), *lava filter*
Moving bed trickling filter (*MBTF)*

Removed pollutants

Especially: odour, H_2S, VOC

To a lesser extent: ammonia

1. Brief description

1.1 Description

The principle of operation of a biotrickling filter is the same as that of a biofilter, namely biological conversion of organic substances in a waste gas and oxygen (in air) into biomass, carbon dioxide (CO_2) and water. A biotrickling filter is an installation consisting of a closed reactor with microorganisms through which not only the waste gas to be treated is passed, but also a water flow. The microorganisms live on a carrier material that is executed as a fixed bed in case of a biotrickling filter or on loose material in case of a moving bed filter. The carrier material consists of synthetic foam, lava, plastic structured packing or plastic balls. The microorganisms on the carrier material convert the pollutants in the waste gas through microbiological processes in order to stay alive, for growth and the energy needed for this. To keep the biofilter active, nutrients usually have to be added, as well as acid or lye to stabilise the acidity. The conversion usually takes place aerobically, i.e. with oxygen, but anaerobically (without oxygen) is also possible.

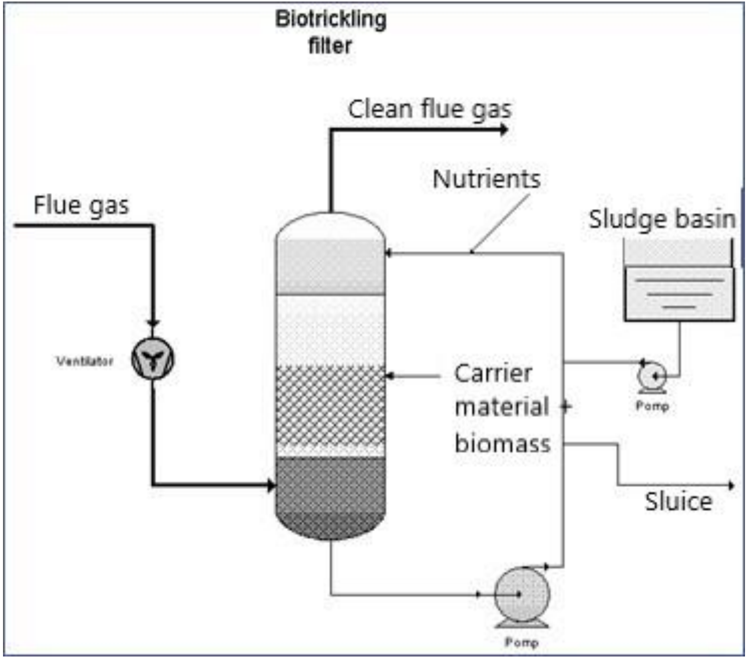
In addition to conversion to biomass, hydrocarbons are converted under aerobic conditions to water and carbon dioxide, and nitrogen- and sulphur-containing compounds are converted to nitrate and sulphate respectively. The nitrate and sulphate formed are discharged as salts dissolved in water. Under anaerobic conditions, methane, ammonia/ammonium, hydrogen sulphide are formed. The water flow allows for the more effective the removal of salts than the stationary water phase of biofilters .

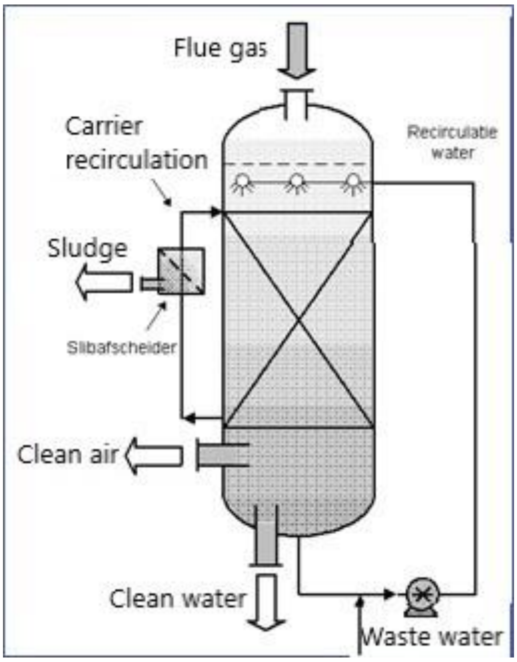
A fixed bed biotrickling filter is operated in such a way that there is no net growth of the microorganisms (biomass). This is possible because microorganisms need energy for their survival and extract this energy from the (grown) biomass. In the case of a moving bed filter, the fouled biomass can be separated and the carrier material recycled and returned to the reactor.

1.2 Process flow diagram

The following is the principle diagram. The figure on the left is the traditional biotrickling filter, the figure on the right is a moving bed biotrickling filter.

Biological treatment: biotrickling filter





2. Applicability

2.1 Scope

(general)

A biotrickling filter is mainly used for the removal of odorants, but is also applied for treatment low concentrations of water-soluble pollutants in cold waste gases, such as hydrogen sulphide (H_2S), ammonia (NH_3), carbon disulphide (CS_2) and hydrocarbons.

Biotrickling is applied for example in the following sectors:

- Wastewater treatment, sludge and waste processing plants
- Livestock
- Textile industry
- Tobacco Industry
- Printing industry, woodworking industry, furniture industry, metalworking industry
- (Petro) chemical industry

(SVHC)

Biotrickling filters may be suitable for treatment air streams with SVHC, but this will not often be the case. The application is highly dependent on the substance to be cleaned. It must be water-soluble, biodegradable and non-toxic to the micro-organisms. There are not many SVHC that meet these criteria. The starting concentration of a biotrickling filter may be low enough to meet the emission limit values for SVHC.

2.2 Combination of technologies

Biological treatment: biotrickling filter

Depending on the previous processes, the waste gas must be pre-treated. This usually involves cooling down to a suitable temperature, trapping particles and possibly removing substances that are toxic to the microorganisms. Fabric filters are often placed before the biofilter. The reactor of a biotrickling filter often has a section that serves as a scrubber. It is not common to place another technique after a biotrickling filter.

The Moving Bed Trickling Filter (MBTF) is a system mainly intended to treat waste gases together with wastewater.

2.3 Environmental performance

The environmental performance is shown in the following table. The values presented depend on the specific configuration and operating conditions. In principle, the values are based on half-hourly average values. In certain situations, deviating values may be justified.

The data is taken from the BREF CWW (2016).

Pollutant	**Biotrickling, removal-efficiency, %**	**MBTF, removal-efficiency, %**	**Concentration after treatment, mg/Nm^3**
VOC	70 - 99	80 - 95	40
Ammonia	80 - 99,95		20
Odour	70 - 95	>90	1.500 ou $_E$/m^3
H_2S	80 - 99,9	>98	0,1
Mercaptans	70 - 95	>95	5
CS_2	98 - 99		1

2.4 Preconditions

Flow rate [Nm^3/h]:

1,000 - 500,000 (biotrickling), or 5,000 - 40,000 (MBTF)

Temperature [°C]:

15 - 40, optimum between 30 - 35

Pressure [bar]:

Atmospheric

Pressure drop [mbar]:

2 - 10

Micro-organism concentration

>15 grams/litre of dry matter

Input concentration [mg/Nm^3]:

Pollutant	**Biotrickling, input concentration [mg/Nm^3]**	**MBTF, input concentration [mg/Nm^3]**
VOC	400 - 4.000	100 - 10.000
Ammonia	100 - 400	

Biological treatment: biotrickling filter

Odour	> 10.000 ou_E/m^3	> 10.000 ou_E/m^3
H_2S	5 - 1.000	10 - 500
Styrene	100	<500

3. Detailed description

3.1 Variations of the technology

Biotrickling filter

A biotrickling filter consists of a packed absorption column, which is continuously or discontinuously wetted and supplied with nutrients by circulation or single inlet. The intention here is that the biomass remains on the packing and is not carried away with the water. The filter can be grafted with active sludge or with a grafting culture aimed at the intended treatment. After dissolution (absorption) in the thin water film, the pollutants are broken down by a layer of microorganisms growing on the packing ('bio film'); the formed salts are carried away by the water. Thanks to the mobile water phase, the removal of acidic degradation products is more effective than with biofilters with a stationary water phase. The acidity of the circulation flow can be corrected by dosing lye or make-up water.
Recirculation promotes the growth of a culture specific for the removal of one type of pollutant. A discontinuous nutrient supply, i.e. without recirculation, allows multiple cultures to grow, which can break down different pollutants in a single system. Biotrickling filters are often applied as two phase filters with a section for removal of acidic substances like H2S and a section for removal of other odour components.

The filter material consists of plastic foam, lava stones or plastic moulds. The surface is of such a structure that the biomass can attach to it well. Lava rocks are often used as a carrier material in wastewater treatment plants. Plastic moulds (for example from polypropylene) are comparatively lighter, have more free space for the microorganisms and are less sensitive to silting up.

Moving bed biotrickling filter

The Moving Bed Trickling Filter (MBTF) is a system primarily intended to treat waste gases together with wastewater. The MBTF basically consists of 1) a reactor filled with loose carrier material, such as grooved plastic balls, 2) a liquid recirculation system and 3) a sludge separator. The wastewater is pumped to the top of the reactor with an adjustable circulation pump and distributed over the bed by means of a rotating spray arm. The treated water is collected in the buffer/settling chamber, where any sludge particles can settle. The waste gas is blown into the reactor with an external ventilator, along with the wastewater. At the bottom, special sections in the sieve plate ensure the effective separation of air and water, after which the treated air is released into the atmosphere. As in any biological treatment process, some of the impurities introduced are converted into biomass. This will increase the amount of biomass in the reactor. The unconstrained growth of biomass, can lead to clogging in conventional trickling filters. In the MBTF, clogging is prevented by pumping part of the surplus carrier material to the top of the reactor where the loose carrier material is deposited on a sieve plate via a cyclone. The cyclone effect and subsequent energy generated by free fall of the carrier material removes a large part of the biomass from the carrier material. The cleaned carrier material falls on top of the bed and once again participates in the treatment process. The separated sludge must be disposed of.

Biological treatment: biotrickling filter

3.2 Installation, design and maintenance

The maintenance of the biological film layer (biofilm) of the packing is essential: too much growth can lead to (local) blockages that eventually result in preferential flows, reducing the exchange surface and thus the performance of the biotrickling filter. This is especially a point of attention in systems that remove hydrocarbons and less so in systems that are aimed at removing H_2S or NH_3 . The growth and thickness of the biofilm can, for example, be controlled by influencing the thickness of the biofilm mechanically (for example, varying the humidity) or by influencing the growth rate of the microorganisms by varying the acidity and/or salt content. In biotrickling filters that are supplied with high H_2S concentrations, there is a chance of elemental sulphur forming as a result of incomplete biological oxidation. This manifests itself through clearly identifiable yellow granular structures and may eventually lead to clogging and preferential flows. Biotrickling filters that process high concentrations of inorganic compounds (NH_3 or H_2S) usually have microorganisms, which use CO_2 from the air as a carbon source. In view of the relatively high and more than sufficient concentrations of CO_2 in the air, extra consideration should be given to strong biofilm growth.

(monitoring)

The composition of the water must be determined by continuous measurements of pH, temperature and conductivity.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Better reliability than a biofilter
- More compact than a biofilter
- An MBTF can clean water flows and air flows simultaneously
- Little use of additives
- Treats flammable and/or explosive gases in a relatively safe way

4.2 Disadvantages

The main disadvantages are:

- A constant air flow is required, fluctuations in flow rate and input concentrations lead to reduced treatment efficiency (not with MBTF)
- Growing biomass can clog a biotrickling filter. MBTF does not have this problem
- Not suitable for substances that dissolve poorly in water
- Production of wastewater

4.3 Resources and energy

Water consumption:

The saturated scrubbing water from a biotrickling filter must be drained and replenished.

Biological treatment: biotrickling filter

Chemicals:

Acids, bases, oxidizing agents to make the conditions of the water suitable for microorganisms. It is often necessary to add specific nutrients.

Energy consumption:

The biotrickling filter itself consumes little energy (approx. 0.5 kW/1 000 ^{3}m/h). In addition, electricity is consumed for the pressure drop that the ventilator has to overcome. This pressure drop amounts to approximately 2-6 mbar, depending on the gas load of the system and the degree of biological growth.

4.4 Environmental considerations

Recovery:

Product recovery is not possible. The sulphate or nitrate formed can be put to good use, but this is not common.

Air:

No other forms of air pollution are created. However, a cooled gas stream will show less plume rise, which is detrimental to the dispersion of emissions in the outside air.

Wastewater:

A small amount of wastewater is generated to counteract the acidification of the bed and to remove the salts formed.

Waste:

With a biotrickling filter no waste is created from the process; with an MBTF a sludge flow is released, comparable to wastewater treatment sludge. Periodically (a part) of the packing should be replaced / refreshed. This is more often the case with lava stones than with synthetic forms. Depending on the application, the replacement for structured plastic forms is between 5 years for CS_2 applications and 20 years for H_2S applications.

Safety:

There are no special safety aspects other than the danger characteristics of any acids or bases used to stabilise the acidity. Flammable and/or explosive gases can be handled with relative safety due to the favourable conditions in biological processes.

5. Financial aspects

Investment [EUR per 1,000 Nm/hour]: ^{3}

10.000 - 30.000

Operating costs [EUR per 1,000 Nm/hour^3]:

N.B.

Biological treatment: biotrickling filter

Staffing [hours/week]:

Approximately 4

Material:

Gasket material normally lasts for many years.

Energy consumption [kWh/1,000 Nm^3]:

0,5 - 1

Benefits:

Rarely except for recovered product (for example sulphur).

Cost determining parameters:

Flow rate, concentration and type of pollution, required efficiency

6. Information source

1. Handreiking luchtemissiebeperkende technieken ['Guide to Air Pollution Control Technologies']; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. BVT 2016
5. VITO LUSS: Biotrickling filter
6. Supplier Azzuro

4.6 Biological treatment: biological scrubber

Biological treatment: biological scrubber

Variations of the technology and synonyms

Biological scrubber, *bio scrubber*

Removed pollutants

Especially: odour, H_2S, VOC

1. Brief description

1.1 Description

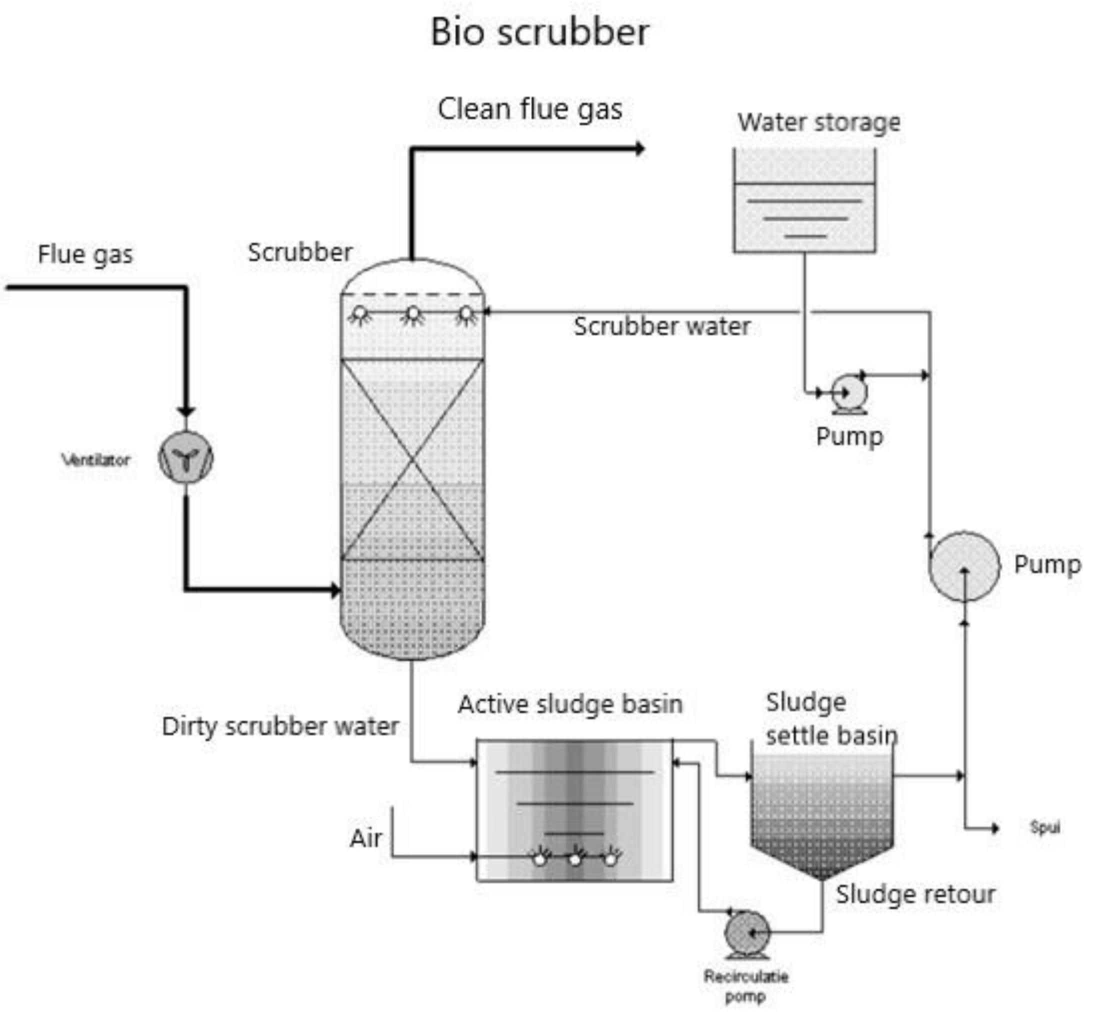
The operating principle of a biological scrubber is the same as that of a gas scrubber, i.e. the dissolving of substances in the waste gas in a scrubbing liquid. The scrubbing liquid is then treated biologically, by biological conversion of organic substances in a waste gas and oxygen (in air) into biomass, carbon dioxide (CO_2) and water.

A biological scrubber thus consists of a gas scrubber and a biological scrubber. In the gas scrubber, the off-gases are brought into intensive contact with scrubbing water, as a result of which the off-gases' pollutants are dissolved in the scrubbing liquid (absorption) and the off-gases are cleaned. The cleaned gas stream can then be discharged to the outside air. The saturated scrubbing liquid with the dissolved pollutants is treated as wastewater. Usually wastewater treatment consists of a reactor where microorganisms (active sludge) break down the dissolved pollutants. The microorganisms break down the pollutants through microbiological processes in order to sustain themselves, for growth and for the necessary energy. To keep the active sludge active, nutrients usually have to be added as well as acid or lye to stabilize the acidity. The formed sludge is separated and disposed of as wastewater treatment sludge. The treated water is pumped back to the scrubber.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Biological treatment: biological scrubber



2. Applicability

2.1 Scope

(general)
Biological scrubbers are used for the capture and degradation of biodegradable pollutants that are highly water soluble. Wide range of applications in the following sectors:

- Cigarette Industry
- Water treatment plants
- Elimination of odour arising from the production of enzymes
- Removal of odour arising from the production of aromas
- Rubber Industry
- Elimination of odour in the production of polymers
- Removal of odour, VOC and nitrogenous substances from the processing of paint waste
- Landfill sites for hazardous waste

Biological treatment: biological scrubber

- Livestock
- Coffee Roasters
- Slaughterhouses

(SVHC)

The residual concentration of biological scrubbers strongly depends on the application and the substance to be removed. Biological scrubbers can be suitable for treating air streams with SVHC, but this is uncommon. The application is highly dependent on the substance to be removed. It must be water-soluble, biodegradable and non-toxic to the micro-organisms. There are not many SVHC that meet these criteria. The starting concentration of a biological scrubber can be low enough to meet the emission limit values for SVHC.

2.2 Combination of technologies

Depending on the previous processes, the waste gas must be pre-treated. This usually involves cooling down to a suitable temperature, trapping particles and possibly removing substances that are toxic to the microorganisms. Fabric filters are often placed before the scrubber. It is not common to place another technique after a biological scrubber. However, biological scrubbers can be part of a combination of technologies, just like general gas scrubbers.

2.3 Performance

The performance of biological scrubbers corresponds to the performance of gas scrubbers that have water as a scrubbing liquid. The presented values depend on the specific configuration and operating conditions. The values are in principle based on half-hourly average values. In certain situations deviating values may be justified.
The data is taken from the BREF CWW (2016), which in turn refers to the 2009 Fact Sheets, BVT 2016 and BREF WGC D1 (2019).

Pollutant	**Removal efficiency, %**	**Concentration after treatment, mg/Nm^3**
Odour	70 - 85	100 - 150 ou$_E$/Nm^3
Ammonia	>99	<1-3
H_2S	90 - 95	<15
VOC	80 - 99	<20 - 40

2.4 Preconditions

Flow rate [Nm ^{3}/h]:
P10: 30
P50: 2.000
P90: 30.000

Biological treatment: biological scrubber

Temperature [°C]:
15 - 40, optimum between 30 - 35

Pressure [bar]:
atmospheric

Pressure drop [mbar]:
2 - 5

Moisture content:
No restrictions

Dust content [g/Nm^3]:
<10; low particulate concentrations are desirable for proper operation.

Input concentration [mg/Nm ^{3}]:
100 - 1.000 (FOX)
50 - 200 (NH_3)
>10.000 (odour, ou $_E$/m ^{3})

3. Detailed description

3.1 Variations of the technology

Biological scrubber with aerobic treatment

Besides conversion into biomass, hydrocarbons are converted into water and carbon dioxide, and nitrogen- and sulphur-containing compounds into nitrate and sulphate respectively. The formed nitrate and sulphate are discharged as salts in water. The conversion usually takes place aerobically, i.e. with oxygen, but anaerobically (without oxygen) is also possible. Under anaerobic conditions methane, ammonia/ammonium and hydrogen sulphide will be formed (anaerobic digestion).
A hydraulic retention time of the scrubbing water of 20 - 40 (maximum) days gives good results.

Biological scrubber with sulphur recovery

By limiting the amount of oxygen, sulphide (dissolved H_2S) is oxidized by some bacteria to elementary sulphur and not further oxidized to sulphate. H_2S-containing waste gas is brought into contact with the scrubbing liquid in countercurrent flow under mildly alkaline conditions, whereby the H_2S dissolves almost completely in the scrubbing water. The liquid containing sulphide (dissolved H_2S) flows to the bioreactor, where bacteria oxidise the sulphide and convert it into sulphur and lye under oxygen-limiting conditions. The bacteria excrete the formed sulphur as granules, which can then be removed from the water as solid elemental sulphur. The system offers a high H_2S removal efficiency (> 99.5 %).

Biological treatment: biological scrubber

3.2 Installation, design and maintenance

A biological scrubber must be designed in such a way that the residence time of the air flow in the scrubber is about 1 second, depending on the solubility of the to-be-captured substance. Attention must be paid to a good sludge flow, because otherwise the active sludge can cause clogging; it grows more as more pollutants are captured.

Per m^2column surface, 1,000 - 3,000 m^3/h of waste gas can be treated.

(monitoring)

Monitoring takes place through chemical analysis (or assessment of odour) of the inlet and outlet gases. Control of the pH of the scrubbing water is necessary.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Better able to deal with changing (peak) loads than a biofilter or biotrickling filter
- Treats flammable and/or explosive gases in a relatively safe way

4.2 Disadvantages

The main disadvantages are:

- The biomass grows and must be removed periodically
- Not suitable for substances that dissolve poorly in water

4.3 Chemicals and energy

Water consumption:

Water needs to be topped up periodically due to discharge, condensate and sludge disposal.

Chemicals:

Chemicals (nutrients, acids, bases) to ensure optimal biological activity.

Energy consumption:

Electricity to drive a pump and possibly a fan.

4.4 Environmental considerations

Recovery:

Product recovery is possible in a limited number of cases. Sulphur recovery is an example of this.

Air

The sludge tanks can give emissions of odour. Therefore, channelling and treatment of displacement air may be required.

Wastewater:

Wastewater is created by the formation of nitrate and sulphate salts.

Biological treatment: biological scrubber

Waste:

Wastewater treatment sludge is created by the growth of microorganisms.

Safety:

There are no special safety aspects other than the danger characteristics of any acids or bases used to stabilise the acidity. Flammable and/or explosive gases can be handled with relative safety.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

7.500 - 25.000

The costs are derived from the costs for a gas scrubber. The costs for biological wastewater treatment have to be considered separately.

Operating costs [EUR per 1,000 Nm^3/hour per year]:

1.000 - 2.000

Staffing [hours/week]:

4

Material [EUR per 1,000 Nm/hour]: ^{3}

Low

Energy consumption [kWh/1,000 Nm^3]:

0,2 - 0,5

Benefits:

None, unless recovered material can be usefully employed

Cost determining parameters:

Flow rate, concentration and type of pollution.

6. Information source

1. Handreiking luchtemissiebeperkende technieken ['Guide to Air Pollution Control Technologies']; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS: bio scrubber
5. Supplier Thiopaq - Paques / Paqell

4.7 Chemical reduction: SCR and SNCR

Chemical reduction: SCR and SNCR

Variations of the technology and synonyms

Selective catalytic reduction; *SCR*

Selective non-catalytic reduction; *SNCR*

Removed pollutants

Mainly: NOx

1. Brief description

1.1 Description

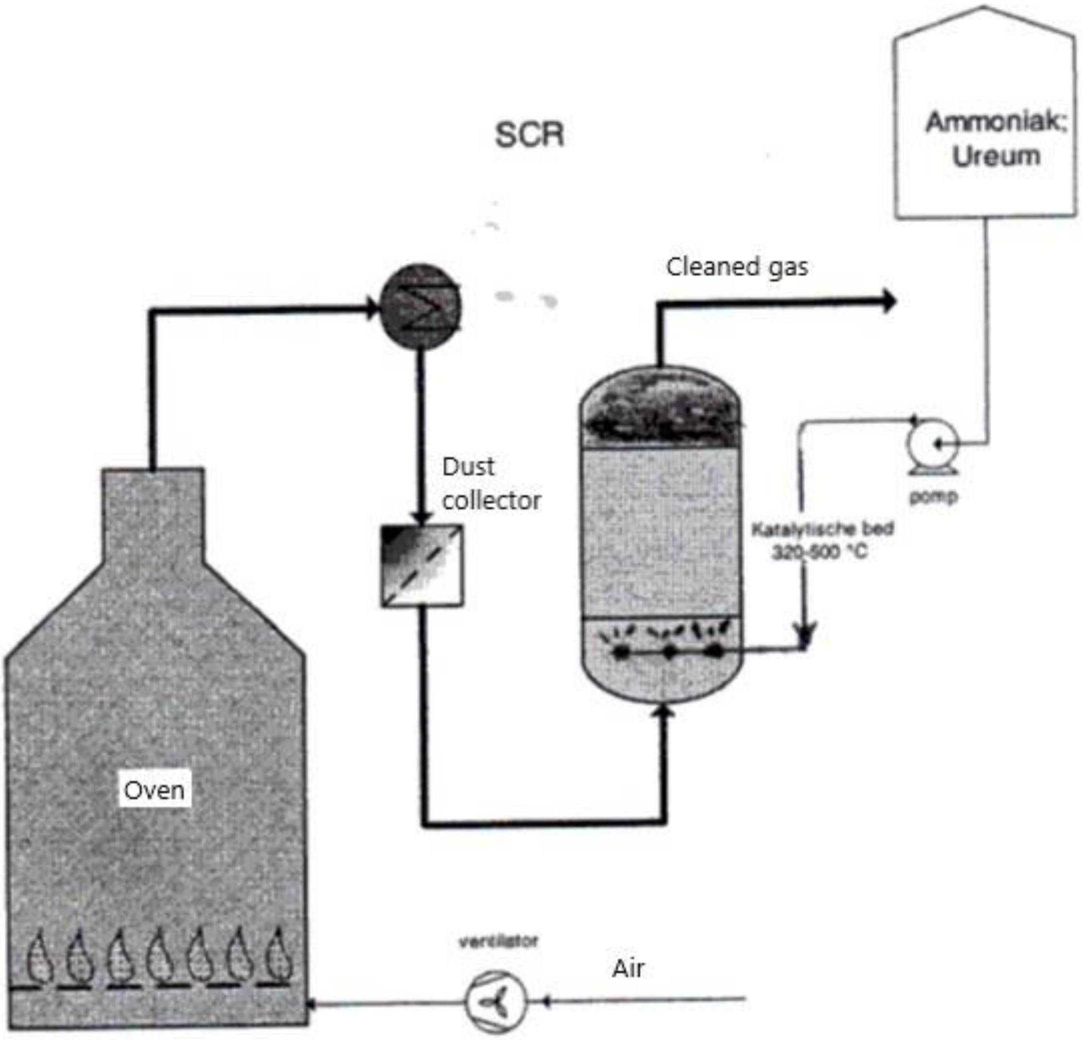
Selective reduction of oxides of nitrogen (NO_x , NO_2) is a chemical process in which oxides of nitrogen are chemically converted with a reducing agent in a targeted (selective) manner to atmospheric nitrogen (N_2) and water. The most commonly used reducing agents are ammonia and urea. The reducing agent is sprayed into the flue gas, after which the reduction reaction can take place at a high temperature. In the case of catalytic reduction (SCR) the flue gas is led over a catalyst. The catalyst makes the process more efficient and at lower temperature. In non-catalytic reduction (SNCR) the process takes place without a catalyst.

SCR and SNCR are commonly used for flue gas treatment. Ammonia (NH_3) can be applied as gas or in an aqueous solution. Urea (NH_2-CO-NH_2) is applied dissolved in water. AdBlue is the registered trade name for a 32.5 % solution of urea. Due to fluctuations in process circumstances it is possible for treated flue gas to contain ammonia or ureum. This is called ammonia slip.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Chemical reduction: SCR and SNCR



2. Applicability

2.1 Scope

(general)

Selective reduction (SCR and SNCR) are mainly used to treat flue gases and flue gas containing nitrogen oxides. SCR has a wide range of applications in the following sectors:

- Waste incineration
- (petro)chemical Industry
- Power plants
- Cement Industry
- Metallurgical industry
- Greenhouse horticulture

Chemical reduction: SCR and SNCR

(SVHC)

SCR is specifically designed for the removal of nitrogen oxides (NO_x). Nitrogen oxides are not substances of very high concern (SVHC), so SCR is not intended for the removal of SVHC.

2.2 Combination of technologies

Catalytic reduction takes place within a limited temperature range. For SNCR, the equipment is usually placed almost immediately after the flame, because the flue gases are still hot enough. A SNCR can even be part of the combustion plant if the ammonia is injected just after the combustion chamber.
It may be necessary to cool/heat the flue gas prior being fed into the SCR,. Particles should also be removed from the flue gas beforehand to prevent clogging or poisoning of the catalyst.
After the reduction step, it may be necessary to reduce the ammonia content (SCR, SNCR) or further treat the flue gas for other pollutants (especially SNCR).

2.3 Performance

The performance is shown in the following table. The values presented depend on the specific configuration and operating conditions. The values are basically based on half-hourly average values. The values for the specific application. Shown are a reasonably achievable lower value for easily controlled processes and an upper value for more complex processes. A lower value for NO_x can lead to a higher value for NH_3.

Pollutant	**SNCR disposal efficiency, %**	**SNCR concentration after treatment, mg/Nm^3**	**SCR removal efficiency, %**	**SCR concentration after treatment, mg/Nm^3**
NO_x	25 - 80	60 - 70	80 - 99	<20 - 150
NH_3	NA	2 - 20	NA	2 - 20

Emission of ammonia, for both SCR and SNCR [mg/Nm^3]. Data from BVT 2016:

P10: 0,7
P50: 1,4
P90: 13,1

2.4 Preconditions

Flow rate [Nm^3/h]:

P10: 2,500 (SCR) - 2,000 (SNCR)
P50: 20,000 (SCR) - 5,500 (SNCR)
P90: 37,000 (SCR) - 36,000 (SNCR)
Example plants with flow rates ~1.5 million Nm^3 / hr are known

Chemical reduction: SCR and SNCR

Temperature [°C]:

930 - 980 (SNCR) or 180 - 450 (SCR, depending on the catalyst). Fluctuations of ~90ºC are acceptable.

Pressure [bar]:

Atmospheric

Pressure drop [mbar]:

<10

Residence time:

1 - 2 seconds

Dust particles:

Particles can have a negative effect on the operation of the catalyst in SCR and should therefore be filtered in advance or another form of catalyst carrier. Particulate matter is not a problem for SNCR.

Incoming concentration:

10 g NO_x/Nm^3

3. Detailed description

3.1 Variations of the technology

SNCR

The optimum temperature for the reduction reaction is between 930 - 980°C (ammonia) or between 950 - 1050ºC (urea). The injection of the reducing agent takes place after the combustion process but before further treatment of the flue gas. Temperature, the ratio NH_3/ NO_x, good mixing and residence time are the most important parameters for the efficiency.

SCR

Compared to SNCR, the SCR process takes place in a temperature range that is considerably lower, namely 180 - 450ºC, depending on the catalyst. Because the operating temperature of SCR is considerably lower than that of SNCR, and because the operation of the catalyst can be limited by pollutants, SCR is often installed after other abatement technologies such as a fabric filter. The catalyst must be protected, in particular, against halogens, alkali metals, alkaline earth metals, phosphate and heavy metals. Sulphur can be treated by an SCR, but this requires a temperature above 300ºC. A heat exchanger and sometimes a burner can be part of an SCR system to control the temperature of the SCR.

The catalyst is typically made of titanium dioxide and alumina as a support material with vanadium, tungsten and molybdenum as the active layer. After a period of 5 - 10 years the catalyst needs replacement, although a longer life is possible if the flue gas is very clean.

Chemical reduction: SCR and SNCR

DESONOX process

The DESONOX process is a combined process for the removal of sulphur and nitrogen from flue gases. Concentrated sulphuric acid and nitrogen gas are produced as end products. The flue gases are dedusted in an electrostatic filter prior to the DESONOX step. The de-dusted flue gas is mixed with ammonia at 450 °C and passed over a catalyst in order to convert NO_x to N_2. Next, the flue gas is led over another catalyst to convert SO_2 through oxidation with oxygen to SO_3 that reacts with water to form sulphuric acid. In the downstream steps, concentrated sulphuric acid (approx. 70%) condenses at a temperature of 120 °C. This places high demands on the materials used. The residual quantity of sulphuric acid is removed in a downstream scrubber.

3.2 Installation, design and maintenance

The key design parameters are:

- Flow
- Temperature
- Molar ratio NH_3 /NOx
- Residence time

The molar ratio NH_3/NO_x that is used is around 1.0 - 1.1. At higher ratios, unreacted ammonia is emitted with a chance of additional reactions such as formation of aerosols with ammonium chloride and ammonium sulphate.

The reaction or retention time is also important to obtain the best possible conversion. If the retention time is too short, it results in an incomplete reaction.

Retrofit of a SNCR is relatively simple, only the nozzles to inject ammonia / urea plus a storage tank need to be installed. The installation of SCR can be complex and require substantial structural modifications.

(monitoring)

Monitoring takes place by measuring the incoming and outgoing concentrations of NO_x, O_2 and reagent in the flue gas, as well as the temperature and the pressure drop (for SCR).

4. Environmental aspects

4.1 Advantages

The main advantages are:

<u>SNCR</u>

- Easy installation, also with retrofit
- Little space required
- Suitable for gas flows with high concentrations of dust

<u>SCR</u>

- Effective at lower temperature than SNCR
- Suitable for NO_x reduction from all sources, not only from combustion plants
- Low ammonia emissions than SNCR

Chemical reduction: SCR and SNCR

- The combustion plant does not have to be adapted when installed

4.2 Disadvantages

SNCR

- High temperature is necessary
- Ammonia emissions
- Unsuitable for sources with low input concentration of NO_x
- Little suitable for sources with variable flow and emission concentration

SCR

- May require previous flue gas treatment steps.
- Ammonia emissions
- Space requirements
- Higher investment compared to SNCR
- Higher operating costs than SNCR due to catalyst replacement and possible flue gas heating.
- If SO_2 is present in the flue gas, the catalyst can convert it into SO_3

4.3 Resources and energy

Water:

No direct water consumption but indirect because when ammonia and urea are used as reducing agents they are dissolved in water. In specific situations, cooling water may be necessary for the gas flow prior to being treated in the SCR.

Chemicals:

- Ammonia or urea. 570 kg/ton NOx removed for SNCR, or 370-450 kg/ton for SCR
- Catalyst (for SCR)
- Steam (to evaporate the ammonia before injection)

Energy consumption:

- SNCR: low, just to inject the ammonia
- SCR: low if flue gases do not need to be heated, to high if they do

4.4 Environmental considerations

Recovery

Not applicable.

Air

Chemical reduction leads to emissions of ammonia. SCR produces nitrous oxide (N_2O), which is a greenhouse gas. If the flue gas contains sulphur compounds, SO_3 can be emitted with SCR. Ammonia and formed SO_3 will lead to 'secondary aerosols' (fine dust) in the ambient air.

Wastewater

Not applicable

Chemical reduction: SCR and SNCR

Waste:

Catalyst (for SCR)

Safety:

Ammonia is a toxic and flammable gas.

5. Financial aspects

Investment [EUR per 1,000 Nm/hour]: [3]

SNCR: 3.000 - 30.000

SCR: 3,000 - 100,000

Costs are known to have very wide ranges. This is because examples are known with widely varying costs. The lower end of the range fits with new MCP's combusting natural gas in the Netherlands. The upper side of the range fits with a large waste incinerator within the European Union.

Operational costs [EUR per tonne NOx removed]:

SNCR: 700 - 1.200

SCR: 200 - 5,000

Staffing [hours/week]:

<1 - 16

Material (part of operational costs):

SNCR: 150 - 200 for the reagent

SCR: 150 - 200 for the reagent, plus EUR 330 / 1,000 Nm^3 flue gas / hour for the catalyst

Energy consumption [kWh/1,000 Nm^3]:

Unknown, but possibly high when reheating of the flue gases is necessary

Benefits:

None

Cost determining parameters:

Contamination of the flue gas, reagent consumption, energy consumption, retrofit costs, catalyst

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS: Selective (non) catalytic reduction
5. Supplier: Yara Netherlands
6. Final Report supporting the article 12 review under the MCP directive, reference ENV.C.4/FRA/2015/0042, 12 December 2019. (costs SCR)
7. BREF LCP tabel 7.13 (costs catalyst SCR)

4.8 Condensation: condenser

Condensation: condenser

Variations of the technology and synonyms

Condenser, *heat exchanger, odour control condensation (OCC),*

Cryocondensation, cryocondenser

Removed pollutants

Mainly: halogenated hydrocarbons, VOCs

Lesser degree: smell

1. Brief description

1.1 Description

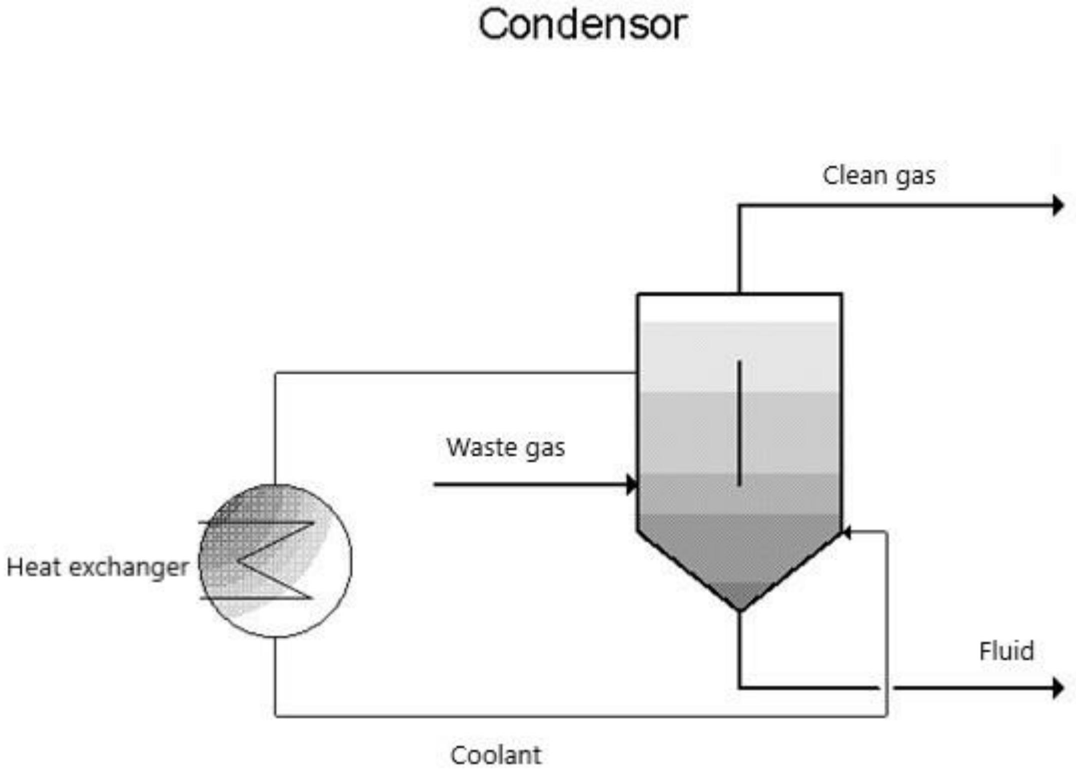
Condensation is the phase transition from gas to liquid. The operating principle of a condenser is based on the heat exchanger that cools a waste gas flow to (far) below the vapour point of the vapours concerned. The vapours in the waste gas will then transfer to the liquid phase, as far as the vapour concentration in the waste gas reaches the saturated vapour concentration. Condensation is promoted by low temperature and/or high pressure.

The condensate that forms on the heat exchanger acts as an absorption liquid, increasing efficiency. This way, odorants can also dissolve in the condensed water. The condensate can then easily be separated from the waste gas. By adjusting the operating temperature and pressure to the dew point of the specific substances, these substances can be successively condensed and thus separated.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Condensation: condenser



2. Applicability

2.1 Scope

(general)
Condensation is mainly used for high solvent concentrations (> 50 g/m^3) or for moist waste gases with odour components. Condensation is generally used as a pre-treatment, so that the end-of-pipe technology is subjected to less pressure, which can reduce the total cost of treatment. Condensation has a wide range of applications in the following sectors:

- Food industry
- Feed industry
- Composting facilities
- Sludge treatment plants

(SVHC)

In principle, condensation is not a suitable technique for the removal of SVHC vapours, but it can be part of a series of treatment technologies that remove organic SVHC vapours from a waste gas stream as a pre-treatment technique. After condensation, the initial concentration will still be too high to meet the emission limit values for SVHC.

2.2 Combination of technologies

Since the cooled waste gas can carry condensation droplets, a drop separator is placed after the condenser.

Condensation: condenser

Condensation is usually used as a pre-treatment so that the end-of-pipe technology is less burdened, which can lower the total cost of treatment.

2.3 Performance

The performance is indicated in the following table. The residual concentration is determined by the saturated vapor concentration at the operating temperature and pressure. The values presented depend on the specific configuration, operating conditions and particles to be captured. The values are in principle based on half hourly average values. NA stands for 'not applicable' and has been used for odour. No emission limits have been set for odours, because acceptability will be tested based on odour concentration s at sensitive receptors.

Pollutant	**Removal efficiency [%]**	**Concentration after treatment [mg/Nm^3]**
VOC	80 - >99	30 - 5.000
Odour	60 - 90	NA

2.4 Preconditions

Flow rate [Nm^3/h]:

Water cooling with : 100 - 100.000 Nm^3/ hour
Cryogenic cooling: <5.000 Nm ^{3}/hour, typically <250 Nm ^{3}/hour

Temperature [°C]:

Water cooling: 50 - 125
Cryogenic cooling: <80

Pressure [bar]:

atmospheric

Pressure drop [mbar]:

Water cooling: 1 - 2
Cryogenic cooling: 30 - 50

Moisture content [%]

If the operating temperature is <0ºC, then the waste gas flow must be virtually moisture free to prevent ice formation. At temperatures >0ºC no limit, but lower moisture levels result in lower energy consumption.

Sojourn time:

Variable, a few seconds

Condensation: condenser

Dust particles:

< 50 mg/Nm ^{3}, no sticking of particles due to clogging.

Incoming concentration:

No limitation for high concentrations but limitation for low concentrations. The vapour concentration must be higher than the saturated vapour concentration at the condenser temperature.

3. Detailed description

3.1 Variations of the technology

Indirect cooling with water, brine or ammonia

With indirect condensers, the refrigerant is not in direct contact with the off-gas flow. The coolant therefore does not get contaminated. The disadvantage is that it is not possible to separate sticky substances. A conventional version consists of a shell-and-tube condenser. The waste gas to be cooled flows through a tube, the coolant flows in the opposite direction through a shell around this tube and absorbs the heat present in the waste gases. A variation of the technology of the same principle is the spiral heat exchanger, consisting of two concentric passages. The coolant flows through one passage and leaves the heat exchanger via the middle. The waste gas stream enters in the middle and leaves the heat exchanger at the periphery.

Common coolants for condensation are cooling water, chilled water, chilled brine and ammonia. With cooling water the temperature is limited to ambient temperature , cooled water is limited to just above freezing (2-5ºC), cooled brine is limited to approx. -14ºC and ammonia to -40ºC (one stage) and -60ºC (two stages). The method of cooling depends on the desired temperature. Cooling water can be discharged after the condenser. If not, the coolant is cooled in the cooling system after the condenser. Commonly used cooling systems are compression cooling with a cooling medium in a closed system or air cooling, whether or not supported by evaporation of water.

The condensed VOCs flow into a collection vessel. The collected VOC can be reused in the downstream process, the cleaned gas stream can be post-treated to further reduce the VOC concentration.

For odour control, cooling is usually limited to cooling with cooling water without additional mechanical cooling. Lowering the condenser temperature from 25°C to 5C has little effect, as most of the water vapour has already condensed at 25°C. The condensation temperature of the vapours in the off-gas must then be higher than 40°C. The condensation temperature of the vapours in the waste gas must then be higher than 40°C.

If the condenser temperature is lower than 0ºC, the waste gas must be dried beforehand.

Direct cooling with a coolant

In direct systems, the coolant (cooling water) is in direct contact with the off-gas flow. This gives a good heat transfer. Practical implementations are for example spray chambers. The disadvantage of this is that the coolant (water) has to be treated again to remove the dissolved substances.

Condensation: condenser

Cryogenic condensation with liquid nitrogen

With cryocondensation, a waste gas stream is cooled down by evaporating liquid nitrogen. The evaporation of the liquid nitrogen reduces the temperature to around -100ºC, which can result in a high yield on VOC condensation. Cryocondensation is often a direct form of cooling, the coolant no longer needs to be separated from the liquid VOC. The evaporated nitrogen also creates a blanket of inert gas over the condensed VOC, which can be beneficial in terms of product quality or fire safety. Because the temperatures are far below the freezing point of water, the off-gas must be dried beforehand. From time to time it might be necessary to thaw the cryocondenser and remove the excess water.

3.2 Installation, design and maintenance

The key design parameters are:

- Composition of the waste gas
- Sufficient residence time and turbulence to cool the waste gas completely

Theoretically, any residual emission can be achieved, provided the cooling is strong enough. In practice, the temperature rarely goes below -95 °C and varies between -50 and -80 °C. The final dimensioning is based on a careful weighing up of the yield, residual emission and the amount of VOC recovered on the one hand and the investment and operating costs, including the nitrogen consumption, for example, on the other hand. Most systems are applied to relatively small waste gas streams (up to 50 m ^{3}/h) and for the processing of batch emissions, whereby the equipment is on stand-by during the most important part of the operating time. Full-continuous systems larger than 250 m ^{3}/h are less common, the largest units supplied are around 500 m ^{3}/h; for application larger than 1,000 m ^{3}/h condensing temperatures are as low as -30 °C. The systems are usually laid out for an efficiency of at least 99 %. If necessary, an adsorption technique (activated carbon, zeolite) is used afterwards in order to guarantee the emission target.

(monitoring)

The efficiency of the system is monitored by measuring the concentration of VOCs at the inlet and outlet. Cryogenic systems also require the measurement of pressure drop.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Compact, robust technology
- Good process control possible
- Recovery of the captured dust
- Limited heat recovery possible

4.2 Disadvantages

- A second cleaning step is almost always necessary in order to achieve emission limit values

4.3 Resources and energy

Condensation: condenser

Water:

In most cases, cooling takes place with a closed cooling system (indirect cooling) and no water is consumed. In direct cooling with water, water is consumed.

Chemicals

Not applicable.

Energy:

Electricity is needed for cooling the refrigerant in closed systems (chilled water, chilled brine and ammonia). This applies to both compression refrigeration and air cooling. Cryogenic cooling with nitrogen does not consume energy per se, but this must be seen in conjunction with the energy required to liquefy nitrogen.

4.4 Environmental considerations

Recovery:

Recovery of product is possible.

Air:

No other forms of air pollution are created during condensation.

Wastewater:

In the case of direct cooling with water, wastewater is produced which must be treated.

Waste:

No waste is created.

Safety:

Safety measures are in place when working with liquid nitrogen. In the event of leakage, cold hydrocarbon vapours may remain low to the ground, with a possible risk of explosion.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

7,500 - 15,000: cooling with chilled water or brine:
400,000: cryogenic cooling with nitrogen (total cost)

Operational costs [hours per week]:

Approximately 4

Staff [hours/week].

2: cooling with cooled water or brine
8: cryogenic cooling with nitrogen

Condensation: condenser

Material:

The choice of material depends on the temperature range. Cryogenic application makes additional demands on the material.

Energy [kWh/1,000 Nm^3]:

70: electricity for chilled water / brine

Benefits:

Recovered raw material / solvent

Cost determining parameters:

Temperature, cooling capacity, desired emission level

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS

4.9 Electric field: electrostatic filter

Electric field: electrostatic filter

Variations of the technology and synonyms

Electrostatic filter, *electrostatic precipitator, ESP, e-filter, electro-filter, electrostatic particulate collector*

Removed pollutants

Especially: droplets, particulate matter

1. Brief description

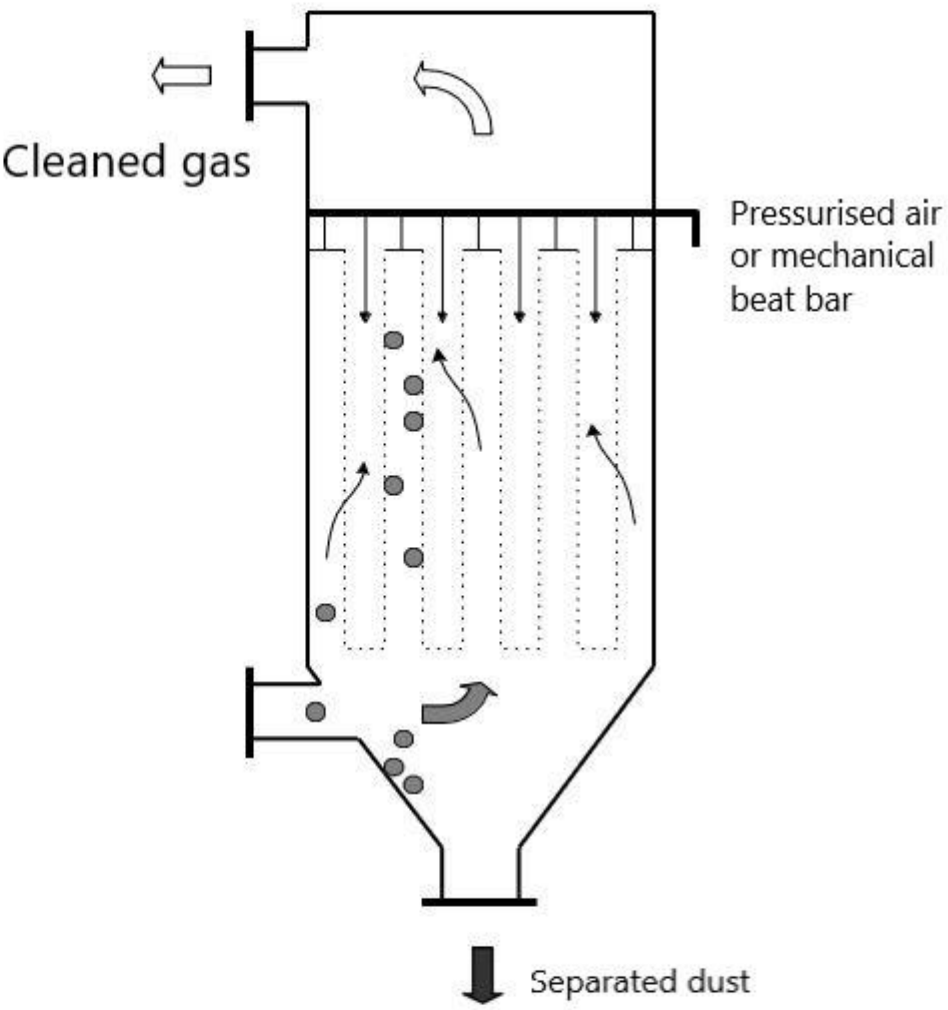
1.1 Description

The operating principle of electrostatic separation is based on the separation of ionized particles in a waste gas stream in an electric field. An electrostatic filter is a device that, by means of electric fields, charges particles (ionisation) and extracts them from a gas stream to collection electrodes. The electrical voltage required is in the order of 20 - 100 kV. The ionisation can take place in the same chamber as the particle collection (single-stage ESP), but a two-stage system is also possible. In that case, the particles are first ionized in a first electric field, after which the particles removal takes place in a second electric field. The separated particles fall down due to gravity and by periodic knocking or vibrating of the collecting electrodes and end up in a deposit hopper.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Electric field: electrostatic filter



2. Applicability

2.1 Scope

Electrostatic filters are used for the removal of particles from gas flows.

The scope includes:

- Power plants
- Waste incinerators
- Metallurgical industry
- Chemical Industry

Electric field: electrostatic filter

(SVHC)
The residual concentration of the electrostatic filter can meet the general emission requirement for dust. Lower residual concentrations that meet stricter requirements for SVHC are in principle also feasible.

2.2 Combination of technologies

Electrostatic filters can be used as a stand-alone technique or in combination with other technologies. Wet electrostatic filters are usually used as a final treatment step to remove residual particles and droplets after for example absorption.

2.3 Performance

The values presented depend on the specific configuration and operating conditions. In principle, the values are based on half-hourly average values. In certain situations, deviating values may be justified.

The data is taken from the BREF WGC D1 (2019) and BVT 2016 (Table 27) and applies to situations where an electrostatic filter was used as an independent technique.

Pollutant	**Removal efficiency [%]**	**Concentration after treatment [mg/Nm^3]**
PM	97-99	P10: 0,2 P50: 4,0 P90: 8,7

2.4 Preconditions

Flow rate [Nm^3/h]:
P10: 1.800
P50: 11.500
P90: 53.000

Temperature [°C]:
<700 (dry ESP),
80 - 90 (wet ESP)

Pressure [bar]:
Atmospheric

Pressure drop [mbar]:
0,5 - 5

Electric field: electrostatic filter

Moisture content:

Below the dew point of water.

Substance [g/Nm^3]:

1 - 10 for pipe filter

2 - 110 for plate filters

3. Detailed description

3.1 Variations of the technology

Plate filter

In a plate filter, the gas flow is passed between two or more plates. Between the plates there are wires which carry a high electrical charge, in the order of 20 - 100 kilovolt. The particles in the gas stream are ionised by this high voltage, after which their electrical charge attracts the particles to the plates. The plates are mechanically moved or 'knocked' so that the captured particles falls down into a particles bunker. This knocking down can cause some of the particles to re-enter the gas stream, reducing the efficiency of the filter. When too many plates are cleaned simultaneously, the residual emission will temporarily be higher. Therefore it is advantageous to limit the number of electrodes knocked simultaneously.

An electrostatic filter consists of one or more chambers over which the gas to be cleaned is discharged evenly. distributed. This is done by means of a gas distribution screen. The system consists of a number of independently operating and serially arranged fields. The first field removes the most of the dust, while the latter fields are there to keep residual emissions low. Independent controllable fields are preferred because of their operational reliability, each of these fields must be equipped with their own particles funnel.

The plates should be regularly beaten to prevent the 'fly ash layer' from becoming too thick which decreases the efficiency. However, when beaten too often, the 'fly ash layer' is not sufficiently thick, breaks into pieces and is carried away in the gas stream. The configuration of the plates is important in this regard, with low gas velocity zones and the height/width ratio of the sheets are decisive for a good return.

This technique can also be used 'wet', for example if the particles contains sticky particles or if the gas stream is very moist. In the 'wet' variation of the technology the plates are continuously or periodically rinsed with water in order to remove the particles. The particles bunker as present in dry ESPs is then replaced by a rinsing system.

Pipe filter

A pipe filter is similar to a plate filter, but instead of plates, parallel tubes are used. In these tubes, over the longitudinal axis, wires are stretched on which a high voltage is applied. The tubes are cleaned of particles by sound waves that vibrate the dust, after which the particles falls down in a particles bunker. A 'wet' variation of the technology is also possible.

Electric field: electrostatic filter

3.2 Installation, design and maintenance

The key design parameters are:

- Flow rate, larger flow rates require a larger electrode
- Particle composition and gas flow
- Moisture or stickiness of the dust, for the choice between a dry or wet version
- Particle size
- Electrical resistance of the particles

Electric filters are relatively sensitive to maintenance and proper adjustments. In particular, the discharge of particles and the knocking mechanism can cause additional maintenance.

(monitoring)

Continuous monitoring of the operation of the system is necessary. This includes at least monitoring of the outgoing particles concentration, the electrical voltage, the operation of the knock mechanism and the temperature of the gas flow. Regular inspection of the electrodes, insulating materials and mechanical systems is necessary to detect corrosion or clogging in a timely manner.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- High efficiency, also for small particles
- Suitable for a wide range of temperature, pressure and flow rate
- Recovery of particles is possible

4.2 Disadvantages

The main disadvantages are:

- Less suitable for gas flows with a fluctuating flow rate or a changing composition of the gas flow
- Large space occupation
- Sensitive to maintenance and correct adjustments (complex electronic control)
- Explosion risk for dry ESPs
- Efficiency is dependent on the electrical resistance of the particles to be captured

4.3 Resources and energy

Water:

Not applicable for dry ESP. In the 'wet' version, rinse with water to remove particles.

Chemicals:

SO_3 or NH_3 can be added to the gas stream to lower the electrical resistance of particles and thus increase removal efficiency.

Energy consumption:

Generation of electrostatic field and pump for wet variation of the technology.

Electric field: electrostatic filter

4.4 Environmental considerations

Recovery:

Product recovery is possible. Fly ash from waste gases is used as a raw material for construction.

Air:

No other forms of air pollution are generated

Wastewater:

Wet ESPs create a wastewater stream that needs to be treated.

Waste:

The captured particles can be waste if it is not reused. Depending on the composition of the gas stream, it can be that heavily polluted particles that must be disposed of as hazardous waste.

Safety:

Systems with an increased risk (explosion, fire) must be fitted with safety measures such as an expansion hatch, or water sprinklers.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

20,000 - 60,000 (dry ESP), wet variations of the technology are usually ~30% more expensive.

Operating costs [EUR per 1,000 Nm/hour per year]: ^{3}

Approximately 0.1 - 1 (only electricity costs)

Staffing [hours/week]:

2

Material:

No consumption of material.

Energy consumption [kWh/1,000 Nm^3]:

0,2 - 2

Benefits:

Cost savings on raw material if recycling is possible or market value of the captured dust.

Cost determining parameters:

Flow rate, discharge temperature, particulate concentration and any costs for disposing of the captured dust.

Electric field: electrostatic filter

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BVT 2016 (Table 27)
4. VITO LUSS: Dry and wet electrostatic filter

4.10 Filtration: dust filter

Filtration: dust filter

Variations of the technology and synonyms

Fabric filter, *hose filter, bag filter, compact filters, cassette filter, envelope filter*

Ceramic filter, *Ceramic filter, high temperature filter, candle filter*

Two-stage fabric filter, *metal mesh filter*

Absolute filter, *HEPA filter, surface filter, cartridge filter, microfilter*

Removed pollutants

Especially: particles

To a lesser extent: odour

1. Brief description

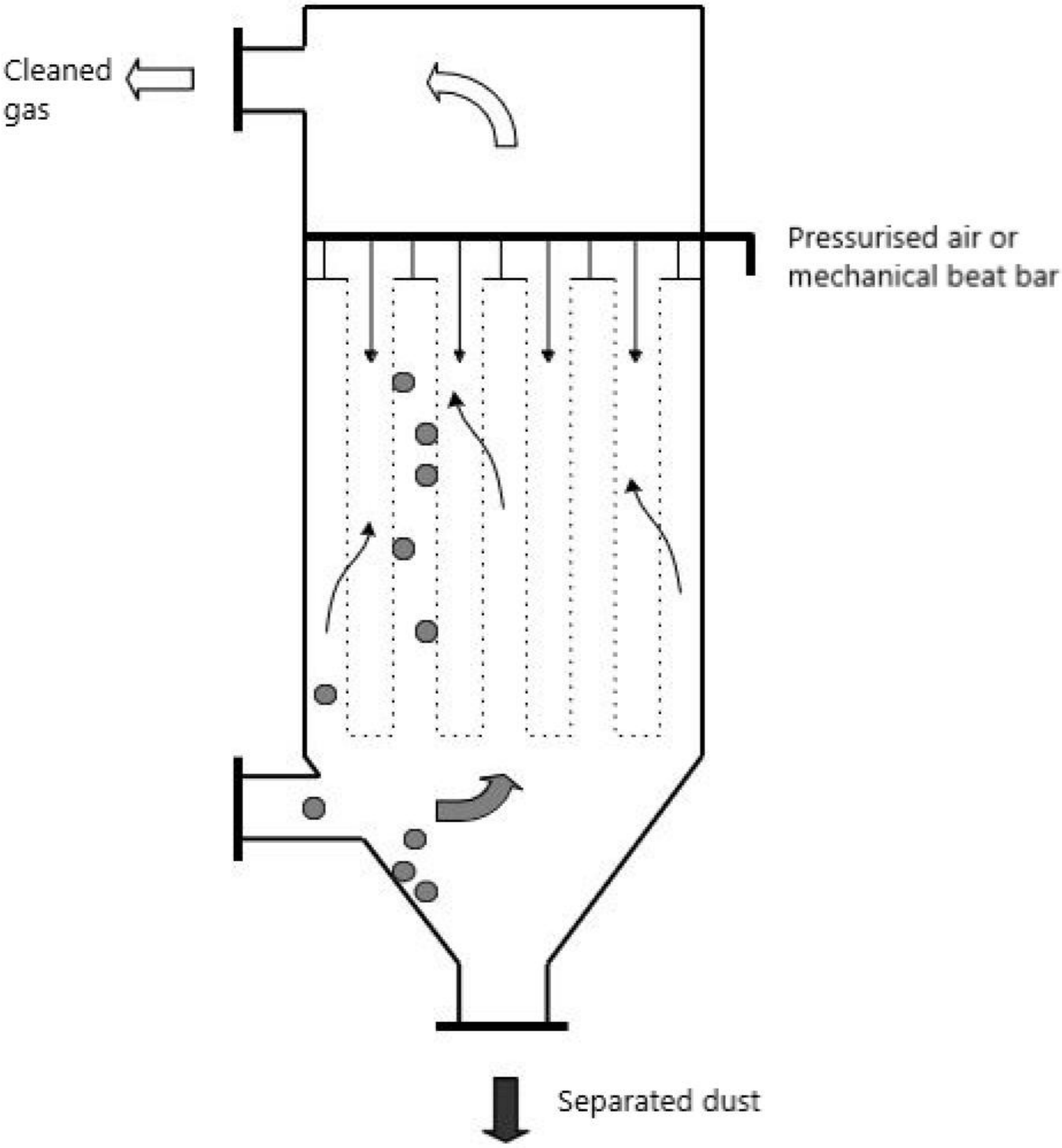
1.1 Description

The operating principle of a fabric filter is the separation of particles from a waste gas on the basis of their size. Particles larger than the filter mesh are retained, smaller particles pass through the filter. The air polluted with particles is led through a filtering material and the particles are removed. The particles are periodically removed from the filter and collected in a hopper located below the filter installation.
The filter material has many designs and can be made of cloth, plastic, metal or ceramic material. The different materials can make the installation suitable for a specific waste gas flow or the particles to be captured. The filter material can be applied in different ways such as hoses, envelopes, etc.
The incoming air usually does not flow directly to the filter, but is led through one or more distribution plates. The purpose of this is to ensure a better distribution over the filter material cloths, so that they are more evenly loaded. Also, the air loses a large part of its kinetic energy, causing a pre-separation of higher density particles under the influence of gravity.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Filtration: dust filter



2. Applicability

2.1 Scope

(general)

The most commonly used filter material is textile cloth. Fabric filters are primarily used for the removal of particles and particles up to <PM2.5. Smaller particles can also be captured if the type of filter is geared to that, such as a HEPA filter. Heavy metals that are present on the particles are also captured.

In combination with injection systems with for example active carbon or catalyst material on the filter cloth, the technique can also be applied for the removal of specific gaseous pollutants such as HCl, mercury and dioxins.

Filtration: dust filter

(sectors)

Wide range of applications in the following sectors, among others:
- Waste processing industry
- Chemical Industry
- Metalworking industry
- Feed industry
- Food and beverage industry

Variation of the technology with ceramic filter are mainly used in the sectors:
- Combustion plants and gasification systems fuelled by coal
- Waste processing industry
- Plastic processing industry
- Chemical Industry
- Glass industry

Variation of the technology with HEPA filters are used in situations where a 'zero' emission is necessary, for example in the pharmaceutical industry.

(SVHC)
The residual concentration of fabric filters meets the general emission requirement in most cases. Lower residual concentrations that meet stricter requirements for SVHC are, in principle, also feasible, whether or not with ceramic filters or several stages.

2.2 Combination of technologies

The fabric filters can in practice be combined with almost all other technologies. Before the fabric filter a gravitational separator is often placed, such as a cyclone or sedimentation chamber, so that the heaviest particles are caught in advance and do not burden the fabric filter.
Before or after the filter, adsorption filters can be placed to capture VOC, dioxins and furans. Combinations with a thermal incinerator are also known. In practice, a fabric filter can also be part of an adsorption system. In this case, a reactive substance, such as lime, is injected in front of the filter. The lime reacts with acidic substances and is then adsorbed by the fabric filter.

2.3 Performance

The performance is shown in the following table. The values presented depend on the specific configuration and operating conditions. In principle, the values are based on half-hourly average values. In certain situations, deviating values may be justified.
The data on general particles and SVHC particles were taken from BREF WGC D1, 2019 (in particular the 10-percentile and the 90-percentile). The data on dioxins/furans were taken over unchanged from the previous version of the guidance.

Filtration: dust filter

Pollutant	Removal efficiency, %	Concentration after treatment, mg/Nm^3
General particles	99 - 99,9	0,5-5 P10: 0,1 P50: 0,4 P90: 4,8
SVHC particles		0,02-0,2
Dioxins/furans	99	0,1 ng/m^{3}ITEQ

By providing the filter material with a catalyst and/or in combination with injection of adsorbents, gases in the waste gas stream can also be treated.

Removed pollutants	Removal efficiency [1], %	Concentration after treatment, mg/m^3 $_0$
HCl	95	unfamiliar
Mercury vapour	NI	NI
SO2	80	unfamiliar
NOx	95	< 200
dioxin	99	unfamiliar

2.4 Preconditions

Flow rate [Nm^3/h]:

300 - 2.000 - 19.000
(10th percentile - Median - 90th percentile)
Reproduced from WGC BREF, D1, 2019

Temperature [°C]:

< 280 for fabric filters
< 500 for wire mesh filters
< 1,200 for ceramic filters.

Pressure [bar]:

atmospheric

Pressure drop [mbar]:

up to 15 for fabric filters
up to 25 for ceramic filter

Filtration: dust filter

Moisture content:

Above dew point

Substance [g/Nm^3]:

0,1 - 230 for fabric filter
< 20 for ceramic filter
No limitation for metal mesh filter

3. Detailed description

3.1 Variations of the technology

Ceramic filter

With a ceramic filter the particle contaminated waste gas is passed through filter material. The filter ensures that particles remain in the filter material and the waste gas is cleaned. The difference with a fabric filter is that the filter material is ceramic. There are types of ceramic filters which also capture acidifying gases such as HCl, NOx and Sox, but also dioxins. In those situations, a reactive filter cloth is used. The filter material is then provided with catalyst material and injection of substances for the filter may be necessary.

The filter material of the ceramic filter can be applied in different forms. It is possible to process the ceramic material into cloth, fibre felt, fibre elements, sintering element or filter candles.

The main advantages over a fabric filter are 1) higher efficiency possible and 2) resistance to high temperatures and aggressive substances such as acids and bases.

The main disadvantages are 1) higher investment and operational costs and 2) vulnerable equipment.

The table below gives an overview of the different types of implementation:

filter medium	filter cloth [1]	fibre felt	fibre element	sintering element
Implementation	bag of support basket	bag of support material	tube, self-supporting	pipe, candle, self-supporting
Surface area weight (g/m^2)	1.000 - 2.000	2.500 - 3.500	2.000 - 3.500	12.500 - 22.800
Mechanical Properties	flexible, low abrasion-proof	flexible, low abrasion-proof	half star, moderate abrasion-proof	rigid, abrasion-proof
Air permeability	High	moderate	moderate	small

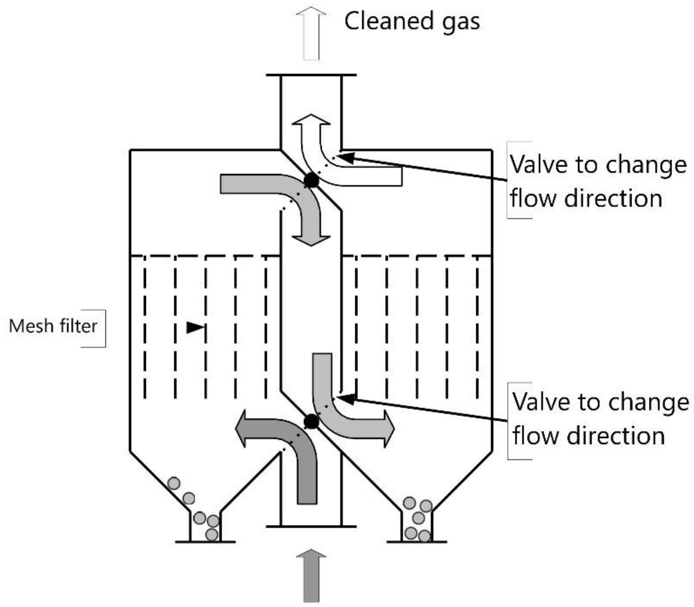
[1] Cloth with ceramic material.

Absolute filter

The gas stream to be cleaned is led into a chamber and passed through what is called a High Efficiency Particle Air filter (HEPA filter). The filter material of a HEPA filter consists of thin glass fibres encased in paper or a paper filter. In order to obtain the largest possible filter surface area, this glass fibre paper is folded like a harmonica. This is necessary because the dense mass of the glass fibre paper allows little air to pass through. To move a sufficiently large amount of air, a large surface area is required. The particulate matter remains on the filter, but does not

Filtration: dust filter
penetrate into it. It is therefore a process of surface filtration. The particulate layer that settles on the filter can initially have a positive influence on the particles collection efficiency. If the pressure drop across the filter becomes too great, after some service time, it should be replaced. The HEPA filter can be placed directly in a pipeline or in a separate housing. HEPA filters do require a pre-treatment step to capture the coarser dust, therefore HEPA filters are often the final filtering step for particles removal. HEPA filters are rarely reused, as cleaning can cause damage and leakage of the filter. The main advantage over a fabric filter is a low residual concentration, even for small particles. The main disadvantages are 1) often pre-filtration is required and 2) more frequent replacement of filter material.
Compact filter (Improved) Compact filters, also called cassette filter or envelope filter. Compact filters are produced in different sizes and capacities. Often standard units are used from which filter installations with larger capacities can be built. The difference compared to the fabric filter is the compact construction and the way the filter elements are placed in the filter housing. They are placed in such a way that they can easily be replaced. Synonyms are Sintamatic, Sinterlamb filter, Spirot Tubes.
Two-stage dust filter The two-stage dust filter contains metal gauze as the filter material. A filter cake is built up in the first filtration stage and the actual filtration takes place in the second stage. Depending on the pressure drop across the filter, the second stage is cleaned and the system switches between the two stages (step one becomes the second and vice versa). A mechanism to remove the filtered dust is integrated into the system. The dust particles drop to the bottom of the chamber where it has to be removed. A variation of the standard two-stage dust filter is a system with more than two metal mesh filters where a filter cake is first built up before the filter is placed in the gas stream to be cleaned. This prevents the treatment efficiency of the filters from decreasing just after treatment. The most important advantages compared to a fabric filter are 1) higher filter loading is possible, 2) high temperature resistance (up to approx. 500°C) and 3) also applicable for moist, sticky, fibrous or static dust. The main disadvantages are 1) the frequent changing between the two compartments (with a normal two-stage filter) which temporarily reduces the efficiency and 2) valves needed in a dusty environment which leads to a greater chance of malfunctions.

Filtration: dust filter



Catalytic cloth

For specific applications, catalysts can be processed into the cloth, so-called catalytic cloths. Vanadium/titanium is used as catalyst. The most important application is the removal of dioxins and furans, but other pollutants such as VOC, PAHs, PCBs and other chlorinated compounds can also be removed.

Reactive filter cloth

This filter material has the characteristics that it breaks down dioxin/furans instead of adsorbing them. The material can withstand a temperature of 260°C and has an optimal performance around an operating temperature of 220°C.

Cloth material

Different types of cloth can be used for different applications. A number of examples are given below.

Material	**Chemical resistance**		**Corporate temperature, ºC**
	Acidic environment	**Basic environment**	
Polyester	Good	Fair	130
M-Aramid	Good	Good	200
PTFE	Very Good	Very Good	260
Polyamide	Good	Good	260

3.2 Installation, design and maintenance

The key design parameters are:

- Exhaust gas flow
- Operating temperature and maximum temperature
- Gasket composition

Filtration: dust filter

- Filter cloth load (filter ratio). The filter cloth load depends on the type and nature of the cloth material, the particles load, the type and particle size of the dust. Examples are for fiberglass: 60-120 m/hr; and for PTFE (Teflon): 80-100 m/hr.
- In the food industry, the cleanability and design of the housing are important for hygiene reasons.

Filter cloths: 11 - 17 m ^{2}per 1,000 Nm ^{3}/h.

The most common filter materials are cotton, wool, nylon, polypropylene, Orlon, Dacron, Dynel, glass fibre, Nomex, polyethylene and Teflon. Precoating of the filter cloth may be necessary with sticky or static substances to protect the cloth.

(monitoring)

The operation of the filter can be checked by measuring the particle concentration in the effluent gas. This can be done by means of for example an isokinetic sampler, UV/translucent meter, etcetera. Temperature and pressure should be checked regularly. The pressure drop over the filter determines when the treatment cycle must be started. Regular inspection of the filters is necessary to check for deterioration of the filters and casing. The filter unit needs to be easily accessible for maintenance and repair operations. A properly maintained fabric filter must have a leak detection system with alarm to prevent uncontrolled emissions.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Commonly known technique
- Modular structure, can be adapted to the task at hand
- High removal efficiency
- Changing load does not affect pressure drop and efficiency
- Captured particles can be reused as raw material

4.2 Disadvantages

The main disadvantages are:

- Not suitable for wet or sticky substances because of filter clogging
- Operating risk
- Possible electrostatic charge
- Large space occupation

4.3 Resources and energy

Water

Not applicable.

Chemicals:

Chemicals can be added to the off-gas flow before the filter.

Filtration: dust filter

Energy consumption

Compressed air: 3 - 7 bar required for cleaning the filter elements and for compressed air and ultrasonic cleaning.

4.4 Environmental considerations

Recovery:

Recovery of product is possible.

Air:

No other forms of air pollution are generated

Wastewater:

No wastewater is generated.

Waste:

Residual materials are the captured particles and the used cloths. The quantities depend on the application.

Safety:

Systems with an increased risk (explosion, fire) must be fitted with safety measures such as expansion shutters or sprinklers.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

1,000 - 9,000 for standard models.

30.0000 - 55.000 for ceramic filters and metal mesh two stage filters

Operating costs [EUR per 1,000 Nm^3/hour per year]:

Approximately 200 - 1,500

Staffing [hours/week]:

2

Material [EUR per 1,000 Nm/hour]: ^{3}

660 - 2.000 (filter material)

Energy consumption [kWh/1,000 Nm^3]:

0,2 - 2

Benefits:

Cost savings on raw material if recycling is possible or market value of the captured dust.

Filtration: dust filter

Cost determining parameters:

Characteristics of particles to be captured (for example explosive, particle size distribution, stickiness), temperature, pressure drop and possible cost of disposal of captured dust

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BVT 2016
4. VITO LUSS: fabric filter

4.11 Filtration: mist filter

Filtration: mist filter

Variations of the technology and synonyms

Mist filter, *demister, droplet filter, aerosol filter, deep bed filter, knock-out drum*

Removed pollutants

Especially: droplets

1. Brief description

1.1 Description

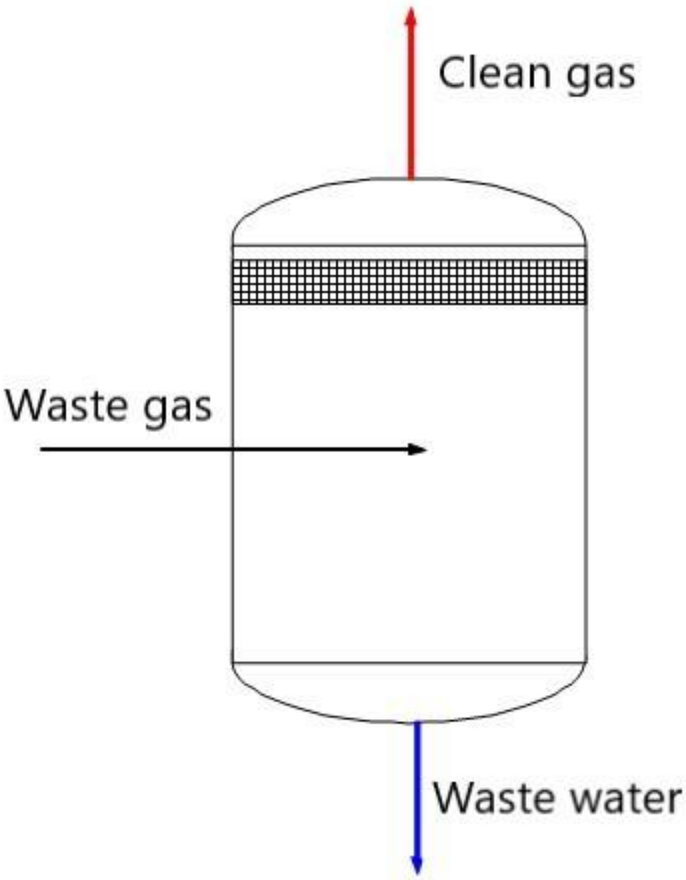
The operating principle is based on the separation of liquid droplets from gases in a waste gas stream by a difference in mass. The waste gas flow is led through a filter where the liquid droplets collide and sink under gravity. The gases and vapours in the waste gas stream pass through the filter. The effect depends on the gas velocity and the meshes of the filter.

In addition, there are designs in which the separation is promoted by rotating vanes against which droplets collide and slide off the vanes as a result of centrifugal force.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Filtration: mist filter



2. Applicability

2.1 Scope

(general)
Mist filters are usually part of other technologies, for example of a gas scrubber. The area of application is indicated for those technologies.

(SVHC)

Mist filters are not used as an independent technique to capture SVHC, because the emission concentration to be achieved is not low enough.

2.2 Combination of technologies

Mist filters are often part of other technologies, either as a pre or post filter. For example, it is common practice to use mist filters to capture oil and water droplets prior to a fabric filter. Mist filters are the last part of gas streams saturated with moisture, such as from gas scrubbers.

Filtration: mist filter

2.3 Performance

The performance is indicated in the following table. The residual concentration is determined by the saturated vapor concentration at the operating temperature and pressure. A smaller mesh size can capture smaller droplets, but is also more susceptible to clogging. The values presented depend on the specific configuration, operating conditions and dust particles to be captured. The values are in principle based on half-hourly average values. There are no emission limit values for liquid droplets, so 'not applicable (NA) is indicated for concentration after treatment.

Pollutant	Removal efficiency, %	Concentration after treatment, mg/Nm^3
Droplets	99	NA

2.4 Preconditions

Flow rate [Nm ^{3}/h]:

Up to 150,000 Nm ^{3}/ hour

Temperature [°C]:

-5 - 170

Pressure [bar]:

Atmospheric

Pressure drop [mbar]:

2,5 - 9

Moisture content [%]

Saturated vapours

Particles:

< 1 mg/Nm ^{3}, no sticky particles because of clogging risk,

Incoming concentration:

In the order of grams per Nm^3.

3. Detailed description

3.1 Variations of the technology

Static mist filter

A mist filter may consist of metal mesh or woven synthetic yarn (also called fibres or filaments). The captured fluid flows away from the mist filter, which means that, in principle, a mist filter is self-cleaning. As a result, small

Filtration: mist filter

quantities of dust particles can also be captured; they will be flushed away with the fluid. High concentrations of dust, or sticky liquids, will clog the mist filter. This does not have to be a problem if an exchangeable filter is used.

Centrifugal mist filter

A perforated drum with specially designed blades rotates at high speed. Oil mist is drawn into the unit and hits the blades at high speed. Special drum plates assist in the coalescence process (confluence of small droplets and dust particles into large droplets). The centrifugal force propels the droplets towards the housing, where the liquid flows back and can be collected for reuse.

3.2 Installation, design and maintenance

The key design parameters are:

- Mesh size
- Degree of saturation of the waste gas stream
- Outlet temperature

Specific attention is required for the cleaning method of the filter. If the off-gas flow only contains liquids, a mist filter is in principle self-cleaning because the captured liquid flows down by gravity, back into the process (or the gas scrubber). Dusty or sticky contaminations require regular filter cleaning or replacement.

(monitoring)

Monitoring of the pressure drop is necessary to detect any clogging or tear in the mesh.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Cheap, simple technique

4.2 Disadvantages

- A second treatment step is almost always necessary in order to achieve emission limit values
- Risk of clogging by solids and greasy vapours

4.3 Resources and energy

Water:

Possible consumption of scrubbing water for cleaning.

Chemicals:

Not applicable.

Energy:

Electricity consumption of fans may increase due to pressure drop.

Filtration: mist filter

4.4 Environmental considerations

Recovery:

Recovery of product is possible.

Air:

No other forms of air pollution are created.

Wastewater:

Captured fluid can usually be returned to the process or the gas scrubber. If the mist filter needs further treatment, this may be a wastewater flow.

Waste:

No waste is created unless the collected fluid has to be treated as waste. In addition, the material of synthetic mist filters must be replaced periodically, which counts as waste.

Safety:

No specific safety measures are required.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

2,500

Operating costs [EUR per 1,000 Nm^3/hour/year].

2,500 + (450 x flow rate/1,000)

Staff [hours/week].

2

Material:

No consumption of material.

Energy [kWh/1,000 Nm ^{3}]:

0

Benefits:

Recovered raw material / solvent

Cost determining parameters:

Flow rate, pressure drop, material selection

Filtration: mist filter

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS: mist filter
5. Supplier : SMC Corporation

4.12 Gravitation: settling chamber

Gravitation: settling chamber

Variations of the technology and synonyms

Sedimentation chamber, *gravity separator, trap chamber, inertial separator*

Impact filter

Removed pollutants

Especially: droplets, dust particles

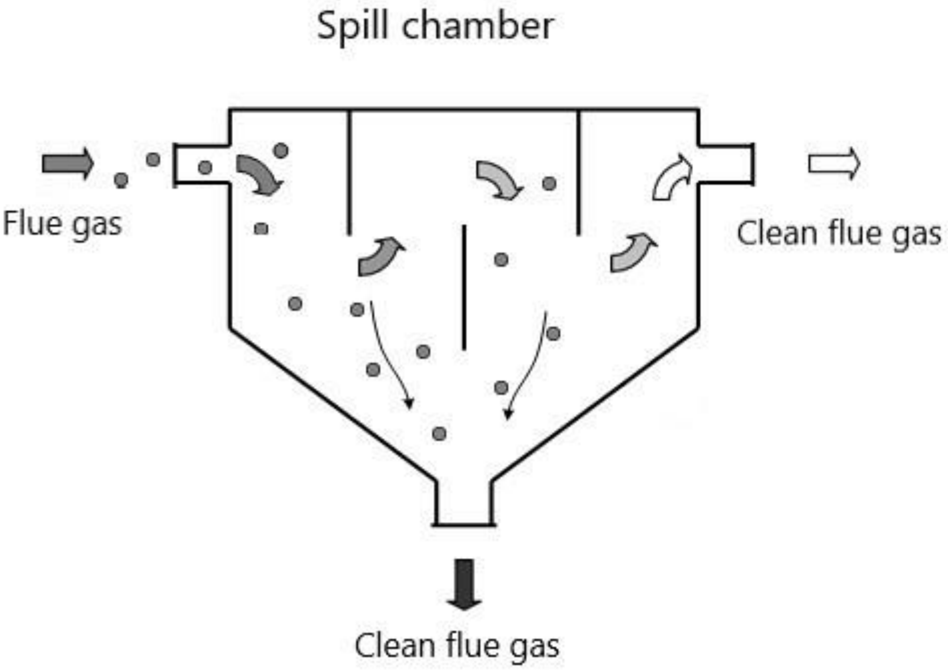
1. Brief description

1.1 Description

The operating principle is the separation of solid particles (particles and gases in a waste gas stream utilizing the difference in mass between solids and gases. Solid and liquid particles settle under the influence of gravity.
The polluted gas stream is led into a chamber, causing the gas velocity to decrease. At low speed more particles will sink under the influence of gravity. The precipitated particles, possibly containing liquid droplets, can then be discharged through a funnel at the bottom. The treated gas leaves the chamber on the side opposite the entrance.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.



2. Applicability

2.1 Scope

(general)

Gravitation: settling chamber

A settling chamber is used as a low-cost pre-separator. Sedimentation chambers are suitable for catching hot particles before the waste gas stream is transported to an end-of-pipe technology. Due to the low yield and high residual emission, post treatment will be necessary.

Settling chambers have a wide range of applications in the following sectors:

- Wood and furniture industry
- Construction industry
- Brickyards
- Glass industry
- Storage and transhipment
- Ferrous and non-ferrous

(SVHC)

Sedimentation chambers are not used as an independent technique to capture SVHC, because the emission concentration to be achieved is not low enough.

2.2 Combination of technologies

A sedimentation chamber is always combined with other end-of-pipe technologies. A settling chamber captures the heaviest, largest particles so that the load on the following technologies is reduced.

2.3 Performance

The performance is shown in the following table. The values presented depend on the specific configuration, operating conditions and dust particles to be captured. The values are basically based on half hour average values.

Pollutant	**Disposal efficiency [%]**	**Concentration after treatment, [mg/Nm^3]**
PM150	90	> 100
PM30	10	> 100

2.4 Preconditions

Flow rate [Nm^3/h]:

Up to 180,000 Nm^3/ hour

Temperature [°C]:

No limitation, depending on choice of material.

Gravitation: settling chamber

Pressure [bar]:
Atmospheric

Pressure drop [mbar]:
0,5 - 2,5

Moisture content [%]
No limitation

Substance [g/Nm^3]:
No limitation

3. Detailed description

3.1 Variations of the technology

Open settling chamber

Gravity crossflow separators: The flow direction of the waste gas in the separator is horizontal. Under the influence of gravity, the particles sink perpendicular to the flow direction.

Gravity countercurrent flow separator: The flow direction of the waste gas in the separator is vertical. Under the influence of gravity, the particles sink in the opposite direction to the flow direction.

Impact filter

By incorporating several obstacles, such as plates, the gas flow is diverted. Due to their inertia, the particles cannot follow in the same direction as the gas flow and are therefore separated from it.

3.2 Installation, design and maintenance

Settling chambers can be built of various materials, including steel, stainless steel and plastic (polystyrene (PS), polyvinyl chloride (PVC) and polyvinylidene fluoride (PVDF)), depending on the corrosive and abrasive nature of the waste gas and the temperature. When using settling chambers, a good uniform velocity distribution is of the utmost importance. Preferential flows have a detrimental effect on the operation. By using internal obstructions (baffles), the efficiency is improved as higher gas speeds are possible, which results in a reduction of the sedimentation chamber. The disadvantage is that the pressure drop over the system increases. Leakage of cold air to the settling chamber must be prevented to prevent condensation of the gas stream. Condensation can lead to corrosion, dust accumulation and clogging.

(monitoring)

The most common cause of malfunction is accumulation of dust particles in the room due to dust. This can be prevented by periodic visual inspection of the chamber.

4. Environmental aspects

4.1 Advantages

The main advantages are:

Gravitation: settling chamber

- Simplicity of the system
- Dust Recovery

4.2 Disadvantages

- Unsuitable for small particles; only suitable for coarse particles (> 15-150 µm)
- Low separation efficiency
- Unsuitable for sticky particles

4.3 Resources and energy

Water:

Possible consumption of wash water for cleaning the chamber and bulkheads. Depending on the application, 100 - 200 litres /m^2 is usual.

Chemicals:

Not applicable.

Energy:

No

4.4 Environmental considerations

Recovery:

Recovery of product is possible.

Air:

No other forms of air pollution are created.

Wastewater:

If the settling chamber needs cleaning then there may be a wastewater flow.

Waste:

No waste is generated unless the captured substance is to be treated as waste.

Safety:

No other safety measures are required other than for the off-gas. For example, the waste gas may be susceptible to dust explosion.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

1.000 - 1.500

Operating costs [EUR per 1,000 Nm^3/hour/year].

200

Gravitation: settling chamber

Staff [hours/week].

2

Material:

No consumption of material.

Energy [kWh/1,000 Nm ^{3}]:

0

Benefits:

Recovered dust

Cost determining parameters:

Flow rate, particles load

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. VITO LUSS: settling chamber
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016 (3.5.1.4.2)

4.13 Gravitation: cyclone

Gravitation: cyclone

Variations of the technology and synonyms

Cyclone, *particulate cyclone, vortex separator*

Multicyclone

Removed pollutants

Especially: dust particles

To a lesser extent: droplets, odour

1. Brief description

1.1 Description

The operating principle is the separation of solid and liquid particles from the waste gas stream according the difference in mass. The solid and liquid particles are separated by centrifugal force.
The waste gas is drawn or blown tangentially (at an angle to the wall) into a cylindrical chamber, which causes the waste gas to rotate in the cyclone. The rotation creates a centrifugal force and the particles are flung towards the wall, after which the particles are discharged at the bottom by gravity. The separation effect is often enhanced by reversing the direction of the gas flow. The solid particles do not change direction with the gas flow because of the inertia and therefore continue to sink. The treated gas leaves the cyclone through the top of the chamber.

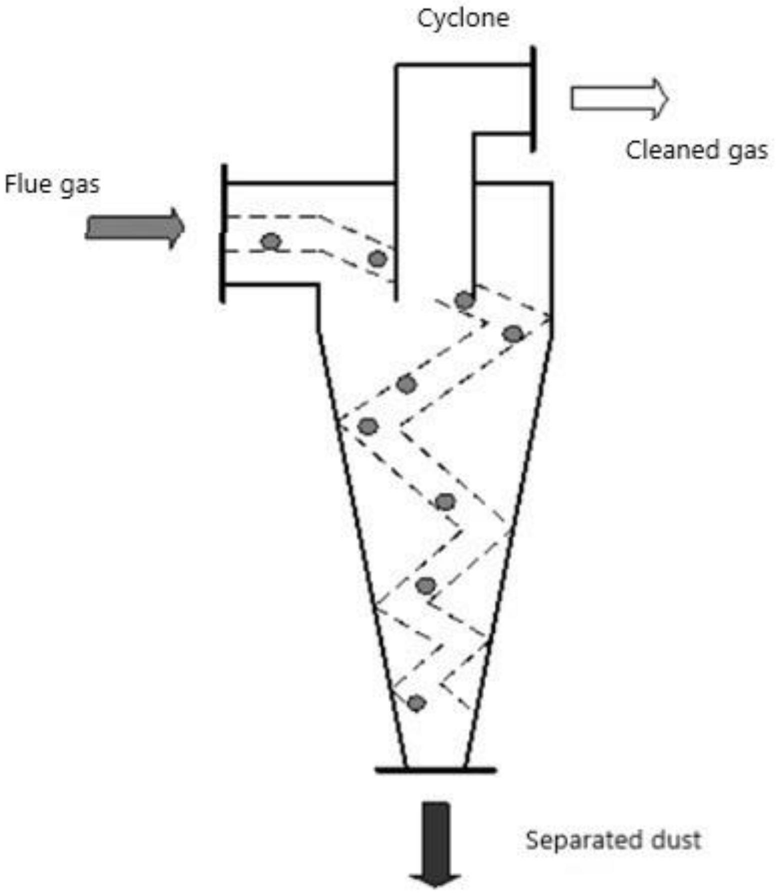
The performance of a cyclone gets better with an increase of:
- Particle size and density
- Aspiration rate in the cyclone
- Length of the cyclone, and therefore the number of vortices that the gas flow can make in the cyclone
- Ratio of diameter of cyclone versus diameter of exhaust
- Inbound concentration of dust
- Smoothness of the inner wall of the cyclone

An efficient cyclone has high gas velocities, a small diameter and a long cylinder.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Gravitation: cyclone



2. Applicability

2.1 Scope

(general)
A cyclone can be used as a stand-alone technique but is usually used as a pre-separator to remove the largest particles load. The pre-separation is usually carried out for particles with a diameter larger than 5µm.

Cyclones have a wide range of applications in many industrial sectors, including:
the following sectors:
- Wood and furniture industry
- Construction industry
- Glass industry
- Storage and transhipment
- Food industry
- Waste incinerators
- Chemical industry

Gravitation: cyclone

- Melting processes in metallurgy
- Sintering processes
- Coffee roasting
- Other food industry

(SVHC)

Cyclones are not used as an independent technique to capture SVHC, because the emission concentration to be achieved is not low enough.

2.2 Combination of technologies

In general, a cyclone is a preceding technique for a fabric filter, a scrubber or an electrostatic filter (ESP). The cyclone captures the heaviest, largest particles so that the load on the other technique is reduced.

2.3 Performance

The performance is shown in the following table. The values presented depend on the specific configuration, operating conditions and particles to be captured. The values are basically based on half-hourly average values. The data is taken from the BREF WGC D1 (2019), BVT 2016 (Table 27) and the 2009 Fact Sheets and applies to situations where a cyclone has been used as an independent technique.

	Cyclone	
Pollutant	**Removal efficiency [%]**	**Concentration after treatment [mg/Nm^3]**
PM (6-10 µm)	50	-
PM (10-50 µm)	90	-
PM (>50 µm)	99	-
PM	90-99	P10: 0,3 P50: 3 P90: 9

2.4 Preconditions

Flow rate [Nm ^{3}/h]:
P10: 1.000
P50: 9.000
P90: 95.000

Gravitation: cyclone

Temperature [°C]:
No limitation, depending on choice of material.

Pressure [bar]:
Atmospheric

Pressure drop [mbar]:
0,5 - 2,5

Moisture content [%]
No limitation

Dust particles:
1 - 16.000 gram/Nm ^{3}

3. Detailed description

3.1 Variations of the technology

Cyclone with reversed gas flow (reverse flow)
A cyclone in which the direction of the gas flow is reversed (reverse flow) is the most common type of cyclone. The gas is sucked or blown into the cyclone from above, at an angle to the wall, and swirls downwards. The top of the cone is where the diameter is at its widest. Due to the cone shape which decreases in diameter, the gas velocity increases as the gas circulates downwards through the cone, thereby increasing the centrifugal force. At the bottom is a pipe that leads the gas upwards again, thus reversing the direction of the gas flow.

High-*throughput* cyclones have a diameter of more than 1.5 m and are suitable for separating particles of 20 µm and larger. High *efficiency* cyclones (pencil cyclones) have a diameter of between 0.4 and 1.5 m and are suitable for separating particles of 10 µm and larger. The performance is indicated as 60-95 % efficiency for PM10 and 20-70 % efficiency for PM2.5.

Multicyclones
Cyclones with a diameter of between 0.005 and 0.3 m are no longer used individually but are assembled in parallel to form multicyclones. In this case, the gas is no longer flowing laterally (tangentially) as in an ordinary cyclone, but parallel to the axis (axial), after which the gas is vortexed via guide vanes. A multicyclone is sensitive to the correct distribution of the gas over the small cyclones. If the distribution is not correct, backflow of gas and clogging can occur.
With multicyclones it is possible to capture smaller particles than with the usual cyclones. The performance is indicated as 80-95 % efficiency for PM5.

Wet cyclone
In order to increase the separation efficiency of small particles (< 20 µm), water is sprayed into the supply line just in front of the cyclone. The water binds with the particles and is discharged as a slurry. A variation of the technology of

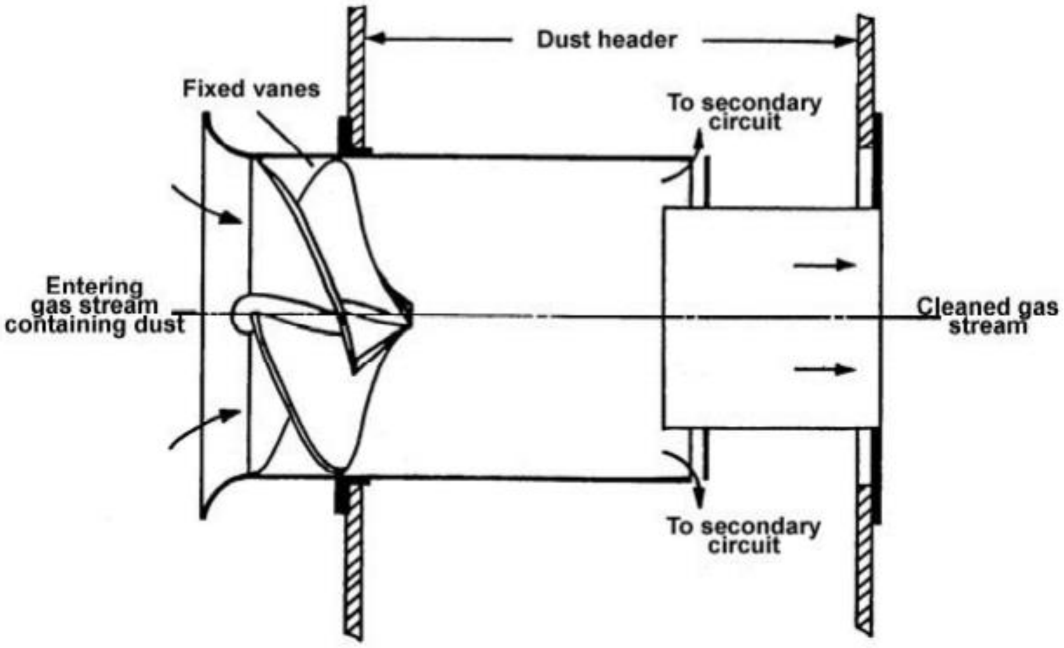
Gravitation: cyclone

this is the condensation cyclone. This cyclone is cooled using a cooling agent. When the temperature is below the dew point, substances such as fats and water condense and can then be separated in the cyclone.

Electro-cyclone
By creating an electric field between the centre and the wall of the cyclone, the driving force on the particles towards the wall is increased, resulting in a higher separation efficiency.

Wringing separator
The operation of the 'Wringing' separator is based on the phenomenon of secondary flows in a boundary layer in addition to the operation by centrifugal forces. The system consists of a spiral-shaped interior. The system has an efficiency of more than 99.5% for particles larger than 1 µm, which distinguishes it from classic cyclones (supplier information).

Cyclone with straight-through gas flow
This variation of the technology is not conical, but a straight tube. At the inlet of the gas stream, blades are mounted, causing the gas stream to spiral around the central axis. The centrifugal force pushes the particles against the wall of the cyclone.



3.2 Installation, design and maintenance

The key design parameters are:

- Dimensions (length, diameter)
- Flow rate

Gravitation: cyclone

The air entry speed of a cyclone is between 10 and 20 m/s, the most common speed is approximately 16 m/s. As the speed decreases, the separation efficiency decreases rapidly.

The maintenance requirements of a cyclone are simple; it must be easily accessible for periodic inspection for corrosion or erosion. The pressure drop should be checked regularly and the dust collection system should be checked for clogging.

A cyclone is a significant source of noise pollution. Measures such as enclosure are necessary to reduce noise.

(monitoring)

Monitoring is in principle not necessary for process operation but differential pressure measurements are common to detect clogging. To monitor the efficiency of the cyclone, the particles concentration in the cleaned gas stream can be determined by means of isokinetic sampling (without affecting the flow of the gas).
disruptors) or a measurement method based on, for example, UV, visible light transmittance, beta radiation or particle detection.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Simplicity of the system, no moving parts, low maintenance
- Low investment and operating costs
- Relatively little space required

4.2 Disadvantages

- Low efficiency, especially for small particles
- Poor part load performance
- Sensitive to wear, especially with corrosive or abrasive particles
- Not suitable for sticky substances
- Noise

4.3 Resources and energy

Water:

Hydrocyclones consume water. In addition, wash water may be required for cleaning.

Chemicals:

Not applicable.

Energy:

Electricity consumption of fans may increase due to pressure drop.

Gravitation: cyclone

4.4 Environmental considerations

Recovery:

Recovery of product is possible.

Air:

No other forms of air pollution are created.

Wastewater:

The particulate slurry from a wet cyclone must be post-treated and the remaining water will need to be treated in a wastewater treatment plant or otherwise. Wastewater can be generated when a cyclone is wet cleaned.

Waste:

No waste is generated unless the captured substance is to be treated as waste.

Safety:

No specific safety measures are required.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

500 - 1.500

Operational costs [EUR per 1,000 Nm^3/hour/year].

No direct costs. Maintenance costs may be high due to wear and tear.

Staff [hours/week].

2 (for residual particles removal, therefore, depending on the particles load)

Material:

No consumption of material.

Energy [kWh/1,000 Nm^3]:

30 - 250

Benefits:

Recovered dust

Cost determining parameters:

Flow rate, pressure drop, wear resistance, operating temperature

Gravitation: cyclone

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS: Cyclone
5. Supplier: Wringing Italia, Mesys Industrial Air Systems

4.14 Cold oxidation: ionizer

Cold oxidation: ionizer

Variations of the technology and synonyms

Ionizer, active oxygen injection, ozone injection, plasma treatment, cold plasma, plasma treatment, aerox injector

Removed pollutants

Mainly: smell

To a lesser extent: VOC

1. Brief description

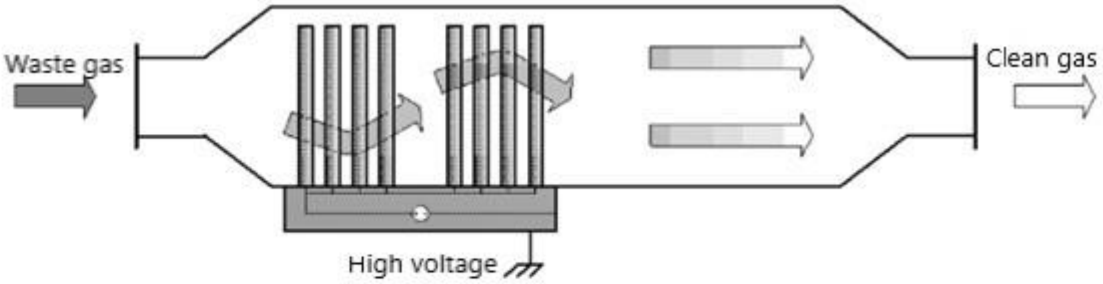
1.1 Description

The operating principle of an ionizer as abatement technology is based on the oxidation of odorants by ozone and other highly reactive substances (radicals). Ionization is a process in which an atom loses one or more electrons and thus becomes positively charged. When enough atoms are ionized to noticeably change the electrical character of a gas, it is referred to as plasma. The most active particles in this process are oxygen and OH-radicals. Oxygen molecules (O_2) are thus oxidized to ozone (O_3). For effective odour control, partial oxidation of the odorants is usually sufficient. No significant temperature increase occurs, which is why this technique is called 'cold' oxidation.

The ionisation is usually achieved by passing clean filtered air through an electric field under high voltage. The ionised air is then injected into the waste gas stream. The ionisation can also be applied directly to the waste gas. This is more efficient, but more sensitive to contamination.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.



2. Applicability

2.1 Scope

(general)
The technique is typically used for the removal of odorous substances and/or low concentrations of VOCs from a gas stream. It is more energy-efficient than alternatives such as a thermal incinerator.

Cold oxidation: ionizer

Cold oxidation is applied in the following sectors:

- Foodstuffs, beverages and feed industry
- Slaughterhouses
- Sludge processors
- Water treatment plants

(SVHC)

Cold oxidation technologies are in principle unsuitable for waste gas streams containing SVHC, because the emission values to be achieved are not low enough to meet the emission limits of SVHC.

2.2 Combination of technologies

A combination with a filtration technology is necessary when the waste gas stream contains a significant amount of dust particles or droplets. Particles will be charged during the ionization process and will stick to the inner parts and cause clogging. Combinations of other technologies are possible, but are uncommon as cold oxidation is primarily intended for odour removal only.

2.3 Performance

The actual performance of an ionizer depends on the specific situation. It is possible to significantly reduce odour loads, provided the equipment is properly adjusted. Feasibility tests are necessary to determine the level of performance that can be achieved.

VOC load reduction is possible, but it is rarely the primary purpose of an ionizer.

2.4 Preconditions

Flow rate [Nm^3/h]:
Ionization: 1.000 - 200.000 Nm^3/ hour

Temperature [°C]:
20 - 200

Pressure [bar]:
Atmospheric

Pressure drop [mbar]:
Single

Moisture content [%]
Ionisation in the waste gas: low moisture content, because of risk of condensation and short-circuiting
Ionization in air: no restriction on the moisture content of the waste gas.

Cold oxidation: ionizer

Residence time:

Few seconds

Dust particles:

Ionisation in waste gas: low particles content, as the ioniser acts otherwise as an electrostatic precipitator.
Ionization in air: no restriction on particles content of the waste gas.

Incoming concentration:

< 500 mg/Nm^{3}VOC

3. Detailed description

3.1 Variations of the technology

Ionisation of the waste gas

The waste gas is passed through a reactor chamber, where it is subjected to a strong electrical alternating field (30 - 40 kV) by means of electrodes. If a dusty gas stream is sent directly into the reactor, it will behave like an electrostatic separator (ESP). To keep the reactor clean, a cleaning system must be installed or cleaned manually. Cleaning can be done by vibration, compressed air or water. In the case of dust-free air flows, this cleaning system is not necessary. Removal of organic substances is possible with direct treatment.

It is no longer common practice, but after the actual ionisation step, the air flow can still be led over a catalyst. This works at room temperature and ensures the removal of the ozone present and further oxidation of the components to be removed.

Ionisation of air (side stream injection, active oxygen injection)

Ionisation of air is preferred when the waste gas is hot, has a high particles load or contains corrosive. Clean air is first ionized (20-30 kV), which is then injected into the waste gas. Because the waste gas is 'diluted', in some cases the operation can be less efficient than direct ionisation. For example, there will be a modification of odour molecules through partial oxidation, but hardly any removal of the organic load (VOC). The quantity of ionised air injected is usually 5 - 15 % of the off-gas flow.

3.2 Installation, design and maintenance

Cold oxidation is a system that is easy to install and maintain. If the gas flow is not dust-free, then periodic cleaning must be incorporated, for example by flushing with water.

(monitoring)

Monitoring of the voltage is necessary, if necessary the incoming and outgoing VOC concentrations can be measured.

4. Environmental aspects

4.1 Advantages

Cold oxidation: ionizer

The main advantages are:

- Compact installation
- Virtually no start-up time
- Effective at low temperature
- Insensitive to variations in gas flow rate and VOC concentration

4.2 Disadvantages

- When applied to VOC streams with large molecules, these molecules will react to smaller VOC molecules, but the VOC load as a total will hardly be reduced
- Unsuitable for gas flows with high VOC concentrations
- Residual ozone concentration possible

4.3 Resources and energy

Water:

Not applicable.

Chemicals:

Not applicable

Energy consumption:

Electricity for ionization

4.4 Environmental considerations

Recovery:

Not applicable.

Air:

Residual emission of ozone is possible (without catalyst). In industrial applications, ozone emission remains below 1 - 3 ppm.

Wastewater:

Possibly rinse water to clean the ionizer in case of direct ionization of the waste gas.

Waste:

In the presence of dust, a solid waste can be formed. Any catalyst will need to be replaced periodically and is also waste.

Safety:

Protection against high electrical voltages.

5. Financial aspects

Explanation of cost figures:

Cold oxidation: ionizer

The costs mentioned are based on VITO LUSS: Ionisation. and on supplier information.

Investment [EUR per 1,000 Nm^3/hour]:
3.000 - 10.000

Annual operating cost [EUR per 1,000 Nm^3/hour]:
500 - 2.000

Staff [hours/week].
1 - 2 days per year

Material:
No consumption of material.

Energy consumption [kWh/1,000 Nm^3]:
0.3 - 3 (ionizer)

Benefits:
No

Cost determining parameters:
Waste gas flow rate and odour concentration

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
3. VITO LUSS: Ionisation
4. Supplier: Aerox

4.15 Dust scrubbing: dust scrubber

Version: dust scrubber, venturi scrubber, spray tower

Dust scrubbing: dust scrubber

Variations of the technology and synonyms

Dust scrubber, *wet dust scrubber*

Venturi scrubber, *Venturi rubber, Swirl scrubber, Lamell-Dust-Scrubber*

Spray tower, *rotary scrubber, dynamic scrubber*

Removed pollutants

Especially: droplets, dust particles

To a lesser extent: ammonia, odour, H_2S, HCl and HF, SO_2, VOC

1. Brief description

1.1 Description

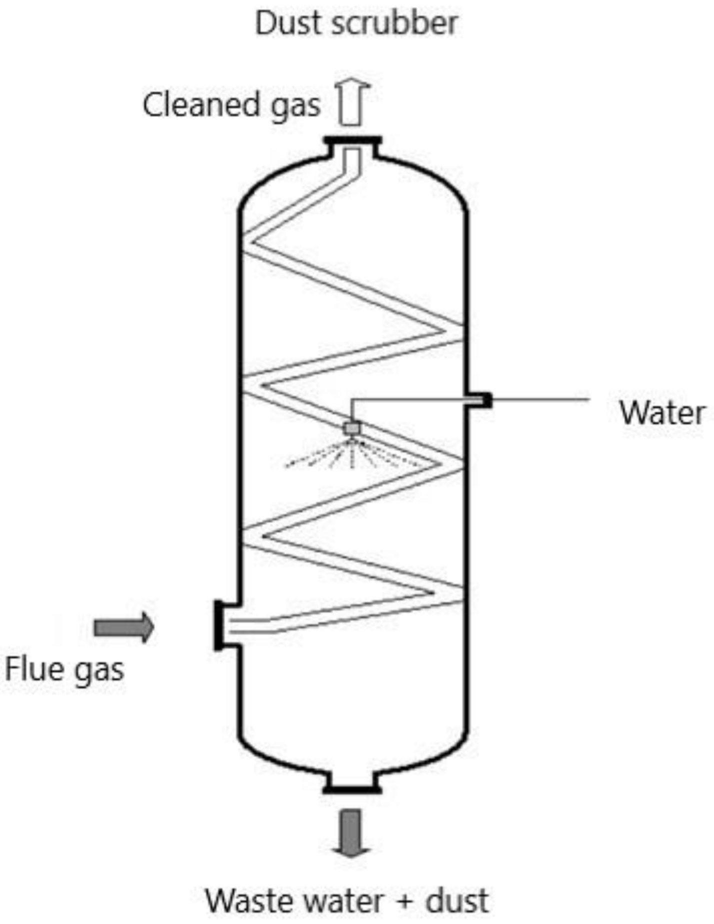
The operating principle is the separation of solid particles and gases in a waste gas stream, using the difference in mass. With wet dedusting, the particles are separated through intensive mixing of the waste gas with water, usually in combination with separation of the coarsest particles through centrifugal force. To this end, the gas is fed tangentially (input slanting from the side of the scrubber) into the dust scrubber. The collected solids are collected in the lower part of the scrubber.

Despite the fact that the main goal is the capture of dust, substances will also dissolve in the scrubber water, just like in a gas scrubber: inorganic substances such as SO_2 and NH_3 and VOC, heavy metals that can be found on particles or other water-soluble gases in the waste gas.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.

Dust scrubbing: dust scrubber



2. Applicability

2.1 Scope

(general)

The technique is mainly used to remove small particles (PM10) from waste gas streams while also removing inorganic gases such as NH_3 and SO_2.

(SVHC)

Dust scrubbing is less suitable for capturing flows containing SVHC, because the emission concentration to be achieved will usually be too high to meet the emission limit values for SVHC.

2.2 Combination of technologies

Dust scrubbers can be combined with other technologies, taking into account that the waste gases will be saturated with moisture after a wet dust scrubber. Also, the temperature of the off-gases will have dropped considerably after the dust scrubber, which may be an advantage or disadvantage, depending on the application.

Dust scrubbing: dust scrubber

2.3 Performance

The performances are indicated in the following table. The residual concentration is determined by the particle size, degree of atomization in the scrubber and pressure drop. The presented values depend on the specific configuration, operating conditions and particles to be captured. The values are in principle based on half-hourly average values.

	Dust scrubber	
Pollutant	**Disposal efficiency [%]**	**Concentration after treatment [mg/Nm^3]**
PM	70 - 99	P10: 0,2 P50: 0,9 P90: 8,0

2.4 Preconditions

Flow rate [Nm^3/h]:

Dust scrubber: 1.800 - 170.000 Nm^3/ hour
Venturi scrubber: 720 - 100,000 Nm^3/ hour
Sprayers: 2.500 - 170.000 Nm^3/ hour

Temperature [°C]:

<370

Pressure [bar]:

atmospheric

Pressure drop [mbar]:

20 - 50 (scrubber, spray towers)
20 - 250 (Venturi scrubber)

Moisture content [%]

No restrictions.

Residence time:

Few seconds

Dust particles:

<11 gram/m^3(scrubber)
No restrictions (sprinkler monitors)

Dust scrubbing: dust scrubber

<115 gram/m^3 (venturi scrubber)

3. Detailed description

3.1 Variations of the technology

Dust scrubber

The basic version of a dust scrubber is similar to a gas scrubber, but specifically designed for the removal of particles . The particles are separated by intensive mixing with water, but also by strong centrifugal forces. The construction of a dust scrubber is aimed at optimizing one or both of these factors.

Venturi scrubber

A venturi scrubber consists of a converging neck (the narrowest part of the venturi), a diverging expansion chamber and a droplet separator. The dust/gas mixture flows through the venturi and reaches the highest velocity in the neck. The mixture then enters the expansion chamber where the gas velocity again decreases. The liquid is added to the gas flow in or before the neck. In the neck of the Venturi tube there is intensive mixing of gas and liquid. Due to the high velocity of the gas and liquid, the water falls apart into small water droplets, which results in intensive contact between the gas phase and the liquid phase. A relatively large amount of energy is required to achieve this smal droplets.

Venturi scrubbers can be used for the removal of small particles (< 1 µm) from a gas stream, although in general the efficiency rapidly decreases as the particles become smaller. However, they can also be used for larger particles, although the energy consumption is then relatively high compared to alternative technologies.

Venturi scrubber with fins

In a venturi scrubber with fins, so-called fins are mounted in the transition from the constriction (venturi) to the expansion chamber, which are sprayed by nozzles from both sides. The nozzles vary in diameter so that smaller and larger droplets are emitted, whereby small and coarse particles are captured and included in the rinse water. The expansion chamber has a specific convex shape which is also sprayed. The convex shape is designed in such a way that the vortex of the air flow, coming from the venturi, collides with this convex shape and with the surface of the water basin situated underneath. By spraying specifically on this convex shape with various nozzles, an extra post-treatment of the particles collection is realized. This type of scrubber has a wider constriction and therefore a lower pressure drop and low energy consumption compared to the usual venturi scrubbers.

Spray scrubber

The scrubbing liquid is dispersed or distributed in small droplets respectively by means of a rapidly rotating nozzle disk or rotating nozzles, thus creating a large contact surface between droplets and gas. There are also versions of spray towers without rotating nozzles. The gas is led tangentially (at an angle to the side) into the dedusting chamber. Centrifugal forces and the rotating atomisation drag the particles towards the wall of the scrubber, thus achieving a high separation efficiency. The separated particles must be dewatered and disposed of.

3.2 Installation, design and maintenance

Dust scrubbers are relatively compact installations, for venturi scrubbers a liquid to gas ratio of 0,5 - 5 m^{3}per 1.000 m^3/h can be expected. The droplet separator can be several times larger than the other components of the scrubber.

Dust scrubbing: dust scrubber

This is to a lesser extent true for venturi scrubbers with fins. Maintenance costs for a dust scrubber can be high due to the many moving parts, whereas a venturi scrubber requires hardly any maintenance. Preferably materials resistant to erosion and corrosion are used in the construction. Contamination of the droplet eliminator should be checked regularly. In principle, the venturi scrubber requires little maintenance, with the condition that the collected matter is removed from the rinse water immediately, or relatively quickly if the rinse water is reused.

(monitoring)

Regular monitoring is necessary in the form of measuring the particles concentration in the inlet and outlet, the pressure drop over the scrubber, the liquid/gas ratio, wastewater production and the pH of the rinse water. In addition, regular inspection of the installation is necessary so that corrosion can be detected early and repaired.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Suitable for gas flows with flammable and/or explosive components
- Simultaneous capture of particles and inorganic gases
- Relatively small land take

4.2 Disadvantages

- Water consumption and wastewater production
- Noise nuisance possible

4.3 Resources and energy

Water consumption:

500 - 5,000 [litres/1,000 Nm^3]

Chemicals:

Any chemicals added to neutralise corrosive substances or to increase efficiency.

Energy consumption:

Electricity for pump and fan.

4.4 Environmental considerations

Recovery:

Possible, but complicated by being in a wet slurry potentially contaminated with inorganic gases.

Air:

A visible plume of smoke is possible because the waste gas stream is saturated with moisture.

Wastewater:

Production of wastewater

Dust scrubbing: dust scrubber

Waste:

Slurry

Safety:

No special requirements except protection against freezing.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

2.000 - 10.000: dust scrubber

5.000 - 15.000: venturi scrubber

8.000 - 30.000: spray scrubber

Annual operating cost [EUR per 1,000 Nm/hour]: [3]

150 - 2.000: dust scrubber

500 - 2.000: venturi scrubber

300 - 2,000: spray scrubber

Staff [hours/week].

2 - 14 days per year

Material:

No consumption of material.

Energy consumption [kWh/1,000 Nm^3]:

0,4 - 2,7 (spray scrubber)

0.5 - 7 (venturi scrubber)

Benefits:

None if the wastewater cannot be re-used beneficially.

Cost determining parameters:

Scale (flow rate), composition of the waste gas and possible presence of corrosive substances.

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS: dust scrubbing in general
5. Supplier: CleanAllAir Industrial Air Scrubbers, Mesys Industrial Air Systems.

4.16 Thermal Oxidation

Thermal Oxidation

Variations of the technology and synonyms

Incinerator, *incinerator, thermal oxidizer, recuperative thermal oxidation, regenerative thermal oxidation (RTO)*

Catalytic incinerator*, catalytic oxidator, catox, thermocat, recuperative catalytic oxidation, regenerative catalytic oxidation*

Removed pollutants

Especially: combustible particles and droplets, odour, VOCs,

Lesser degree: ammonia,

1. Brief description

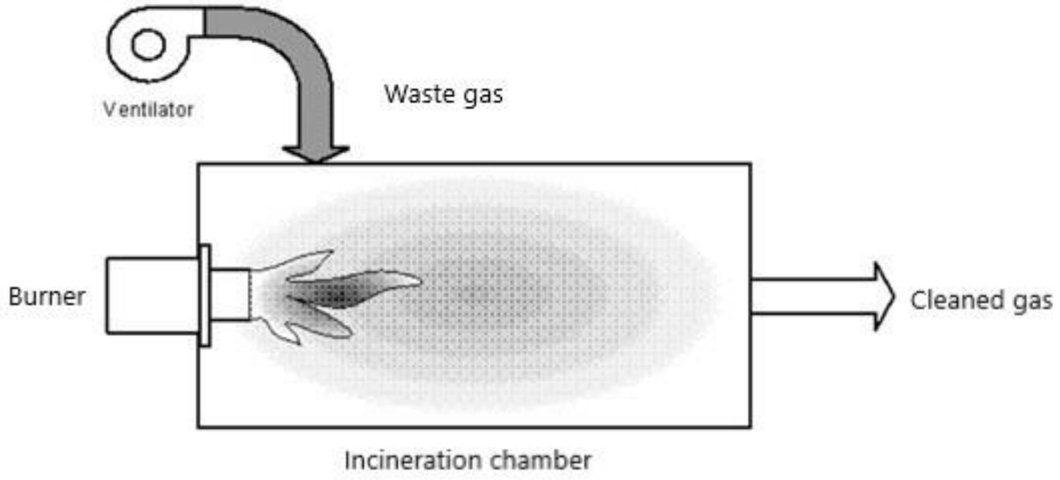
1.1 Description

The operating principle is based on complete oxidation of all combustible substances in the waste gas with oxygen in the air.

Thermal oxidation is a treatment technique in which a waste gas stream containing combustibles is mixed with air, possibly oxygen, to above the auto-ignition point in a combustion chamber. The gases are kept at a high temperature for 2 - 3 seconds, in the order of 750 - 1,200ºC, as a result of which the combustible substances oxidise with oxygen to form substances such as CO_2, H_2O, NO_x , SO_x . If the waste gas contains too little VOC to keep the combustion process going, support fuel is needed. Depending on the composition of the waste gas stream, it may be necessary to further clean the waste gas stream of non-combustible substances such as heavy metals, halogens and the combustion products NO_x and SO_x.

1.2 Process flow diagram

The following diagram illustrates the main process flow of the technology.



2. Applicability

2.1 Scope

Thermal Oxidation

(general)

This technique is widely used for the removal of odour or volatile hydrocarbons in almost all types of sectors. Thermal oxidation is especially suitable for applications with an average to high VOC concentration in the waste gas. Otherwise, thermal oxidation will require substantial energy, typically delivered by a commercial fuel. The technique is most efficient when there is a stable gas flow with few fluctuations in flow rate and VOC concentration.

(SVHC)

Thermal oxidation is suitable for removing SVHC from a waste gas stream, insofar as this concerns substances which are flammable within the temperature range of the installation. An emission of almost zero can then be achieved, provided the process parameters are optimally adjusted. If the waste gas contains chlorides, dioxins (SVHC) can be formed under unfavourable conditions in or after the thermal incinerator.

2.2 Combination of technologies

Incinerators can be part of an extensive combination of technologies. Usually, the incinerator is the first technique used in the chain, because the waste gases are often still warm after the production process. Subsequent technologies are then used in order of temperature range. In this way, the need for support fuels is kept to a minimum. If the waste gas contains a lot of particles or droplets, a particulate separator and/or demister will be needed as a pre-treatment step.

2.3 Performance

The performance is indicated in the following table. The residual concentration is determined by the saturated vapor concentration at the operating temperature and pressure. The values presented depend on the specific configuration, operating conditions and particles to be captured. The values are in principle based on half hourly average values. NA stands for 'not applicable' and has been used for odour. No emission limits have been set for odours, because acceptability will be assessed on the basis of odour concentration s at sensitive receptors. The specification for particles (PM10) relates to combustible dust.

Pollutant	**Removal efficiency [%]**	**Concentration after treatment [mg/Nm^3]**
VOC	98 - >99,9	<1
PM10	25 - 99,9	<1
Odour	98 - >99,9	NA

2.4 Preconditions

Flow rate [Nm^3/h]:

Thermal oxidation:

Thermal Oxidation

P10: 1,000 - 1,500 (recuperative) - 4,000 (RTO)
P50: 5,000 - 12,000 (recuperative) - 21,000 (RTO)
P90: 21,000 - 75,000 (recuperative) - 70,000 (RTO)

Catalytic oxidation:
P10: 1.000
P50: 6.000
P90: 80.000

Temperature [°C]:
Input temperature as high as possible.

Pressure [bar]:
Atmospheric

Pressure drop [mbar]:
10 - 50

Moisture content [%]
Preferably dry, but no technical restrictions.

Residence time:
Standard minimum of 2 seconds, but minimum of 3 seconds for combustion of halogenated VOCs.

Dust particles:
< 3 mg/Nm^3

Incoming concentration:
<25% of the lower explosion limit (LEL) for safety reasons, especially for RTOs

3. Detailed description

3.1 Variations of the technology

Thermal incinerator
The simplest variation of the technology of the principle is an incinerator which consists of a combustion chamber without further heat recovery. If the combustion chamber is not closed but open to the outside air, this is referred to as a flare.

Catalytic incinerator
A catalytic incinerator works in a similar way to a thermal incinerator except that the gas, after passing through the flame, passes through a catalyst once more. This catalyst ensures an accelerated oxidation at lower temperatures. The oxidation can therefore take place at lower temperatures.

Thermal Oxidation

The gas is heated up to approx. 300 - 500 °C before the catalytic converter. The maximum gas temperature after the catalytic converter is approx. 500 - 700 °C. New low-temperature catalytic converters can already operate at 200 - 250 °C. The use of a catalytic converter also reduces CO and NO_x emissions by ~70 – 80 %, but is more expensive and makes the system more sensitive to pollutants in the waste gas. Due to the lower operating temperature, the required quantity of support fuel is also lower. From about 10 - 14 g/m^3 VOC, no support fuel is required.

The catalysts used are mostly precious metals (platinum, palladium, rhodium,...) on a ceramic or metallic support, base metals on a ceramic support or metal oxides. For chlorinated compounds, catalysts such as chromium/aluminium, cobalt oxide and copper oxide/manganese oxide are used. Platinum-based catalysts are suitable for sulphurous compounds but are rapidly deactivated in the presence of chlorine.

The presence of catalyst poisons or deposits on the catalyst can greatly reduce the life of a catalyst. In addition, erosion may occur due to the abrasive action of particles . If, for example, fats and oils are deposited on the catalyst surface, the catalyst may be reactivated by increasing the temperature. Most catalyst poisons permanently inactivate the catalyst, for example phosphorus, bismuth, arsenic, antimony, lead and mercury (fast-acting), and iron, tin and silicon (slow-acting). With sulphur, halogens, zinc it is often possible to reactivate the catalyst.

Regenerative thermal incinerator

A regenerative incinerator uses two or more ceramic beds. Three beds are most common. The principle is that the heat of the treated waste gas is stored in the bed and is subsequently released to the waste gas to be treated. The thermal efficiency can be as high as 97 %. In the combustion chamber the gas is heated further (when necessary) , so that thermal oxidation takes place. The hot gas that leaves the combustion chamber heats the second ceramic bed. The cooled gas can then be discharged. When the second bed is sufficiently heated, the gas flow is reversed, so that the second bed heats the waste gas to be treated and the first bed cools the treated waste gas. Peak emissions may occur during the switch in gas flow. The ceramic beds can be expanded with a catalyst to further increase the efficiency of the technique.

The technique has a maximum inlet concentration (25 % LEL, order of magnitude 10 g VOC/m^3), and due to the high thermal efficiency is often already autothermic at 2-3 g VOC/m^3. A RTO is very efficient because very little combustion air is needed. A RTO can be free of NO_x emissions if no additional heating is required with a flame, but if only the heat already present in the waste gases is used. An emerging variation of the technology of the technique is the electrically heated version.

Recuperative thermal incinerator

The recuperative incinerator is almost identical to the thermal incinerator, but now extended with a heat exchanger. Using the heat exchanger, the gas flow is first pre-heated by the combustion gases, as a result of which up to 80% of the released heat can be used. The incinerator can be further expanded with a catalyst in the combustion chamber.

Thermal Oxidation

Oxicator

This technique is based on catalytic oxidation of VOCs whereby the catalyst is heated with microwaves. By using microwaves, the system uses little additional energy. Typical energy consumption is approximately 20 W/m^3. Due to the relatively high costs of the specially developed catalyst, this technology is mainly used for smaller gas volumes (< 1,000 m/h^3). Advantages of the system are the energy efficiency and the high treatment efficiency (> 99% and residual emissions < 1 mg/m ^{3}). The system can be set up with one or two microwaves, depending on the input concentration. At a sufficiently high concentration of VOC, the oxidation reaction is self-sustaining and no extra energy needs to be added.

Combustion in a combustion plant

Waste gases containing combustible substances such as VOCs can be mixed with a regular fuel gas such as natural gas or propane to achieve the required heating value. The mixed gas can then be used as fuel for a combustion installation, for example a boiler installation, a gas engine or even a gas turbine. At low concentrations of combustible substances and with sufficient oxygen, the waste gas can be used as combustion air. Combustion plants are not primarily intended as an abatement technology, and therefore fall outside the scope of the 'fact sheets on abatement technologies' and have not been considered further.

3.2 Installation, design and maintenance

The key design parameters are:

- Temperature: this must be high enough to ensure complete combustion of the VOCs
- Time: long enough to ensure complete combustion of the VOCs. Minimum 2 seconds, often longer if the temperature is lower
- Turbulence: the gas stream must mix as well as possible with oxygen in the combustion chamber, so that the oxidation reaction can proceed optimally

(monitoring)

Monitoring is required on an ongoing basis to quickly signal if combustion is not proceeding optimally. Parameters that must be monitored minimally include:

- Combustion chamber temperature
- VOC concentration before and after the incinerator (for example with a flame ionisation detector - FID)
- Concentration of CO in the waste gas, to signal incomplete combustion
- Pressure drop

Burners should be inspected regularly, and cleaned when necessary, for optimal performance and efficiency. If excessive deposition occurs, preventive measures should be taken, for example, by treatment the waste gas before it enters the burner.

4. Environmental aspects

4.1 Advantages

The main advantages are:

- Good, consistent performance
- Simple operating principle, reliable technology

Thermal Oxidation

- Possibility of using the energy content of the waste gas

4.2 Disadvantages

- Emissions of carbon dioxide, carbon monoxide and nitrogen oxides
- Risk of dioxins if halogenated substances are incinerated
- High energy consumption if the waste gases do not contain enough VOCs
- Not very suitable for gas flows with fluctuating flow and/or VOC concentration, especially for RTO and recuperative incinerators
- Catalysts are sensitive to particles and poisoning

4.3 Resources and energy

Water:

Not applicable.

Chemicals

No process aids but the catalyst (if used) must be replaced or regenerated periodically.

Energy consumption:

Fuel, possibly electricity, for maintaining the temperature of the oxidation reaction (in addition to the heat generated by burning the waste gas). The minimum concentration of VOCs to keep the reaction going independently is 1 - 10 gram/m ^{3} (lower in the case of catalytic oxidation).

An incinerator can be energy-efficient if the heat can be (re)used in a production process by means of heat exchangers, or if a boiler is heated with the flame. On the other hand, an incinerator can also have a high energy consumption if the waste gas stream contains little VOC.

4.4 Environmental considerations

Recovery:

Not applicable.

Air:

Thermal incinerators are associated with emissions of carbon monoxide, nitrogen oxides and possibly dioxins if the waste gas contains chlorides or organically bound chlorine.

The expected NOx concentrations are [mg/Nm ^{3}]:
P10: 7
P50: 51
P90: 160

The expected CO concentration at a VOC concentration of 5 mg/Nm ^{3} as final concentration [mg/Nm ^{3}]:
P10: 0,8
P50: 4

Thermal Oxidation

P90: 30

Wastewater:

No

Waste:

None, unless a catalyst is used. It must be replaced periodically and is waste.

Safety:

Safety measures include: protection against flashback; keeping burners clean; shutting off the gas supply in case of burner failure; limiting the maximum temperature.

5. Financial aspects

Investment [EUR per 1,000 Nm^3/hour]:

10.000 - 40.000 for standard thermal oxidation
30,000 - 100,000 for regenerative thermal oxidation
30.000 - 100.000 for recuperative thermal oxidation

Annual operating cost [EUR per 1,000 Nm^3/hour]:

2.500 - 30.000 for standard thermal oxidation
2,500 - 12,000 for regenerative thermal oxidation
2.500 - 12.000 for recuperative thermal oxidation

Staff [hours/week].

2 - 5 days per year

Material:

The catalyst (if used) must be replaced or regenerated periodically. The oxidation bed of an RTO is susceptible to fouling and usually requires periodic replacement.

Energy consumption [kWh/1,000 Nm^3]:

3 - 8 (thermal incinerator)
1,5 - 2,25 (regenerative thermal incinerator)

Benefits:

Possibly, if the heat can be recovered and put to practical use.

Thermal Oxidation

Cost determining parameters:

Waste gas flow rate, heat content of the waste gas, VOC concentration in the waste gas, combustion temperature, type of catalyst, possibility for heat recovery.

6. Information source

1. Handreiking luchtemissiebeperkende technieken [Guide to Air Pollution Control Technologies]; DHV, 15 April 2009
2. BREF Waste Gas Management and Treatment Systems in the Chemical Sector; first draft, 2019
3. BREF Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016
4. VITO LUSS: Catalytic/thermal oxidation (recuperative/regenerative)
5. Supplier: Kranz Clean Air Solutions

5 Related topics

5.1 Fugitive emissions

Environmental policy for diffuse sources focuses mainly on measures which prevent emissions. This is in contrast to channelized emission control techniques which treat emissions. The following is a reference to documents describing measures for diffuse emissions.

5.1.1 VOC

In addition to the BREF documents, the following references provide a description of measures for diffuse VOC sources or information that can help in selecting appropriate measures.

- Branch document licensing Wabo liquid bulk - VOC measures; Cooperating BRZO environmental services; version 2.1 of 11 May 2020
- Knowledge Inventory Document 'Liquid Bulk Storage and Transfer in Tanks', Interprovincial Consultation, IPO publication number 278, March 2009
- Diffuse emissions and emissions during storage and transhipment, Emission Factors Manual, Environmental Monitor Number 14, March 2004.
- European Sealing Association: sealing-technology-bat-guidance-note

5.1.2 Dust particles

The following references provide a description of measures for diffuse sources of particulate matter.

- Knowledge Centre of the Dutch Ministry of Infrastructure and Water Management: Factsheets storage, transhipment and processing based on the VROM publication 'Onderzoek maatregelen fijn stof, op- en overslag'; TAUW; 1 October 2010
- VITO: Stoffiches, based on VITO publication 'Guide to reduction techniques for diffuse particles emissions during storage and transhipment of dry bulk goods; December 2012'

5.2 Cost effectiveness

Cost-effectiveness is an important concept related to best available techniques (BAT). Cost-effectiveness indicates the cost of the emission-reducing measure in relation to the emission avoided by that measure (expressed in euros per kilogram). The method used to calculate cost-effectiveness is laid down in the BBA. A page on cost-effectiveness is included on the website of the Knowledge Centre for the Environment (Kenniscentrum RWS).

The general parameters mentioned in the fact sheets can be used in a cost-effectiveness calculation. For example, if in a specific situation not all parameters are known, then an estimate can be made for the missing figures based on information from the relevant fact sheet. It should be kept in mind that the fact sheets provide general data on a technology, which need not apply to all practical situations. Cost figures are usually highly situation-specific. A cost-effectiveness calculation based on figures from the factsheets can therefore only be regarded as indicative.

Appendix 1 Suppliers who contributed to the update

Technology Supplier	Cleanallair industrial air scrubbers	Desotec	Azzuro	Thiopaq	Yara Netherlands	JOA Air Solutions	SMC Corporation	WingingItalia	Aerox	Kranz Clean Air Solutions	Mesys Industrial air systems	Clean All Air
Absorption: scrubber	X											
Adsorption filter		X										
Biological filters			X	X								
Chemical reduction: SCR and SNCR					X	X						
Filtration: dust filter							X					
Filtration: mist filter								X				
Gravitation: cyclone									X			X
Cold oxidation: ionization										X		
Dust scrubber	X											X
Thermal Oxidation											X	