Chair of Mining Engineering and Mineral Economics

Master's Thesis

Influences on the efficiency of water-based dust binding and the effects of dust

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Kurzfassung

Ziel dieser Diplomarbeit ist die Erforschung der Einflüsse auf die Staubbindefähigkeit von Wassernebel um festzustellen wo noch ein Verbesserungspotential besteht und wo noch weitere Nachforschungen und Versuche durchgeführt werden sollen, um die allgemeine Effizienz von dementsprechenden Anlagen zu erhöhen. Damit dies erreicht werden kann ist es vorab notwendig den Prozess der Staubbindung zu verstehen und in weiterer Folge die Einflüsse zu identifizieren. Die Staubabscheidung mithilfe von Wassernebel soll mit anderen Abscheidemechanismen verglichen werden und als Abschluss soll erklärt werden, warum eine Verringerung des Staubausstoßes notwendig ist.

Diese Arbeit lässt sich durch die verschiedenen Einzelschritte in mehrere Kapitel gliedern. Vorab werden die genauen Ziele ausgearbeitet, welche notwendig sind um ein vollständiges Verständnis und eine saubere Aufarbeitung des Themas zu gewährleisten.

Im zweiten Schritt erfolgt die Aufarbeitung der Interaktion zwischen Partikel und Tropfen, sowie welche verschiedenen Bindungsformen und Abscheidemechanismen auftreten können. Dies inkludiert sowohl die physikalischen, als auch die chemischen Bindungsarten.

Anschließend, im Hauptteil dieser Diplomarbeit, gilt es die Einflüsse auf die vorher beschriebenen Bindungen zu bestimmen. Dabei sollen die unterschiedlichen Auswirkungen sowohl erörtert, als auch die Stärke des jeweiligen Einflusses bei unterschiedlichen Partikelgrößen bestimmt werden. Dies soll anhand von bereits durchgeführten Versuchen aus weltweiter Literatur erfolgen. Des Weiteren soll eine Gruppierung der Faktoren erfolgen.

Danach sollen die unterschiedlichen Staubabscheidesysteme erklärt und ihre Wirkungsgrade dargestellt werden, um sie vergleichen zu können und um zu zeigen, wo welcher Typ von Filter verwendet werden soll, sowie welche Vorteile die Abscheidung mithilfe von Wassernebel besitzt.

Die nächsten beiden und somit auch abschließenden Kapitel sollen die Notwendigkeit aufzeigen, warum es wichtig ist so wenig wie möglich Staub zu emittieren.

Im vorletzten Kapitel sollen die Auswirkungen von Staub auf die Menschheit behandelt werden. Dies inkludiert sowohl das Einatmen, als auch die Einflüsse auf die Arbeitsumgebung, zum Beispiel die Explosionsfähigkeit von Stäuben und welche maximalen Staubkonzentrationen es dabei zu beachten gilt.

Im letzten Kapitel gilt es die Auswirkungen von Staub auf die Umwelt zu erklären und welche Grenzwerte dabei einzuhalten sind.

Abstract

The aim of this master thesis is to investigate the influences on the dust binding capacity of water mist in order to determine where there is still potential for improvement and where further research and experiments should be performed to increase the overall efficiency of the corresponding systems. To achieve this, it is first necessary to understand the process of dust binding and subsequently identify the influences. Dust collection using water mist will be compared to other collection mechanisms and as a closure it will be explained why a reduction of the dust emission is necessary.

This work can be divided into several chapters by the different individual steps. First, the exact goals are elaborated, which are necessary to ensure a complete understanding and a clean processing of the topic.

In the second step, the interaction between particles and droplets and which different bonding forms and separation mechanisms can occur is worked through. This includes both the physical and the chemical bonds.

Subsequently, in the main part of this thesis, the influences on the previously described bond types have to be determined. The different effects shall be discussed as well as the intensity of the influence at different particles sizes will be determined. This will be done on the basis of experiments already carried out in worldwide literature. Furthermore, a grouping of the factors will be made.

Then, the different dust collection systems will be explained and their efficiencies will be discussed in order to compare them and to show where which type of filter should be used, as well as the advantages of separation of using water mist.

The next two topics, and thus the final ones, are intended to show why it is important to emit as minimal dust as possible.

In the penultimate chapter, the effects of dust on mankind will be discussed. This includes the inhalation of particles as well as the effects on the working environment, for example the explosiveness of dust and which maximum dust concentrations have to be considered.

In the last chapter, the effects of dust on the environment and the threshold values that must be observed are explained.

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List of abbreviations

ACGIH ....*American Conference of Governmental Industrial Hygienists*
AQG..*Air Quality Guidelines*
CCN...*Cloud Condensation Nuclei*
CDC...*Center for Disease Control and Prevention*
ESP ....*Electrostatic Precipitator*
FF ....Fabric Filter
IG-L...*Immissionsschutzgesetz- Luft*
IN ....*Ice Nuclei*
MAK...*Maximale Arbeitsplatz Konzentration*
MEC...*Minimum Explosible Concentration*
MIE ....*Minimum Ignition Energy*
NIOSH ....*National Institute for Occupational Safety and Health*
OEL ....*Occupational Exposure Limit*
OSHA ....*Occupational Safety and Health Administration*
PELs...*Permissible Exposure Limits*
PM ....*Particulate matter*
Stk ....*Stokes number*
TLVs ....*Threshold Limit Values*
WHO...*World Health Organization*

1 Introduction

Since dust can be very harmful to health and the environment in many different ways, it is necessary to reduce it as much as possible or collect it with the help of different separation mechanism. This can happen either with a filter, or with a scrubber, and should be done to reduce the effects onto the environment and the health of the workers in the surrounding area. The idea of sustainability also plays a role here.

The main topic of this master thesis is the wet scrubber, with a main focus on the binding of dust particles with fine water particles, especially water mist. This happens with a nebulization of a water stream. This step is necessary, so that a lot of very small water particles can come into contact with the dust particles. A wide range of particle sizes is necessary, since the binding is dependent on the size, which will be explained later in this master thesis.

Dust is in a lot of different processes a problem, especially in the mining and stone/ore processing industry, dust is a very hot topic. As seen in the next figure, dust can come in very different particle sizes, depending on the kind of dust and how it is processed. The particles smaller then 2,5µm are the most dangerous, since they can go into the lungs and into the alveoli. [1]

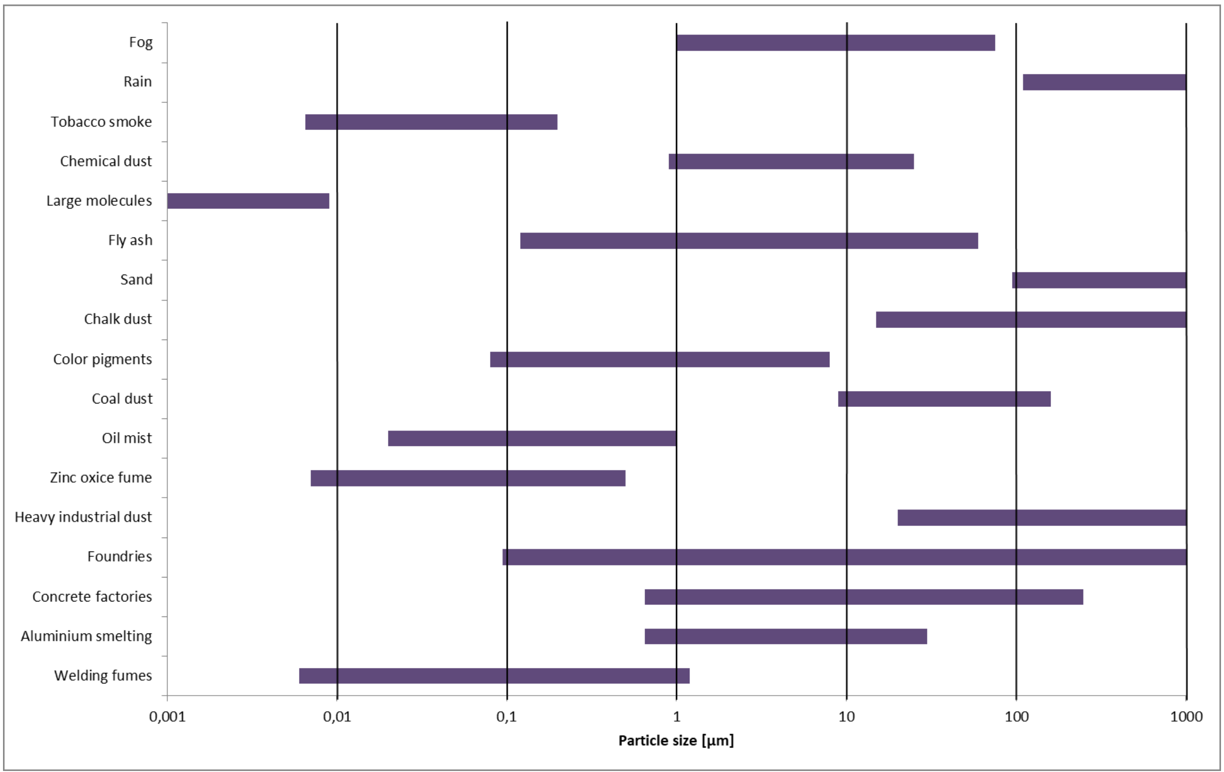


Figure 1-1: Particle sizes of different dust types [1]

This master thesis is written in cooperation with the company *EmiControls,* which is part of the *TechnoAlpin* Group founded in 1990. *TechnoAlpin* plans and builds snowmaking systems for artificial snow worldwide and has become one of the world market leaders within a few years. With the knowledge they acquired in mechanical and plant engineering, the desire to use atomized water beyond ski slopes occurred. With this knowledge in mind *TechnoAlpin* launched 2008 the "Dust" division with the name "Pro Air Solutions". The first dust controller was made within the first year. In 2011, the "Pro Air Solutions" division then became the subsidiary with the name "*EmiControls*" and the philosophy "We protect people around the world from emissions and fire". The name is derived from the activity of emission control, as in **Emi**ssion **Control** + **s**. Also in this year, the first attempts to use the water mist turbines to extinguish fires happened with success and the company expanded to include a "Fire" division. In 2012, the new founded division made the largest documented test in Europe, where 2400 liters of fuel were ignited over an area of 160m^2. The resulting flames were extinguished in 30 seconds. The first attempt to control odor from a recycling plant with the help of water mist happened in 2014 and 3 years later, the first machine suitable for this job was brought onto the market. A partner approached *EmiControls* with the desire to develop a machine for mechanical evaporation in 2016 and the first model was designed, constructed and sold in the same year. From that ongoing, the four different divisions (Fire, Dust, Odor and Evaporation) kept on growing. [3]

This master thesis is divided into five necessary sections, which are explained below.

The first section is the explanation of the interaction between the water particle and the dust particle. This is necessary to gain a general knowledge of how the binding of the dust onto the water spheres can happen and to get an idea of what possible influences on this process can occur.

The next step is to take a closer look on all the possible influences on the explained interaction. They will be divided into different subdivisions in order to categorize the different influences.

Subsequently, the different filter systems will be explained and compared with each other, to get a better understanding which filter is used on different kinds of dust and to get an overview of the efficiencies.

The following chapter deals with the effects of dust on humans. There are a few possibilities in which small particles can harm the health of a person exposed to dust, for example the particles can get into the lungs.

The final chapter focuses on the environmental impact of dust, with several subchapters focusing on different implications, for example on vegetation or cloud formation.

2 Goals

In order to be able to investigate the possible influences on the binding of dust particles to water particles in more detail, it is necessary to explain in advance how the binding actually occurs in order to be able to work out the influences in the further stages of the master thesis. When this is done, the different dust separation methods will be compared with each other, including the different possibilities how dust can be collected and/or separated. Afterwards, the effects of dust on humans and the environment will be analyzed to show why dust reduction in companies is becoming more and more important.

2.1 Objectives

The entire project can be divided into five subcategories, each of which has its own objectives. These subcategories can be divided into the interaction between particles and droplets, the influences on this interaction and finding out the effectiveness of different separation methods. Furthermore, the effect of dust on humans and on the general environment will be analyzed in more detail.

2.1.1 Interaction between particle and droplet

In the first step, the interaction between particle and droplet will be explained in more detail. This is necessary to gain a better understanding in the physical and chemical processes during the binding of dust on a water particle and to be able to go into more details on the possible influences in the next chapter.

2.1.2 Influences on the efficiency of dust binding

Since the interaction has already been explained at this point, all the factors influencing the bond between the water particle and dust can be worked out in this chapter. A subdivision is introduced in the subchapters in order to categorize the influences, such as particle size, retention time, spray nozzles or the general factors relating to the water and surfactants used.

2.1.3 Efficiency of dust binding systems

In this section, the different possibilities for dust separation and/or binding will be explained in more detail. The aim is to explain the various methods and then compare them with each other and determine where separation with the aid of water mist can be best used and what efficiencies can be achieved with the different systems.

2.1.4 Effects of dust on humans

Within this chapter, we will take a closer look at the effects of dust on people. Both, the direct damage to health, as well as the influence on occupational safety in areas with increased dust occurrence is to be considered.

2.1.5 Effects of dust on the environment

In the final chapter, the effects of dust on the environment will be explained in more detail. Subchapters will again be formed in order to be able to categorize the damage caused by the spread of dust in more detail and to show why the reduction of dust is of great importance.

2.2 Non goals

In this chapter, the framework conditions are to be defined so that the target is not overshot. That means that there are also some points in this master thesis, which should not be included. Afterwards these points are listed with an explanation.

- Experiments

If enough data from literature can be found on the different topics, own experiments should not be necessary. Several experiments of different people were already achieved in researching the behavior of dust within wet scrubbers and the effect of dust on people and the environment, but a good overview of the needed chapters should be given.

- Overelaborate a topic

The focus should be on the mist scrubber and how to catch dust with it and what the possible influences on this binding mechanism are. This means, that the explanation of the different scrubbers, as well as the effects of the dust on the environment and on humanity should be included, but not be overelaborated, so that the focus stays on the research of the scrubber and the general effects of dust.

- Over explaining the legal situation

The legal limits are to be given, but it is not to be discussed why exactly these are the prescribed limits. Otherwise, it would go beyond the scope of this master thesis.

3 Interaction between particle and droplet

The main principle of dust reduction with the help of water mist is the binding of the particle on the surface or inside the water droplet. For this purpose, drops of liquid will be sprayed in a moving or resting aero-dispersion, which means, that the dust is distributed inside airflow. The dust particles flow around the droplet as long as there is a relative velocity between these two particles, as seen in the Figure 3-2.

3.1 Physical processes

The aim of this chapter is to explain the interaction between particle and droplet which happens through physical processes. There are a few different forces which lead to adhesion of the dust particle on a water droplet and they can be seen in the next figure. The different mechanics will be explained in this subchapter.

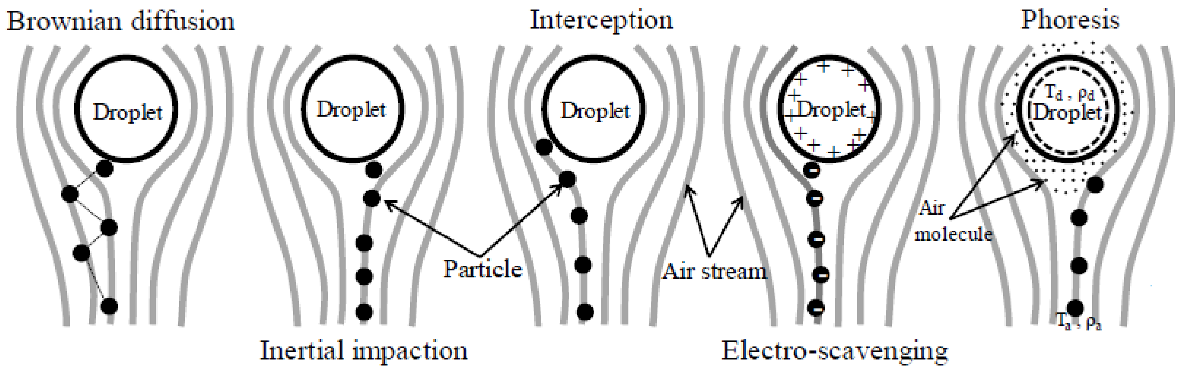


Figure 3-1: Different collection mechanisms [55]

3.1.1 Inertial Force

This is the most dominant collection mechanism for particles larger than 5μm. [5]

When they get closer to the droplet, the streamlines are bent around the surface of the droplet, which leads to an inertial force on the moving particle. The dust is moved onto the surface of the droplet, because of the high inertia force they cannot follow the streamlines, and get adhered to the water sphere. The next figure shows the particle paths and limiting particle paths when flowing around a spherical water droplet. [2]

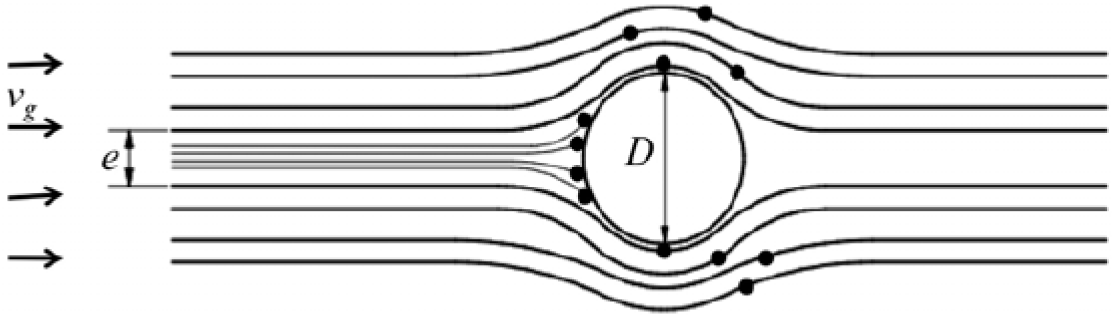


Figure 3-2: Particle streamline on a round droplet [2]

From this figure it follows that the capture cross section or effective cross-section of a droplet is effectively not calculated by the diameter (D) of it, but by the distance of the limiting particle paths (e). The effective cross-section (F) of a water droplet is calculated with the next formula: [2]

$$F = \frac{\pi}{4} e^2$$

Equation 3-1: Effective cross-section [2]

The projection area results from the following formula:

$$A_T = \frac{\pi}{4} D^2$$

Equation 3-2: Projection area [2]

Via the quotient from the above formulas the degree of impact (η_T) can be calculated as seen in the next equation:

$$\eta_T = \frac{F}{A_T}$$

Equation 3-3: Degree of impact 1 [2]

With the help of the equations Equation 3-1, Equation 3-2: Projection area and Equation 3-3 it is possible to calculate the degree of impact via the distance of the limiting particle paths and the droplet diameter:

$$\eta_T = \left(\frac{e}{D}\right)^2$$

Equation 3-4: Degree of impact 2 [2]

As seen in the calculations above, an equation can only be made if the limiting particle streamline is known. This depends on the size of the droplet, the size of the particle and the velocity of the airstream. [2]

If the particle streamline is not known, then the impaction can also be described with the help of the Stokes number (Stk): [5]

$$Stk = \frac{\rho_p {d_p}^2 (U_{sd} - U_{si})}{18\mu D}$$

Equation 3-5: Stokes number [5]

U_{si} is the settling velocity of the dust particle, U_{sd} is the falling velocity of the droplet relative to the air stream, μ is the viscosity of the air and ρ_p is the particle density.

The higher the Stokes number, the higher the chance of a collection by impact or inertial force, which can be calculated by the following equation: [5]

$$\eta_{imp} = \left(\frac{Stk}{Stk + 0{,}35}\right)^2$$

Equation 3-6: Impact collection efficiency [5]

This calculation can be roughly estimated by assuming proportionality to (Stk) ^{l}, so there is an approximate equation to the efficiency.

For $\leq 0{,}5$:

$$\eta_{imp} = 3{,}4 \left[\frac{\rho_p (U_{sd} - U_{si})}{18\mu D}\right]^{\frac{9}{5}} {d_p}^{\frac{18}{5}}$$

Equation 3-7: Impact collection efficiency for Stk ≤ 0,5 [5]

And for $Stk > 0{,}5$ the efficiency equals $\eta_{imp} = 1$

The influence of the Stokes number means, that a higher number equals a higher probability of collection by impaction and for Stk >0,5 all particles should be collected by impaction.

3.1.2 Condensation

This method is used for very small particles in the range of 0,25µm - 1µm and is also known as “Phoresis”, as seen in Figure 3-1. These small dust particles act as condensation nuclei for a droplet formation around the particle. To allow a condensation, it is necessary that a supersaturated steam near the dew point is available in the wet scrubber. This means, that saturation is necessary at the beginning and afterwards steam is injected to the gas steam. Thereby a supersaturated system is created and this leads to the condensation of water on the small dust particles in the gas stream. The result of this process is a growth of the particles. The now larger particles can then be removed by either a mist eliminator, or through inertial force, impaction, and interception. This means, that condensation is primarily used to make the small dust particles larger, so that they can be caught by the other forces explained in this chapter. [18]

3.1.3 Diffusion

Most small particles get collected by diffusion in wet scrubbers. Small particles have a high diffusion coefficient, because it is inversely proportional to the particle size. This mechanic is also known as “Brownian diffusion” and an example of the particle path is shown in Figure 3-1. It refers to the “random” collision between the small dust particles and air molecules. If they bounce off these molecules, it is possible for them to get trapped on the surface of the water particle, which would not have happened without these collisions. Therefor it can only occur on very small dust particles. [55]

The following equations are necessary to calculate the diffusive collection efficiency η_{diff} of a single liquid sphere. This also includes the effects of induced internal circulation. The packing density is represented by α, σ stands for the viscosity ration of water to air, P_e is the Peclet Number and D_{diff} is the diffusion coefficient. [5]

$$\eta_{diff} = 0{,}7\left\{\frac{4}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}} {P_e}^{-\frac{1}{2}} + 2\left(\frac{\sqrt{3}\pi}{4P_e}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}}\right\}$$

Equation 3-8: Diffusive collection efficiency [5]

$$J = 1 - \frac{6}{5}\alpha^{\frac{1}{3}} + \frac{1}{5}\alpha^2$$

Equation 3-9: J-Factor [5]

$$K = 1 - \frac{9}{5}\alpha^{\frac{1}{3}} + \alpha + \frac{1}{5}\alpha^2$$

Equation 3-10: K-Factor [5]

$$P_e = \frac{DU}{D_{diff}}$$

Equation 3-11: Peclet Number [5]

$$D_{diff} = \frac{kTC}{3\pi\mu d_p}$$

Equation 3-12: Diffusion coefficient [5]

In the last equation, the k is representing the Boltzmann constant, T the absolute temperature, μ the air viscosity, d_p the diameter of the particle and C the Cunningham slip correction factor. The Following forms of C are based on the Knudsen-Weber equation. [5]

For Kn > 2,6 or d_p < 0,05μm

$$C = \frac{2(1{,}664)\lambda}{dp}$$

Equation 3-13: Cunningham slip correction factor 1 [5]

For 0,15 < Kn < 2,6 or 0,05μm < d_p < 1,0μm

$$C = \frac{2{,}609\sqrt{2\lambda}}{dp^{\frac{1}{2}}}$$

Equation 3-14: Cunningham slip correction factor 2 [5]

Kn is the Knudsen number and λ the free path length of molecules.

If the particles are smaller then 0,05μm in diameter, then the Peclet number can be calculated with the help of Equations Equation 3-12 and Equation 3-13. [5]

$$Pe = \frac{3\pi\mu DU}{2(1{,}664)kT\lambda} dp^2$$

Equation 3-15: Peclet number for <0,05 μm particles [5]

D equals the droplet diameter and U equals the velocity of the falling water droplet.

When we substitute the last equation into the equation for the diffusive collection efficiency we get the complete diffusion collection efficiency for small particles: [5]

$$\eta_{diff} = \frac{2,8}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}}\left(\frac{3\pi\mu DU}{2(1,664)kT\lambda}\right)^{-\frac{1}{2}} d_p^{\ -1} + 1,4\left(\frac{\sqrt{3}\pi}{4}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{-\frac{1}{3}} \times \left(\frac{3\pi\mu DU}{2(1,664)kT\lambda}\right)^{-\frac{2}{3}} d_p^{\ -\frac{4}{3}}$$

Equation 3-16: Diffusive collection efficiency for <0,05 µm particles [5]

If the dust particle has a size around 0,05µm to 1,0µm, then the correction factor is proportional to (λ/d_p) and the Peclet number changes to the following: [5]

$$Pe = \frac{3\pi\mu DU}{2,609kT\sqrt{2\lambda}} dp^{\frac{3}{2}}$$

Equation 3-17: Peclet number for 0,05µm <d_p <1,0µm particles [5]

The diffusive collection efficiency changes to:

$$\eta_{diff} = \frac{2,8}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}}\left(\frac{3\pi\mu DU}{2,609kT\sqrt{2\lambda}}\right)^{-\frac{1}{2}} d_p^{\ -\frac{3}{4}} + 1,4\left(\frac{\sqrt{3}\pi}{4}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{-\frac{1}{3}} \times \left(\frac{3\pi\mu DU}{2,609kT\sqrt{2\lambda}}\right)^{-\frac{2}{3}} d_p^{\ -1}$$

Equation 3-18: Diffusive collection efficiency for 0,05µm <d_p <1,0µm particles [5]

As seen in the equations above, the diffusive collection efficiency will decrease with increasing velocity of the water droplet. [5]

3.1.4 Interception

The binding of dust by inertial force was already explained, but it is also possible, that a dust particle may be collected, even if the trajectory of a particle follows the streamline. This may be possible when the particle passes the water droplet within one particle radius, as seen in Figure 3-1. Then the particle will touch the surface of the water droplet and will stick to it, even although the particle was moving with the streamlines around the droplet. [55]

The next equations show the interception collection efficiency of a single liquid droplet: [5]

$$\eta_{int} = \frac{(1-\alpha)}{(J+\sigma K)}\left[\left(\frac{R}{1+R}\right)+\frac{1}{2}\left(\frac{R}{1+R}\right)^2(3\sigma+4)\right]$$

Equation 3-19: Interception collection efficiency [5]

$$R = \frac{d_p}{D}$$

Equation 3-20: Interception parameter [5]

The efficiency increases with an increasing particle diameter and packing density, and as the droplet diameter decreases. If the size of the water droplet is much bigger than the dust particle, we can assume that $R \ll 1 \; or \; \frac{R}{1+R} \cong R$, then the efficiency is calculated as followed:

$$\eta_{int} = \left[\frac{(1-\alpha)}{(J+\sigma K)D}\right]d_p + \left[\frac{(1-\alpha)(3\sigma+4)}{(J+\sigma K)2D^2}\right]{d_p}^2$$

Equation 3-21: Interception collection efficiency with bigger droplets [5]

As seen in the equation above, the interception collection efficiency is relatively independent of flow velocity, whereas the diffusion and impaction is flow velocity dependent.

3.1.5 Electrostatic Force

Also known as “Electro-scavenging” or “Electrophoresis”, as in Figure 3-1, the “catching” of the dust particle happens via the Coulombic force. This force can act as attractive or repulsive force between two particles, depending on their electric charges. The efficiency of this binding is dependent upon the electrostatic charge of the droplet, and an opposite charging of the droplet and dust particle. The charging of the mist can happen before the nozzle with the help of an electrode inside the pipe adjacent to the spray nozzle, or the nozzle itself can be charged with a specific voltage. The efficiency of a single spherical charged droplet can be described as followed. [17]

$$\eta_{coulombic} = \frac{4C_c q_p Q_d}{3\pi^2 \mu_g {D_d}^2 U_d \varepsilon_0}$$

Equation 3-22: Coulombic efficiency single droplet [17]

q_p is the charge of the particle, μ_g is the gas viscosity, D_d the diameter of the droplet, Q_d is the droplet charge, C_c the particle Cunningham Slip Correction factor, U_d the velocity of the droplet and ε_0 is the permittivity of vacuum. [17]

3.2 Chemical processes

This chapter should include the possible chemical reactions between a particle and a droplet. Since this is kind of bonding between a dust particle and a droplet is not really existent, just between a gas particle and a washing fluid to clean of exhaust gases. It only serves to mention it for the sake of completeness, since all binding variants of wet scrubbers are discussed in this main chapter.

3.2.1 Chemical reaction

The cleaning of the gas results from the passing of exhaust gas of engines or processes through a purification medium, in this case a washing fluid. The washing fluid can be sea water, fresh water, or any kind of fluid which fills the role of reacting with and neutralizing the hazardous gases. When the gas particles come in contact with the washing liquid, a chemical reaction happens and the particle gets bonded to the droplet, or it reacts and forms a new compound. In the following example, water is used as fluid and the gas is sulphur dioxide. It dissolves in water and forms sulphurous acid (H_2SO_3). The acid decomposes in solution into bisulphite/sulphite (HSO_3^- / SO_3^{2-}). [6]

$$SO_2 + H_2O \leftrightarrows H^+ + HSO_3{}^-$$

$$HSO_3{}^- \leftrightarrows H^+ + HSO_3{}^{2-}$$

$$SO_3{}^{2-} + \frac{1}{2}\,O_2 \leftrightarrows SO_4{}^{2-}$$

Afterwards the scrubbing liquid can contain a reactive agent, which neutralizes the absorbed acid and the liquid can be treated as wastewater to clean it in the next steps.

4 Influences on the efficiency of dust binding

This Chapter as well as its subchapters should focus on the Influences on the dust binding mechanism with water mist. It should be the main part of the master thesis and its purpose it to understand which and how strong the influences are, and how the efficiency could be raised.

There are a lot of different influences, which will be grouped in different topics and explained in the following subchapters.

4.1 Particle and droplet size

As already explained in Chapter 3, the size of the particle and the droplet has effects on the different catching mechanisms, for example the inertial force. This leads to the important fact that the dust particle and the water droplets should have a size proportion of about 1 to 5. This means that the dust particle should be 1 to 5 times smaller than the droplet. Another important part of the size is that very small droplet diameters lead to a fast adaptation of the relative velocity, which leads to a more insufficient binding. The next figure shows a good balance between the two diameters, where the dust particle collides with the droplet and the suppression will be successful. [4]

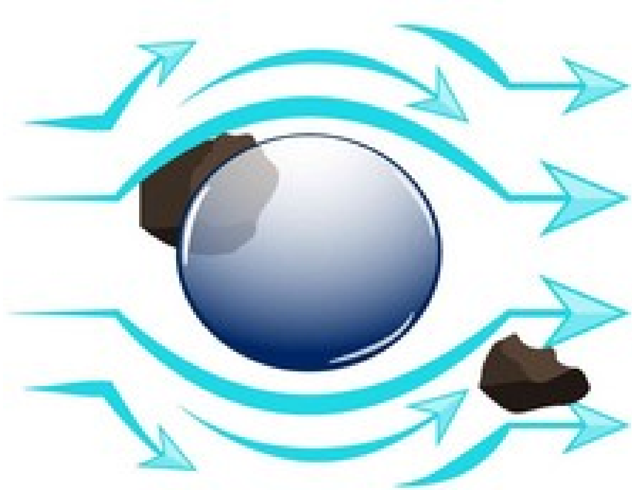


Figure 4-1: Particle and droplet diameter in a favorable ratio [20]

The following picture shows what happens when the dust particle is more than 5 times smaller than the droplet. The particles tend to move around the droplet caused by less inertia in the same way the air does.

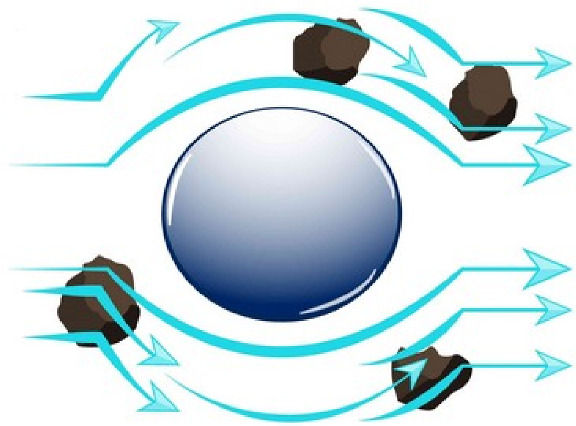


Figure 4-2: Droplet way bigger than particle [20]

As seen in the figures above, it is necessary to match the size of the water droplet according to the diameter of the dust particles. Since most of the time the dust particles vary in size, it is necessary to not just generate a single diameter of droplet, but more importantly a whole spectrum of particle sizes. This can be achieved by using special nebulization nozzles, spraying procedures (for example the pressure) and additives, but more on these factors in their respective chapter. One small influence is still to notice on the subject of particle size: the particle changes its size while it is in the air due to the evaporation effect. But this influence is very small in water mist scrubbers, so it will not be further explained. [4]

The binding efficiency is shown in the Figure 4-3 as well as the relation between the two diameters of particle and droplet.

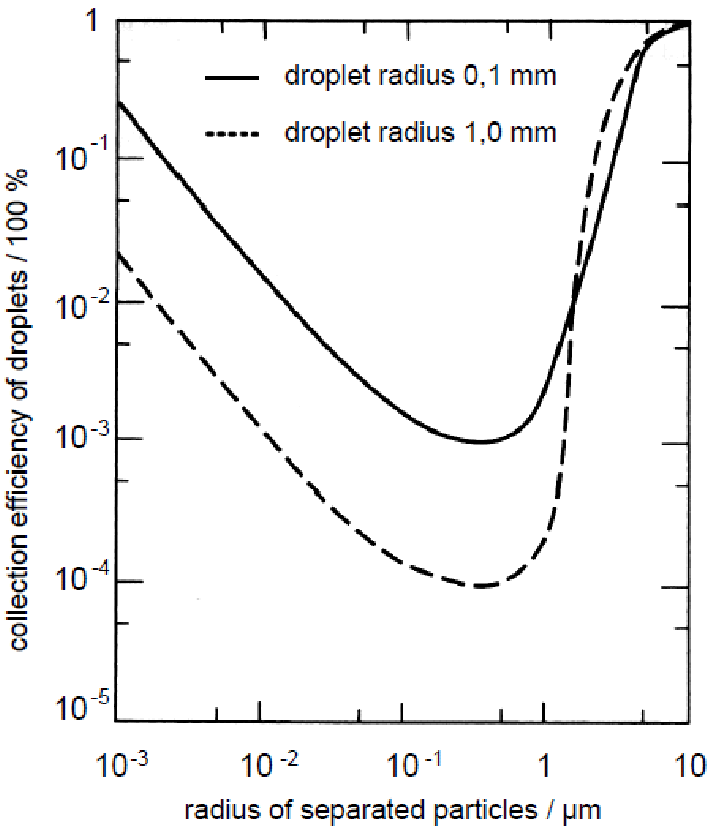


Figure 4-3: Collection efficiency depending on droplet and particle size[21]

The necessary formulas to calculate the efficiency of collection are already given in the chapters 3.1.1 and 3.1.3, so they will not be listed again in this subchapter.

The figure shows that dust particles larger than 5µm in radius are easier to separate than smaller particles, whereas the minimum of the efficiency is located at a radius of 1µm. The name of this effect is “Greenfield Gap”. [21]

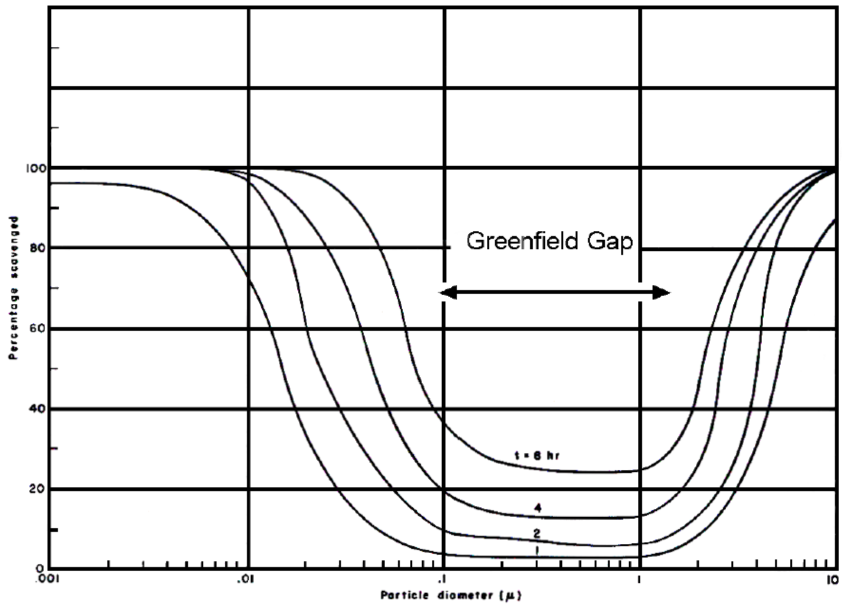


Figure 4-4: Greenfield: Particle scavenging efficiency for 20 µm droplets [23]

Figure 4-4 shows the drop in scavenging efficiency in a larger scale. Greenfield discovered that this gap results from the collecting efficiencies from the two main binding forces, the inertial and diffusional. The inertial collection mechanism is the dominant force for catching larger particles (>1µm) because they collide easier than smaller particles. The diffusional mechanism is responsible for scavenging small particles (<0,1µm) and the efficiency increases with decreasing particle size. Between these two diameters, neither of this two binding mechanisms operates efficiently, which results in the "Greenfield Gap". Coincidentally the particles within the gap have higher retention efficiency within the human respiratory system, which creates a significant health hazard to humans. [22]

4.2 Retention time

The retention time is the time period in which the dust particles and the water droplets are in contact with each other and where it is possible for them to meet. This can only occur when they have a relative velocity to each other, so one of the two can follow up to the other and get in contact with it, as seen in the following figure. [2]

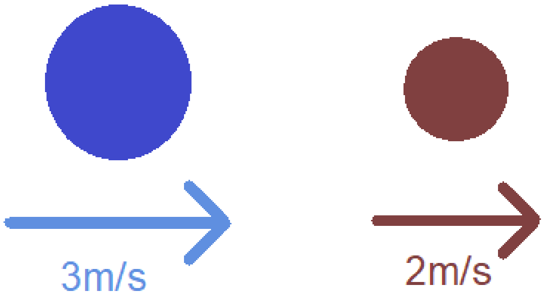


Figure 4-5: Relative velocity particle and droplet

The water droplet has a speed of 3m/s and the dust particle 2m/s. The resulting relative velocity is 1m/s. This leads to the water sphere catching up to the dust particle and it can therefor get in contact with it. If there is no relative velocity between the dust and water particle, it is not possible for them to meet each other.

The retention time of a droplet in the aero-dispersion is a decisive factor and is also influenced by the relative velocity, which will be explained later. This is based on the fact that there must be a different relative speed of movement between the droplet and the dust particle for them to meet. The retention time with a relative velocity can be terminated by two circumstances: [2]

- The relative velocity between the two particles becomes 0, which means that they continue to move at the same speed and thus do not meet.
- The drop reaches the end of the covered space, for example the ground.

If water is sprayed into an air flow or into an open area, the droplets need a certain time to adapt to this respective movement. The so-called “Relaxation time” can be calculated according to the following formula.

$$\tau = \frac{\rho_D \times D^2}{18 \times \eta_g} \times C_C$$

Equation 4-1: Relaxation time of a water droplet [2]

ρ_D is the droplet density, D the diameter, C_C the correction factor and η_g represents the dynamic viscosity of the air.

The correction factor is 1 at Reynolds numbers Re <1 and for Re <4000 it needs to be calculated as followed with the help of the resistance coefficient C_R.

$$C_C = \frac{24}{Re \times C_R} = \frac{24}{Re\left(\frac{21}{Re} + \frac{6}{\sqrt{Re}} + 0{,}28\right)} = \frac{24}{21 + 6\sqrt{Re} + 0{,}28Re}$$

Equation 4-2: Correction factor relaxation time [2]

If only the resistance force is considered for the acceleration of the water drop, then it can be represented as a function of the relaxation time:

$$\frac{dw_x}{dt} = \frac{v_{g,x} - w_x}{\tau}$$

Equation 4-3: Equation of movement [2]

If the air stream has a constant velocity, then the droplet speed for a resting droplet at t=0s can be calculated with the help of the next equation.

$$w_x = v_{g,x}\left(1 - e^{\frac{-t}{\tau}}\right)$$

Equation 4-4: Equation of movement with constant velocity [2]

During the relaxation time τ, the first not moving droplet reaches about 63,2% of the air velocity and 3τ to reach 95% of its speed. If the water particle moves in the opposite direction than the air stream, then the particle will be slowed down till it reaches no movements. This time needs to be calculated and afterwards the time till it reaches the same speed as the air flow can be calculated too. The time it needs to adjust to the air velocity is also depending on the particle size. In the next two figures, the time to adjust is shown for two different particle sizes. The velocity of the air is 4m/s in x-direction and 0 in z direction. Droplet speed at the start is w_x=-4m/s and w_z= 4m/s. Density of the droplet is ρ_D = 999,1 kg/m^3 and the dynamic viscosity of the air is η_g= 1,7984*10^{-5} Pa s. [2]

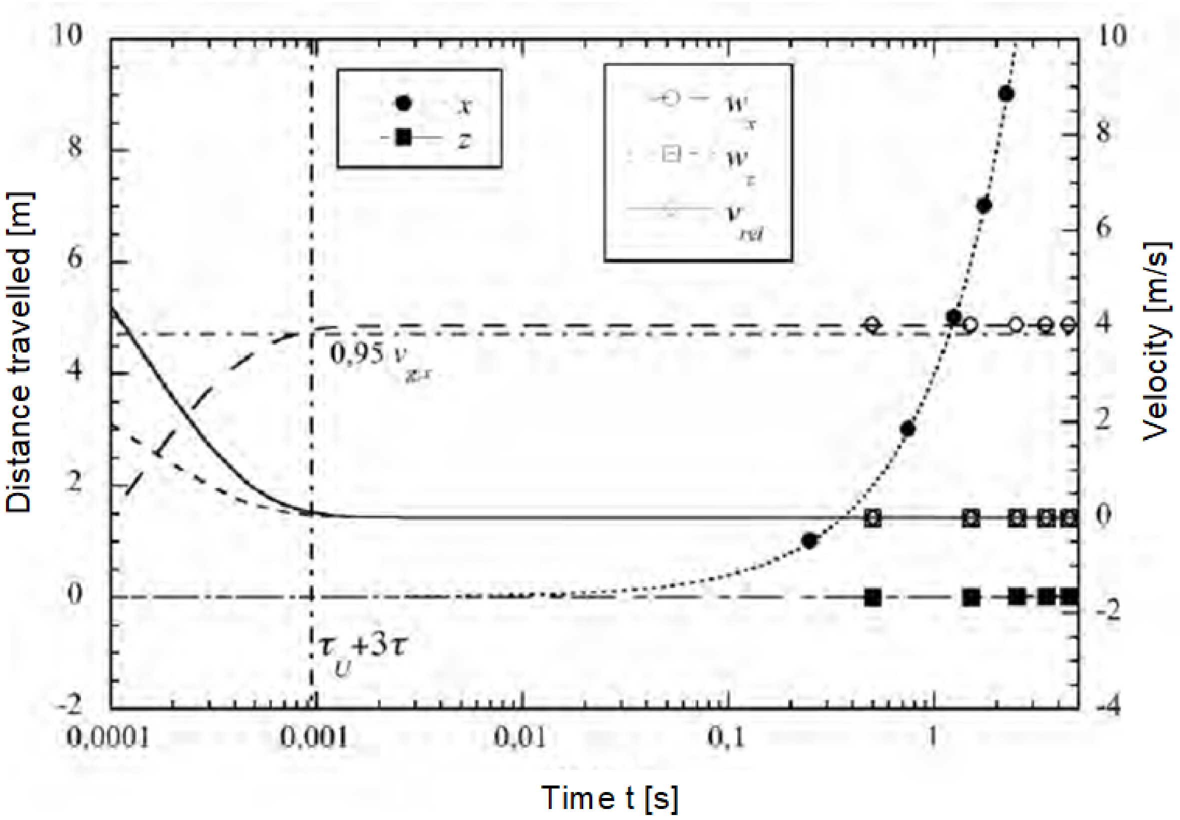


Figure 4-6: Retention time 10 µm [2]

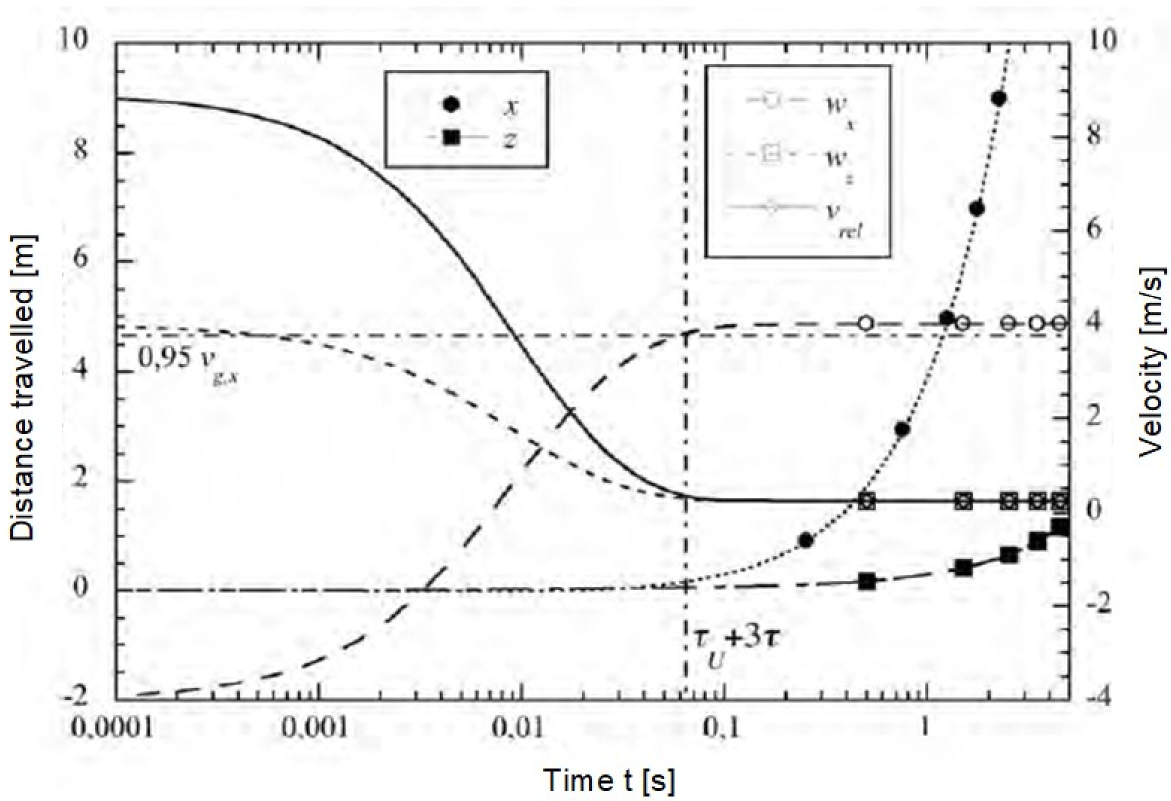


Figure 4-7: Retention time 100 µm [2]

As seen in the two Figures above, a smaller droplet adjusts way faster than a bigger droplet to the air velocity. This means, that the smaller one loses its relative velocity way faster, which needs to be concerned for the retention time.

4.3 Angle of collision

The angle at which the dust particle hits the water drop plays a very minor role and no literature was found on this subject. This is because the angle does not play a role in any of the binding mechanisms found in chapter 3, as the particle either hits the droplet directly, or trapped by other forces. The only thing where the angle plays a role is the retention time or better said the relative velocity to each other. This would play a role, for example, when spraying at a right angle, since there is little relative velocity acting in the same direction, as well as the retention time would be very low. But this factor was already explained in the previous subchapter. Further influences with the degree of impact will be explained in chapter 4.6.1 Position of nozzles.

4.4 Electrostatics

The main principle of binding dust with the help of electrostatics via the coulomb force was already explained in chapter 3.1.5 “Electrostatic Force” including all the necessary formulas and equations. For an electrostatic force, electric current is needed to generate an electric field and to enable a charge on the particles, so that this force can catch the dust particle and to bind it onto the surface of a charged water droplet.

Michael J. Pilat has done some significant research in 1975. He calculated that the collection of small aerosol particles (0,05-5µm), which is shown in Figure 4-8. His calculations show an increase in the collection efficiency for 1,05µm particles from 68,8% uncharged to 93,6% charged with a two chamber spray scrubber and 7 seconds gas residence time. [24]

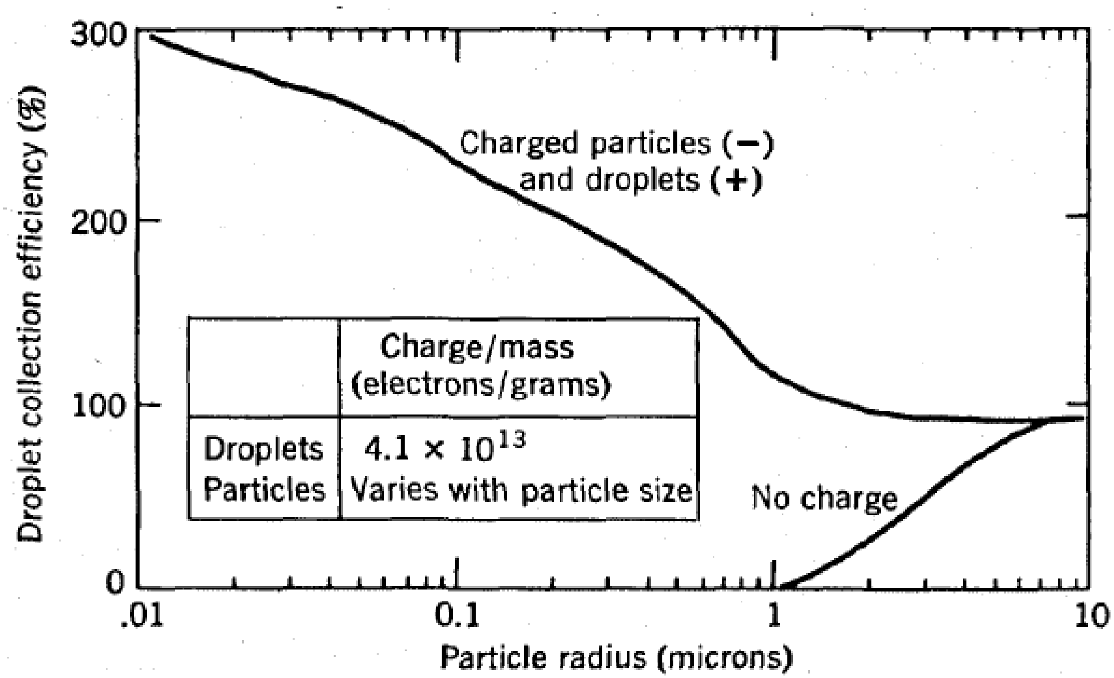


Figure 4-8: Calculated particle collection efficiency [24]

After the necessary calculations, Michael J. Pilat has done some experiments to back up his calculations. 30kV particle charge voltage and 2kV water charge voltage were used in the experiments and the collection efficiency showed an increase on smaller particle sizes. The result of this is presented in the next picture. [24]

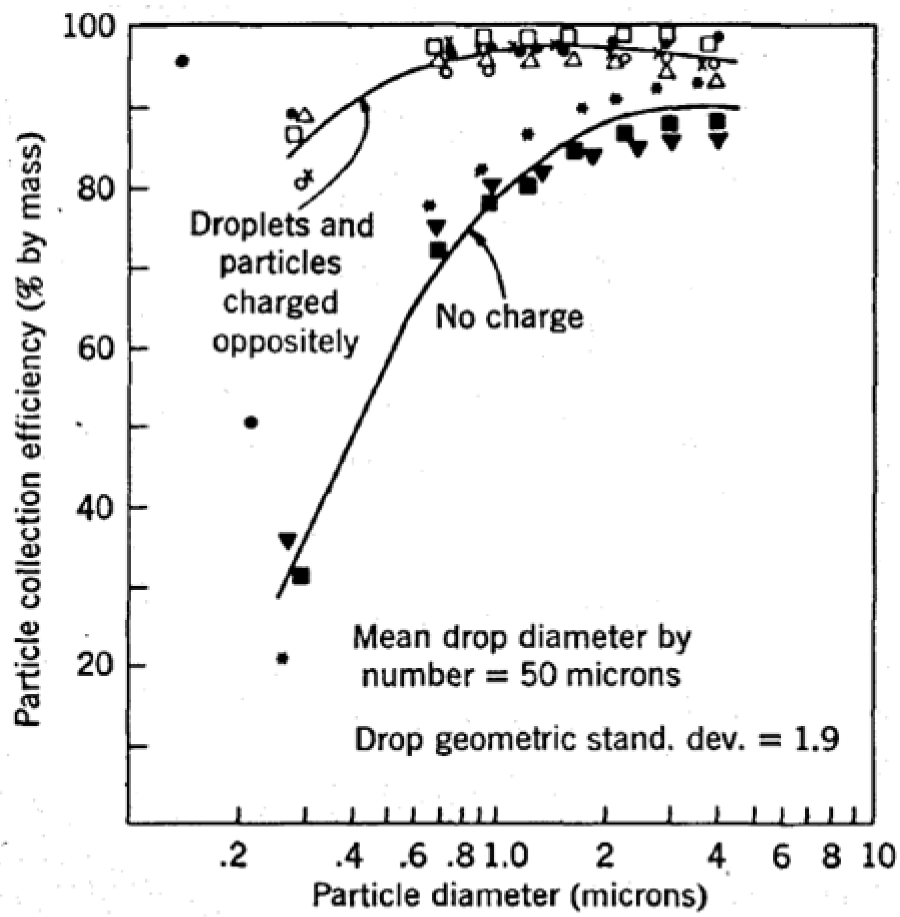


Figure 4-9: Particle collection efficiency [24]

The results show that for small particles, a binding through electrostatic force has a substantial increase and for particles of a larger size, the inertial force is again the dominant force. This also depends on the power of the charging, as well as the particle size. This method is useful for closed wet scrubbers, but could be hard to achieve in an open field with an water mist spray canon, since only the water could be charged and this could create a dangerous environment for the rest of the equipment and the workers in this area, since a high voltage would be needed and the water mist would work as electric conductor.

4.5 Water influences

This chapter should focus on all the influences which come from the use of water to create mist. Since pure water, or combined with an additional environmental friendly additive, is mostly used in open field water mist scrubber, other influences like generating acidic compounds will be ignored.

4.5.1 pH value

The main part of this master thesis is to find influence on the binding of dust, therefore the pH value plays just little to no role. No significant influence was found for collecting dust particles. The real influence of the pH value comes into play when a gas or a special emission should be collected, where the main binding mechanism is through a chemical reaction with intermediates. If an acidic or alkaline dust should be collected, then it could come into play, but not for catching the particles, far more if they should be cleaned of this substance.

A reason for the pH value to be more noted in this thesis is the fact, that a high or low pH value can be harmful for people or the environment. The machines used from "*EmiControls*" operate in an open field environment, where the water cannot be easily treated after catching the dust. Therefor an important impact should be kept in mind, namely a possible negative impact on the surrounding environment can occur when working with acidic or alkaline liquids.

The second reason for the pH value to be noted is the fact, that it can interfere with the wanted effects of some surfactants, which will be explained in the following subchapter.

4.5.2 Surfactants and Hydrophobicity

There are a lot of different surfactant additives to improve dust collection. They are surface-active agents and the main effect of using these amphiphilic substances is to lower the surface tension of the water droplet. The result of this is that the droplets vary in different diameters. This means, that the diameter of droplets with additives is smaller than droplets with pure water. In theory a greater efficiency in binding particles should be achieved with surfactants, but only if the original droplets are too large compared to the dimension of the dust particles. If a special nozzle is already used for an optimized droplet size distribution, then there is a negative effect on the efficiency, because the added additives would reduce the size of the droplets too much. [2] [4]

Surfactants consist of two different parts, a hydrophobic and a hydrophilic part. Hydrophilic means that it wants to combine with water molecules, whereas hydrophobic means that it doesn't want to get into contact with water molecules. This effects lead to the fact, that surfactants arrange themselves in a specific order on the surface of a water droplet when they are mixed with water. They form a layer on the water sphere thus reducing the surface tension. This is shown in the Figure 4-10. [2]

A lowered surface tension also means a lowered contact angle of the liquid, which results in a better "wetting" of hydrophobic particles, for example coal dust or petroleum coke. These particles tend to repel water and are therefore hard to bind with water. In comparison if a particle is hydrophilic, it strongly interacts with water particles and is easier to bind with water, for example most metal dusts. [27]

Before using surfactants in an open field, is has to be clarified if they can be harmful for humans or the environment, since they consist of chemicals.

As a conclusion it has to be said that the addition of surfactants has an influences on the droplet size distribution, which was already explained in the chapter on the influences of the particle and droplet sizes, and on the binding with hydrophobic materials.

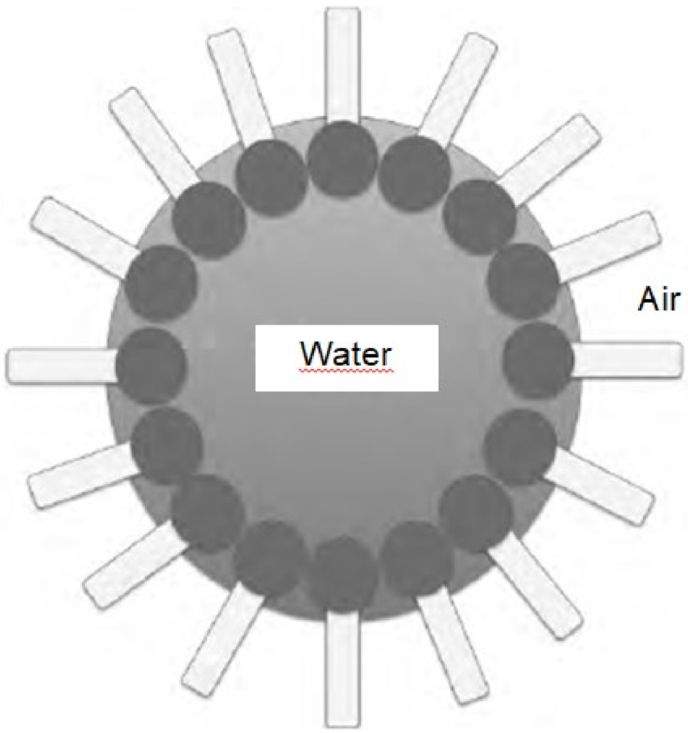


Figure 4-10: Water drop with surfactant molecules [2]

Ulrich Klenk did some research on this topic in 2012, where he added additives to the water stream of wet scrubbers. Like already explained above, the surfactants create a bigger variation on the droplet size distribution depending on the used nozzle. The next figures show one of his results, where it is clearly visible, that the smaller particles get caught more efficiently, since the addition creates smaller droplets. The experiments where made with three different nozzles and three different additives (CD, PD, CDS) at two mixing rates. Concentrations of the additives were recommended by the vendors of the surfactants. The results are displayed in the next figures. [4]

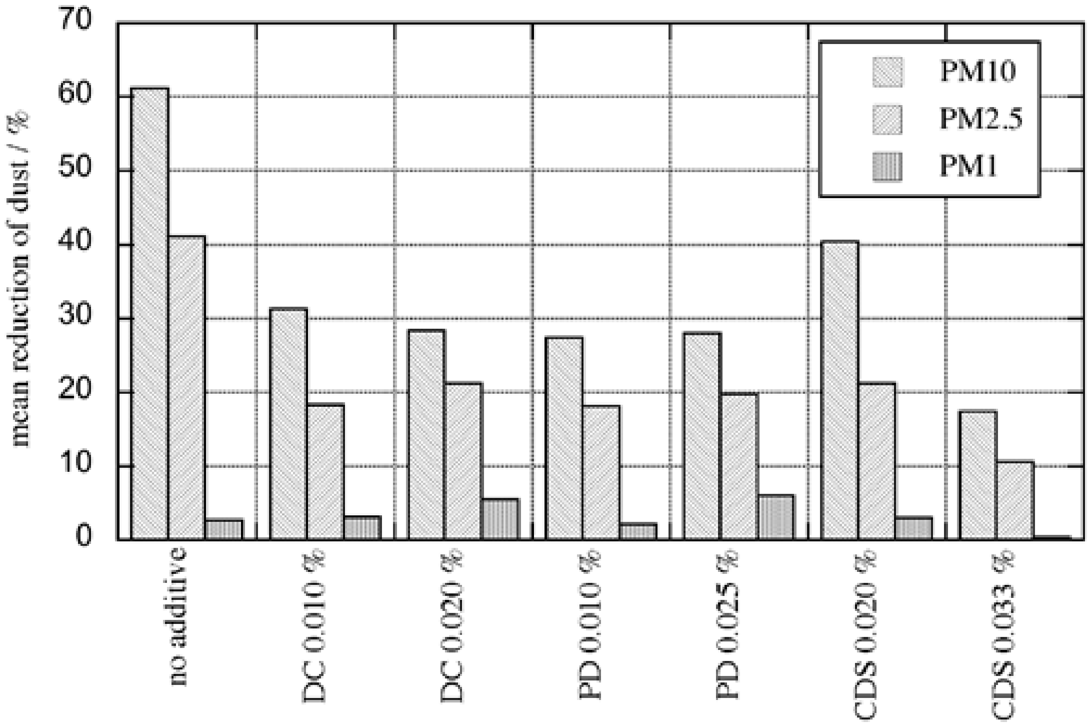


Figure 4-11: Twister nozzle efficiency surfactants (0,58-0,62 L/s, 5 bar) [4]

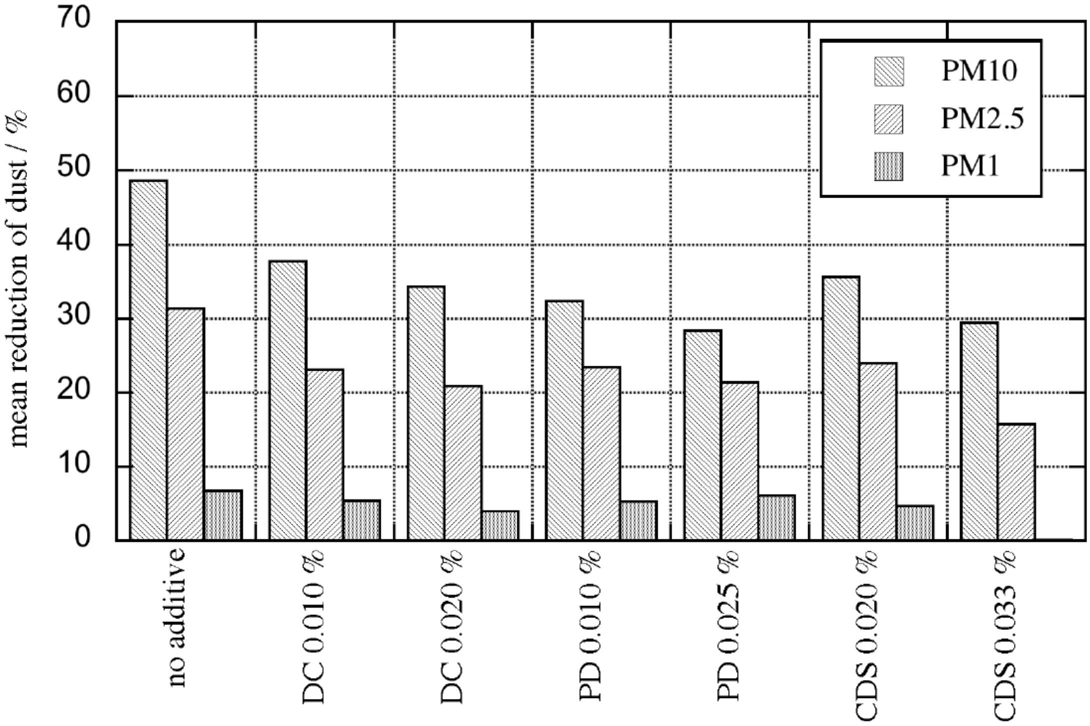


Figure 4-12: Hollow cone nozzle efficiency surfactants (1,06-1,12 L/s, 5 bar) [4]

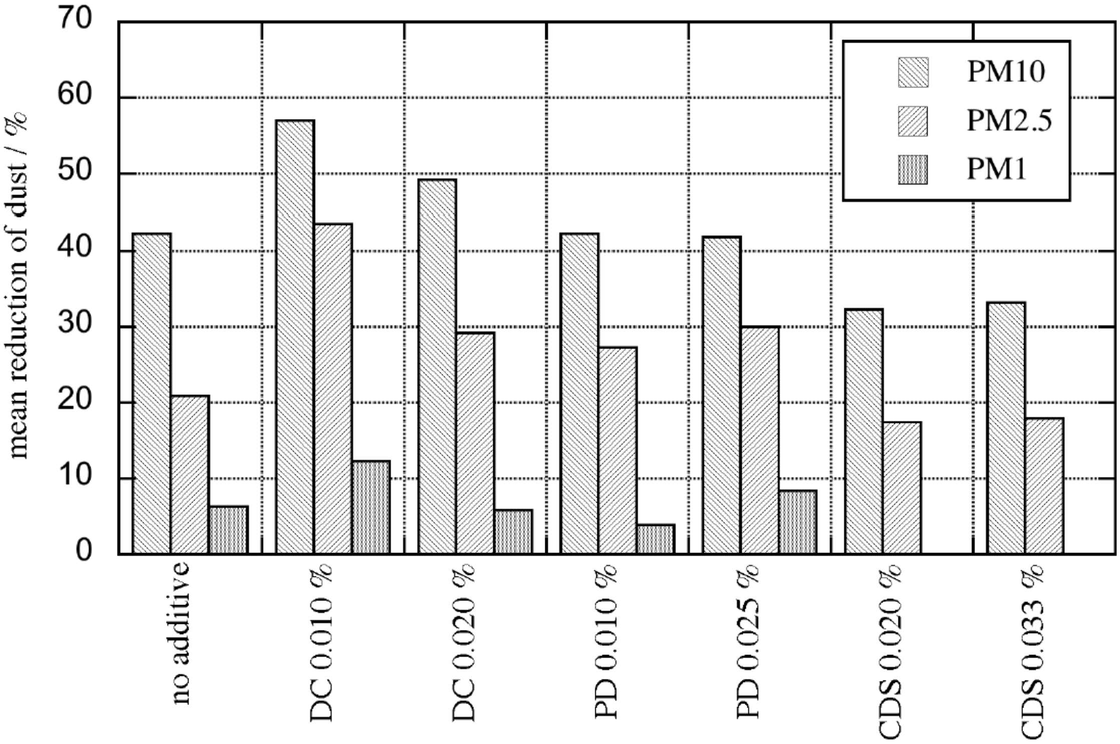


Figure 4-13: Fan nozzle efficiency surfactants (1,16-1,23 L/s, 5 bar) [4]

As seen in these results, there is a difference in the efficiency between nozzle types, when using additives. It depends mainly on the distribution of the droplet size and to a small part on the water flow rate, but a higher flow rate doesn't necessary mean a higher efficiency. Using additives lowers the efficiency of the twister nozzle and the hollow cone nozzle, but it can be improved for the fan nozzle. [4]

As a conclusion of Klenks experiments, it can be assumed that the usage of surfactants can be useful, but it depends on the used nozzle and the distribution of the dust particle diameters. So it is necessary to know which particles sizes will be given in the dust, and to adjust the nozzle to this distribution. If the necessary droplet sizes cannot be reached with the given nozzle, then the addition of surfactants can be useful.

Yen-Yi Lee and his team did some research on the binding efficiency of surfactants on dust from an iron ore pile using conventional Sprinkler and a water mist generator. Like already said, the addition of chemicals lowers the surface tension, which makes binding for hydrophobic particles easier. The results are shown in the next Figure. [29]

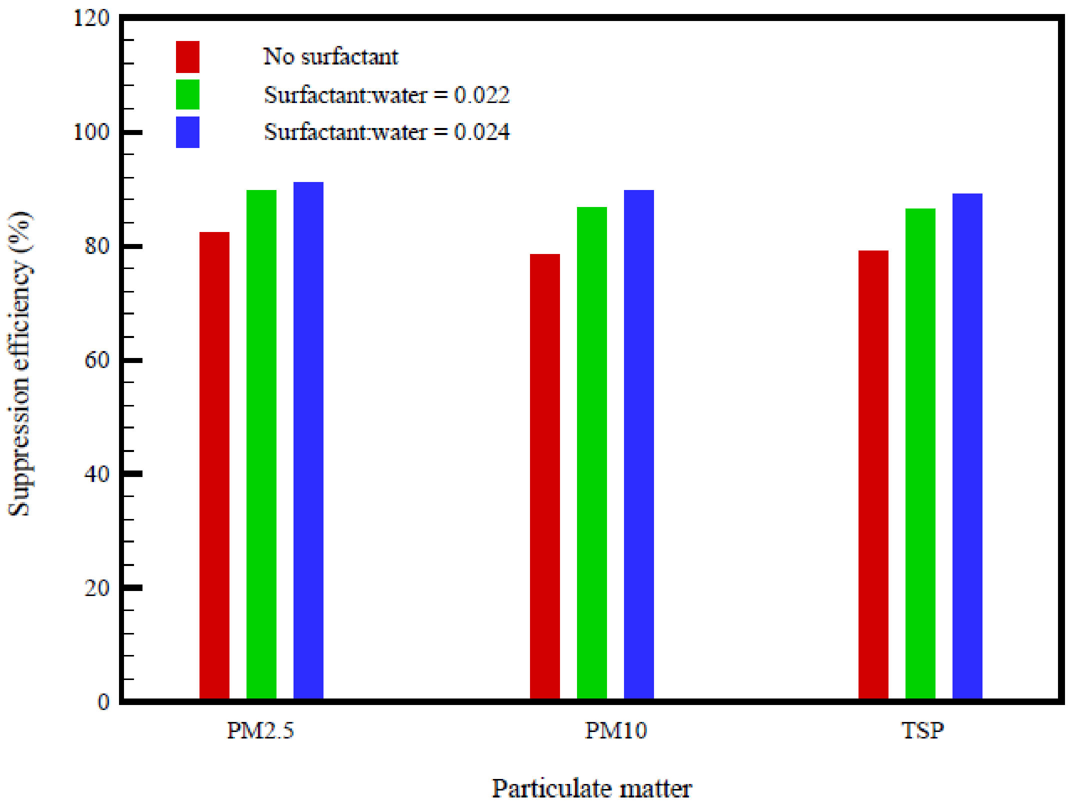


Figure 4-14: Dust suppression efficiency with surfactants [29]

4.5.3 Temperature

The influence of the temperature is the same as it is for the pH value. It is mostly used in chemical bonding. Since the main topic of this master thesis is the binding of dust, the chemical binding can be neglected. But the temperature also has an influence on the condensation effect, which means, that dust particle can act as condensation nucleus. The nucleus can then start to grow and get caught with the help of the inertial force. No direct literature on the influence of the water temperature was found for dust. One usage is the flux force and condensation scrubber. There are a few companies which work on the development of condensation scrubbers and also a few patents were found on that topic and a few experiments are planned for the next few years.

The effect of condensation was already explained in Chapter 3.1.2. As a conclusion it is possible to say that the condensation effect works in favor for the inertial force and that it leads again to the distribution of the particle diameters, where the main influence lays. [18] [25]

4.6 Spray nozzles

The influences associated with the use of different nozzle types are examined in more detail in this chapter. To begin with, it is necessary to know which nozzle will be used and where the nozzle will be placed. So to start, a closer look on the positioning will be given and as a next step, the different types of nozzles will be explained and what are the influences of the dust binding capacity originating from the different types.

4.6.1 Position of nozzles

There is no hard and fast rule for specifically locating spray nozzles because of the unique characteristics of each new application, but there are a few guidelines: [30]

- For the usage of wet dust prevention, nozzles should be located upstream of the transfer points on which the dust emissions occur. They should be located in a way that the best mixing of material and water can happen.

- The surface area of the ore should be wetted as much as possible, so the usage of additional nozzles is recommended.

- If the main target is the prevention of airborne, then the optimum distance between nozzle and material should be used. This means close enough that air currents do not carry away the droplets, thus reducing the efficiency, but far enough away that the whole necessary area is covered.

- When setting the optimum distance, the droplet size needs to be considered.

- A maximum retention time for the water droplets to interact with the airborne dust particles should be enabled by the location of the nozzle.

- To prevent the escaping from the droplets or particles before agglomerating, there should be a maximum available enclosure around transfer points.

- For maintenance work they should be placed accessible

The next two figures show a typical application and location of the nozzles.

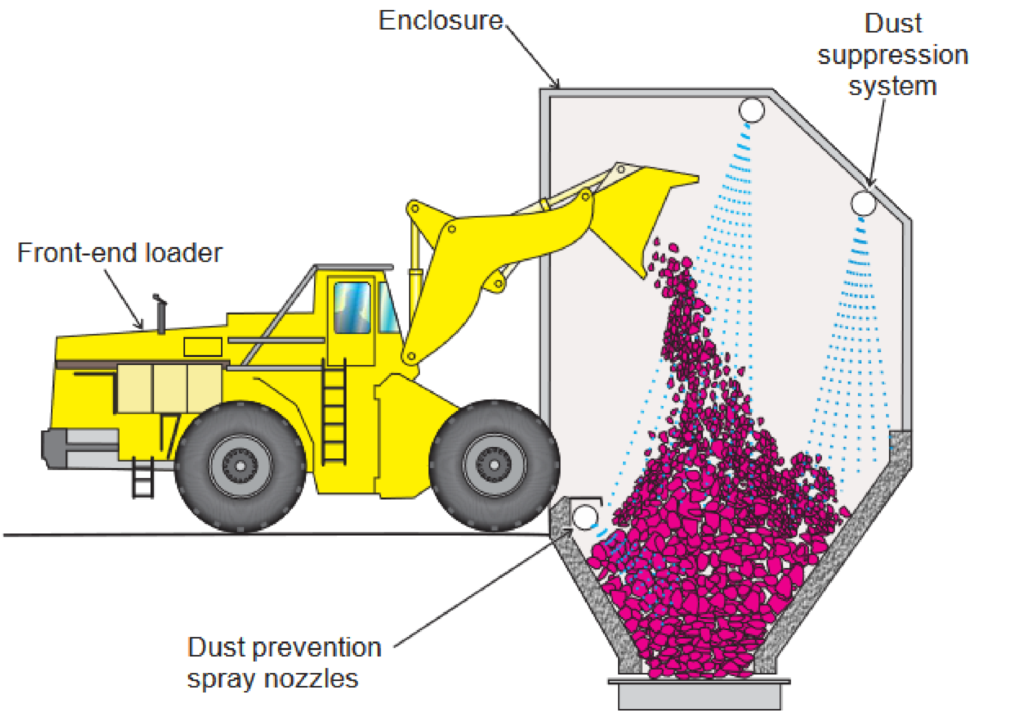


Figure 4-15: Typical loader dump application [31]

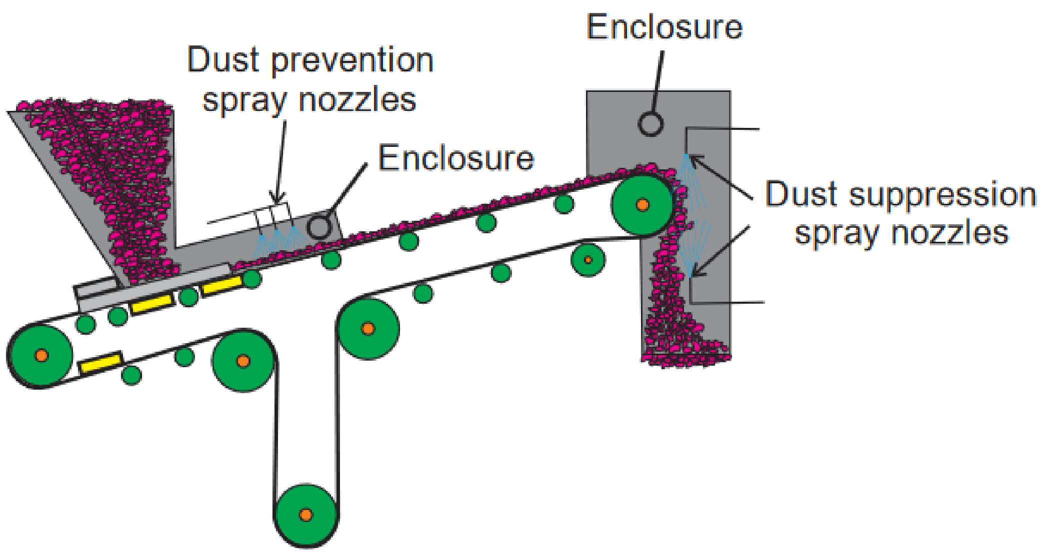


Figure 4-16: Typical conveyor belt application [31]

4.6.2 Spray nozzle types

In the following picture, the different types of nozzles are given with the respective applications, features and spray patterns.

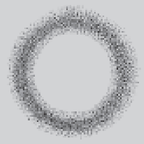
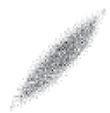
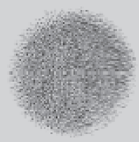
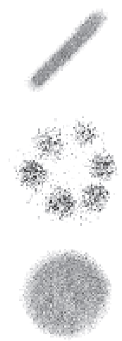
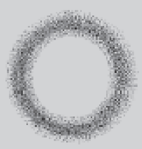
SPRAY NOZZLE TYPE	SOLUTION	APPLICATIONS	FEATURES	SPRAY PATTERN
HOLLOW CONE	Dust Prevention/ Airborne Dust Suppression	• Transfer Points • Transport Areas/Roads • Jaw Crushers	• Large nozzle orifices that reduce clogging • Small drop size – generally smaller than other nozzle types • Typically used in locations where dust is widely dispersed	
FLAT SPRAY	Dust Prevention	• Stockpiles	• Small- to medium-size drops • Typically used in narrow or rectangular enclosed spaces	
FULL CONE	Dust Prevention	• Stackers, Reclaimers • Transfer Points	• High velocity over a distance • Medium- to large-size drops • Commonly used when nozzles must be located a good distance away from the area where dust suppression is needed or to clear mechanical obstructions	
AIR ATOMIZING	Airborne Dust Suppression	• Jaw Crushers • Loading Terminals • Primary Dump Hopper • Transfer Points	• Small drops • Commonly used to capture small dust particles in enclosed areas to minimize drift	
HYDRAULIC FINE SPRAY	Dust Prevention/ Airborne Dust Suppression	• Stackers, Reclaimers • Stockpiles • Transfer Points • Jaw Crushers • Loading Terminals • Primary Dump Hopper	• Small drops • Commonly used to capture small dust particles in enclosed areas to minimize drift	

Figure 4-17: Spray nozzle types [28]

4.6.3 Velocity

The velocity of the water droplet comes from the nozzle; therefore it is included in this chapter. Like already explained in the chapter of the retention time, it is necessary for the droplet to have a relative velocity compared to the dust particle, for agglomeration to happen. The velocity depends on the used nozzle and the pressure. After the drop is deployed into an air stream, the gravitation force takes place and depending if it is sprayed in an open field or a closed pipe, the air stream has to be considered for the movement. Other forces need to be evaluated too, namely the inertia and the resistance force. The buoyancy force can be neglected. The weight force results from the mass and the acceleration due to gravity. [2]

$$\overrightarrow{F_w} = m \times \vec{g}$$

Equation 4-5: Weight force [2]

With the mass and the acceleration due to the air flow, it is possible to calculate the inertia force as followed:

$$\overrightarrow{F_D} = -m \times \frac{d\vec{w}}{dt}$$

Equation 4-6: Inertia force [2]

To calculate the mass of the droplet:

$$m = \frac{\pi}{6} \times D^3 \times \rho_D$$

Equation 4-7: Droplet mass [2]

Relative velocity is the difference from the velocity of the droplet $\vec{w}$ and the air $\overrightarrow{v_g}$.

$$\vec{v}_{rel} = \vec{v}_g - \vec{w}$$

Equation 4-8: Relative velocity [2]

The relative velocity can then be split in the values for the x and z direction.

$$v_{rel,x} = v_{g.x} - w_x$$

Equation 4-9: X proportion of relative velocity [2]

$$v_{rel,z} = v_{g.z} - w_z$$

Equation 4-10: Z proportion of relative velocity [2]

The absolute value of the relative velocity can then be calculated as:

$$|\vec{v}_{rel}| = \left|\begin{pmatrix} v_{rel,x} \\ v_{rel,z} \end{pmatrix}\right| = \left|\sqrt{v^2{}_{rel,x} + v^2{}_{rel,z}}\right|$$

Equation 4-11: Absolute relative velocity [2]

In the next picture, the relative velocity is illustrated, as well as the air stream and water droplet.

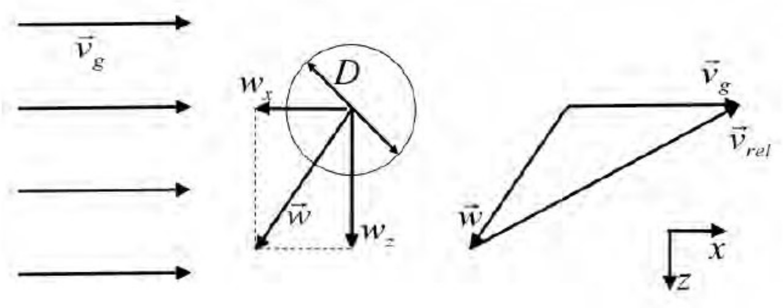


Figure 4-18: Illustration of the relative velocity [2]

The next step is to calculate the flow resistance value c_R(Re) which is depending on the Reynolds number:

$$c_R(Re) = \frac{21}{Re} + \frac{6}{\sqrt{Re}} + 0{,}28$$

Equation 4-12: Flow resistance value [2]

$$Re = \frac{|\vec{v}_{rel}| \times D \times \rho_g}{\eta_g}$$

Equation 4-13: Reynolds number [2]

With these necessary formulas it is possible to calculate the resistance Force $\overrightarrow{Fw}$:

$$\overrightarrow{F_w} = \frac{1}{2}\rho_g \times \vec{v}_{rel} \times |\vec{v}_{rel}| \times A_D \times c_w(Re)$$

Equation 4-14: Resistance force [2]

From the individual forces, the balance of the equation of motion can be formed as follows:

$$\begin{pmatrix} F_{D,x} \\ F_{D,z} \end{pmatrix} + \begin{pmatrix} F_{w,x} \\ F_{w,z} \end{pmatrix} + \begin{pmatrix} 0 \\ F_{G,z} \end{pmatrix} = 0$$

Equation 4-15: Balance of the motion equation [2]

By applying the individual forces and deriving them by time, the acceleration of the droplets can be calculated:

$$\frac{dw_x}{dt} = \frac{3 \times \rho_g \times c_w(Re)}{4 \times \rho_D \times D} \times \vec{v}_{rel,x} \times |\vec{v}_{rel}|$$

Equation 4-16: Acceleration droplet x-direction [2]

$$\frac{dw_z}{dt} = \frac{3 \times \rho_g \times c_w(Re)}{4 \times \rho_D \times D} \times \vec{v}_{rel,z} \times |\vec{v}_{rel}| + g$$

Equation 4-17: Acceleration droplet z-direction [2]

The velocity and distance traveled from the starting point can then be calculated:

$$w_x(t_i) = w_x(t_{i-1}) + \frac{dw_x}{dt} \times (t_i - t_{i-1})$$

Equation 4-18: Droplet velocity [2]

$$s_x(t_i) = s_x(t_{i-1}) + w_x \times (t_i - t_{i-1})$$

Equation 4-19: Droplet distance traveled [2]

With this equations, it is possible to calculate the traveled distance of different sizes in x and z direction. The used values are the same as for Figure 4-6.

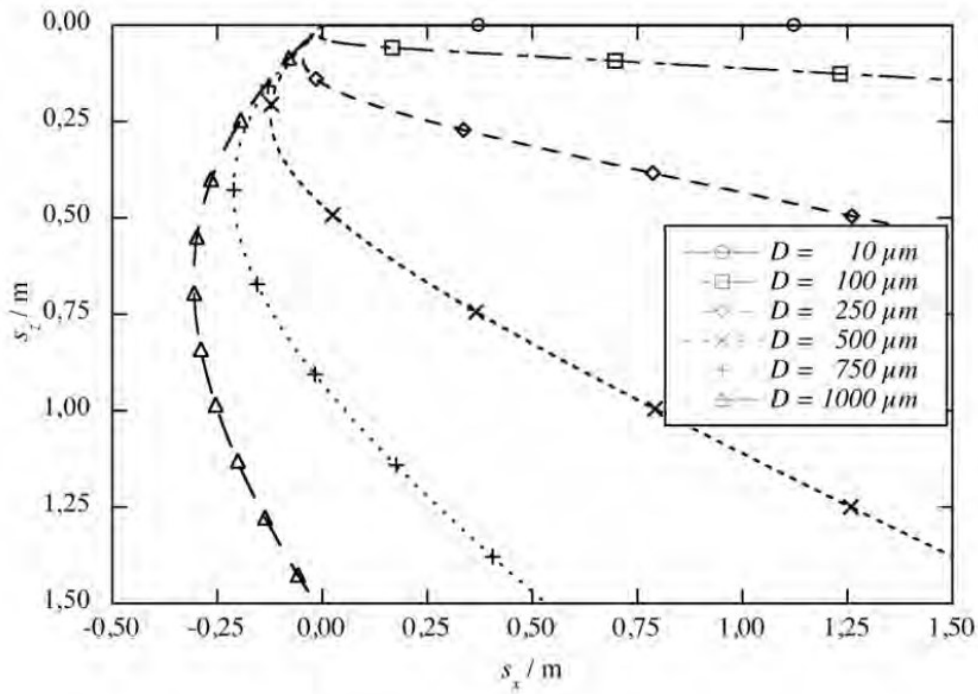


Figure 4-19: distance traveled by droplets [2]

The absolute value of the relative velocity in dependence of time can also be calculated with the equation above.

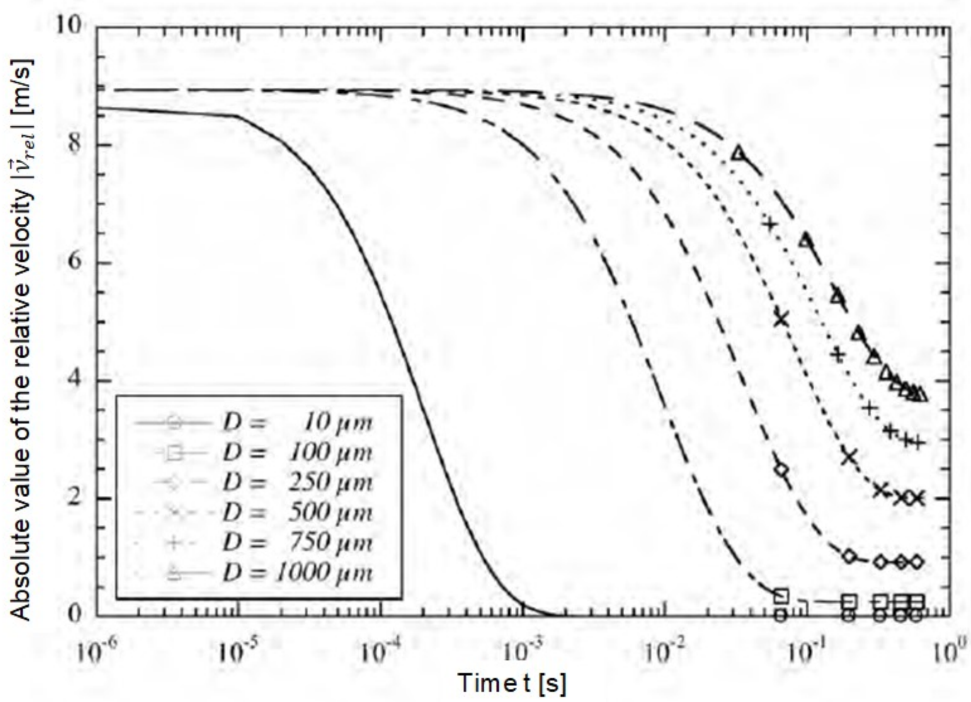


Figure 4-20: Absolute relative velocity depending on time [2]

4.6.4 Volume und flow rate

The volume of the water needs to be considered because every nozzle adds more moisture to the material. If the material needs to be heated up again after the process, more water means more energy for the same amount of material, because of the evaporation energy. This has a huge impact for example in burning coal. Another problem occurring with more water is that the material can get sticky and start to agglomerate, complicating the flow characteristics of the material being conveyed. The different suppression technologies add different volumes of moistures, as seen in the next figure. [27]

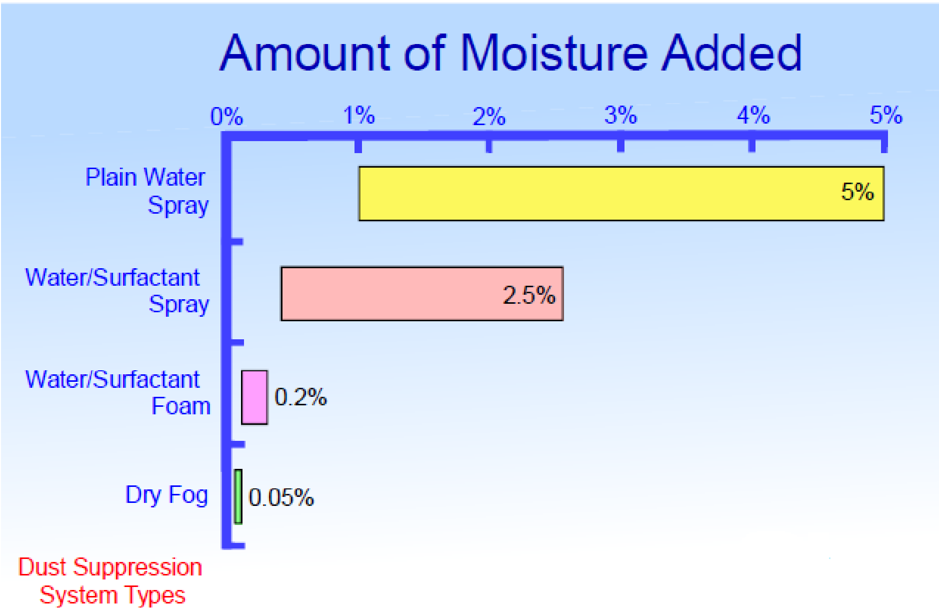


Figure 4-21: Amount of moisture added [27]

The flow rate depends on two things:

- Nozzle constant K (different for every nozzle and manufacturer)
- Operating pressure $p_{operating}$

Their relation is seen in the next equation:

$$Q = \dot{V} = K^2 \sqrt{p_{operating}}$$

Equation 4-20: Flow rate [30]

Therefore it is necessary to know both of these values, to be able to calculate the moisture added.

4.6.5 Pressure

By increasing the velocity of the impact the wetting of the surface can be improved, or better said the relative velocity needs to be higher, and this can be increased with higher pressure. [30]

An ideal operating pressure is dependent on many variables and thus not easy to decide, but there are three principles which should be taken into consideration: [28]

- Increasing pressure decreases drop size
- High-pressure nozzles are better for enclosed areas
- High-pressure nozzles should be placed closer to the dust emission area to minimize the amount of air set in motion

The next figure shows the airborne suppression performance of different spray nozzles at different operating pressures. Atomizing nozzles are the most efficient ones for dust suppression. [31]

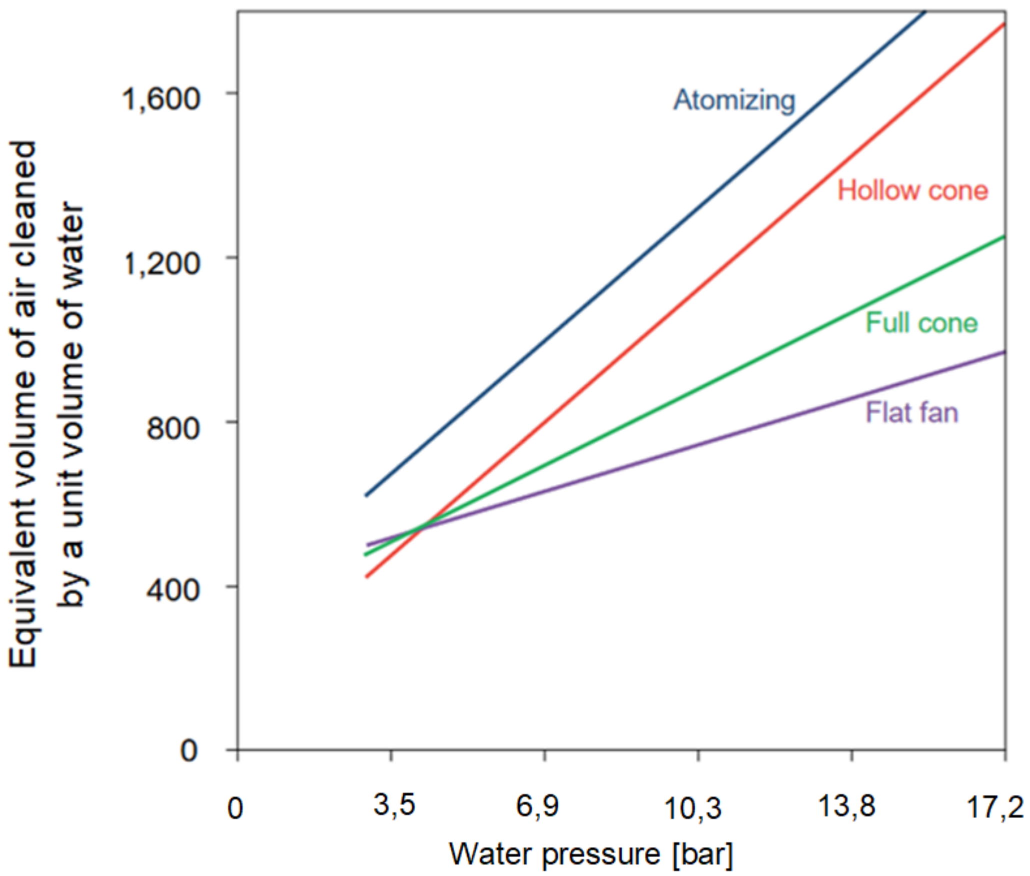


Figure 4-22: Airborne suppression performance [31]

4.7 Other influences

Within this chapter, all the other suspected influences should be dealt with, which do not fit into the previously mentioned groups.

4.7.1 Air humidity

For the influence on the air humidity on dust suppression, Peter Werner Grundnig and his team did some significant research in 2006. The development of a mathematical model to correlate air humidity, water flux and the dust emission (PM10) were worked out.

For the test, sand from the "Yellow River" in China was used and the particle size distribution is given in the next picture. [26]

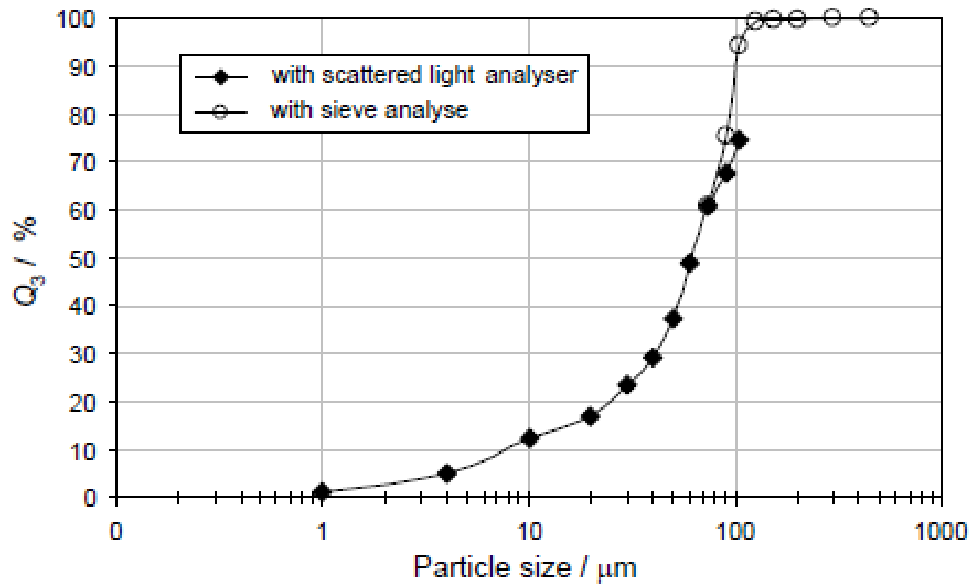


Figure 4-23: Particle size for the influence of the humidity [26]

As a first approach, the falling bulk mass flow was kept constant at 1 kg/min with different water flux rates. The next figure shows that the dust emission can be reduced by either a higher water flux, or higher air humidity. It also shows that the dependency on the air humidity is nearly linear. He also stated that after a certain amount of water flux, there was no significant higher capture rate of the dust. [26]

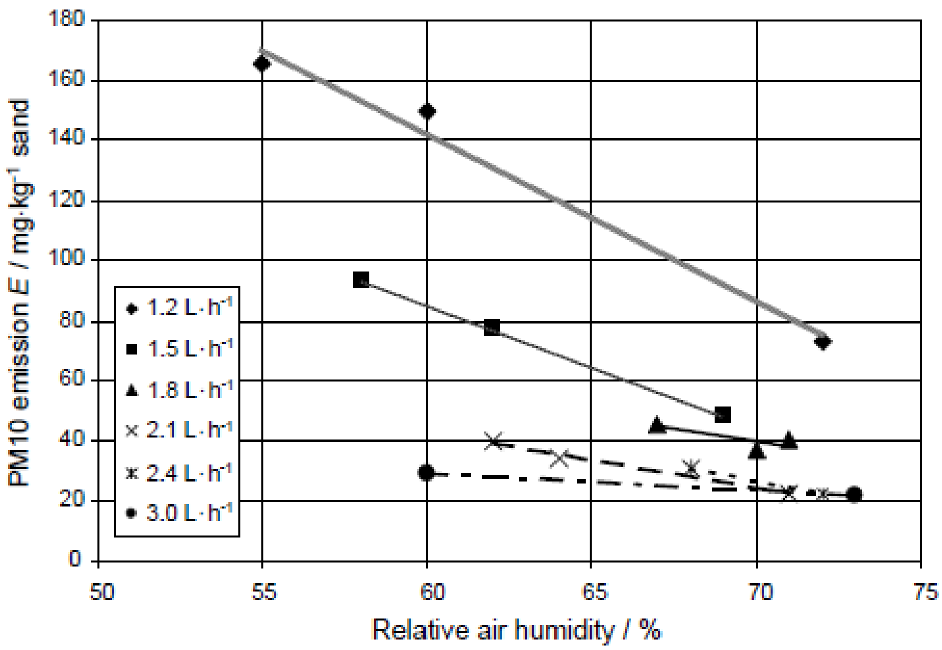


Figure 4-24: PM 10 emission for different humidity values and water flux [26]

With this data and on the basis of the deep-bed filtration model, a mathematical model was formed. The following equation describes the reduction of the particle concentration dc over the thickness dz. The proportional factor λ_d is proportional to its concentration c. [26]

$$\frac{dc}{dz} = -\lambda_d \times c$$

Equation 4-21: Deep-bed filtration model [26]

The relationship can also be interpreted alternatively as the dust particle reduction mechanism of water sprayers. The filter grains which form the filter layer have a similar function to the particle separation as the stationary mass of water dispersed in the dust, which means that the filter layer thickness can be replaced by the water flow. The particle concentration can be replaced by the PM10 emission E.

$$\frac{d\,(E - E_{res})}{dQ} = -\lambda \times (E - E_{res})$$

Equation 4-22: Modified deep-bed filtration model [26]

E_0 is the emission without water sprayer, E_{res} the residual emission for high water, Q for the water flux and Q_0 for the initial water flux necessary to start the reduction of the emissions.

After integration to above formula leads to:

$$\ln(E - E_{res}) = -\lambda \times Q + C$$

Equation 4-23: Integrated modified model [26]

C can be derived from the initial conditions Q_0 and Q_0.

$$Q = Q_0 \rightarrow C = \ln(E - E_{res}) + \lambda \times Q_0$$

Equation 4-24: Determine the constant

The substitution of C leads to the final forms of the model with λ as an empirical factor which controls the emission reduction and denotes the influence of the water sprayer (for example the droplet size):

$$\ln\left(\frac{E - E_{res}}{E_0 - E_{res}}\right) = -\lambda \times (Q - Q_0)$$

Equation 4-25: Form 1 of the influence model [26]

$$E = E_{res} + (E_0 - E_{res}) \times e^{-\lambda \times (Q - Q_0)}$$

Equation 4-26: Form 2 of the influence model [26]

With the help of this equation, it is possible to generate three curves with the above stated values. This graph shows different initial water masses needed for three different relative air humidity values.

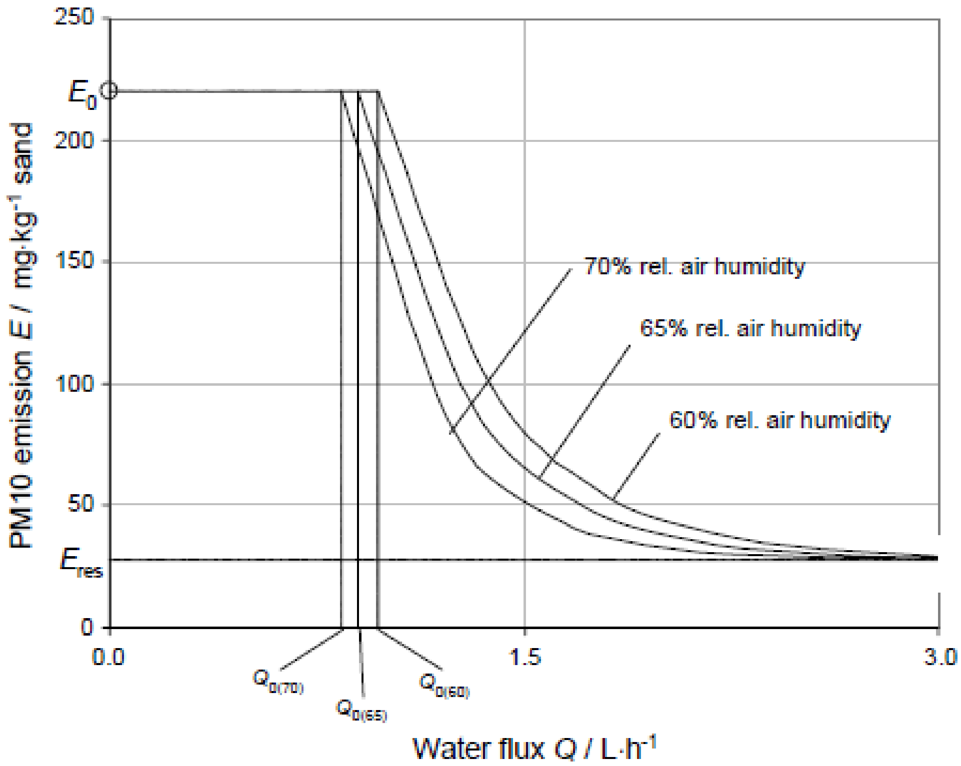


Figure 4-25: Calculations of the mathematical model [26]

The two parameters λ and Q_0 can then be found by regression of the data.

E_{res} [mg/kg$_{sand}$]	E_{res} [mg/kg$_{sand}$]	Rel. air humidity [%]	Q_0 [L/h]	λ [h/L]
27,9	220	60	0,97	2,4
		65	0,89	2,6
		70	0,84	3,1

Table 4-1: Determined values of parameters [26]

As a conclusion it was found that if the air humidity is higher, then the water flux can be lowered for equal effective dust suppression. Furthermore it is possible to assume that higher air humidity equals in a lesser water consumption because the initial water flux can be lowered to get equal values. There is also a specific maximum value, on which a higher water flux has no real benefit anymore. [26]

4.7.2 Particle surface

There was no literature found for the influence of the particle surface, only on the surface tension of the water droplets, which was explained in the chapter of the surfactants. This comes from the fact, that the main binding mechanisms are not dependent on the surface of the particle, but mainly only on the size of the particle. All the possible catching mechanisms were already explained in chapter 3.

4.8 Degree of impingement and separation

As last subchapter on this main topic, the degree of impingement of a single water droplet caused by inertial forces can be reduced on six different variables:

- Droplet diameter D
- Particle diameter x
- Particle density ρ_p
- Air density ρ_g
- Dynamic air viscosity η_g
- Relative velocity between particle and droplet v_{rel}

With the help of these key figures it is possible to calculate the Reynolds number Re, inertia parameter ψ and the correlation between the air and particle density Kρ.[2]

$$\psi = \frac{\rho_p \times v_{rel} \times x^2}{18 \times \eta_g \times D}$$

Equation 4-27: Inertia parameter [2]

$$K_\rho = \frac{\rho_p}{\rho_g}$$

Equation 4-28: Correlation air and particle density [2]

Now it is possible to calculate the degree of impingement, whereby the parameters a and b originate from the Reynolds number. With this equation, the flow around the droplet is taken into consideration.

$$\eta_D = \left(\frac{\psi}{\psi + a}\right)^b$$

Equation 4-29: Degree of impingement [2]

With the help of Equation 4-29 and the adhesive part h, it is possible to get the degree of separation:

$$\varphi = h \times \eta_D$$

Equation 4-30: Degree of separation [2]

To finish this chapter, the degree of separation will be in dependency of the droplet diameter D in the next figure.

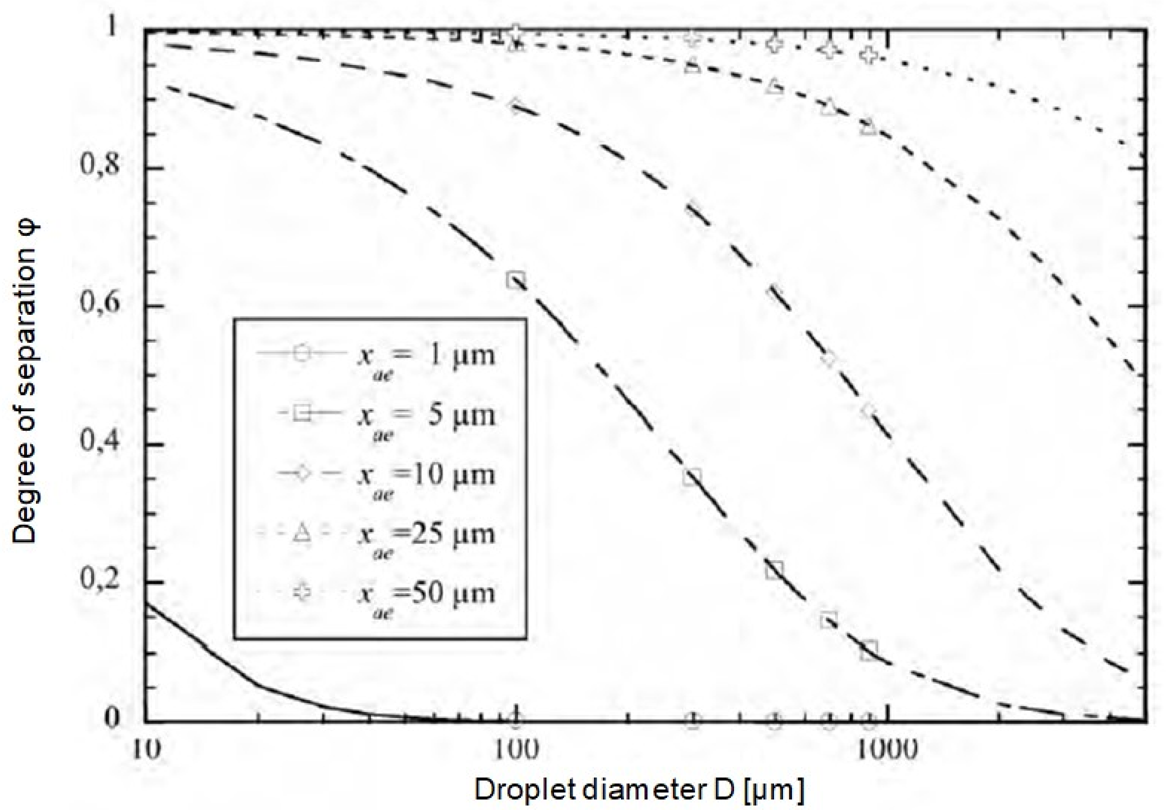


Figure 4-26: Degree of separation [2]

As expected, φ gets higher with increasing particle size, and gets lower with bigger diameters of the droplets.

5 Efficiency of dust binding systems

In this chapter, the different separation methods will be explained in more detail. The purpose of this is to get knowledge of the different variants and to compare them with each other, to determine the advantages and disadvantages of the respective methods and to determine the efficiencies that occur. Finally in this chapter the efficiency is related to the respective particle sizes and a comparison within the different dust binding systems is made.

5.1 Inertial separators

These kinds of separators collect or concentrate the particles by changing the direction of motion on the gas flow, in such a way that the particle trajectories cross the gas streamlines. With the help of the inertial and centrifugal forces, the particles are either separated, or can be concentrated. This surface can lead to a chamber, where the dust can be collected and removed. The most widely used type of inertial separator is the cyclone, as seen in Figure 5-1: Schematic cyclone, in which the gas undergoes a vortex motion, so that the gas acceleration is centripetal. This leads to a centrifugal movement of the particles towards the outside of the cyclone. Most of them induce the vortex motion passively by an appropriate design of the gas flow channel. With such a design, it is possible to get rid of moving parts. Some rotating devices, which are also called “gas centrifuges”, have seen very limited application. [8]

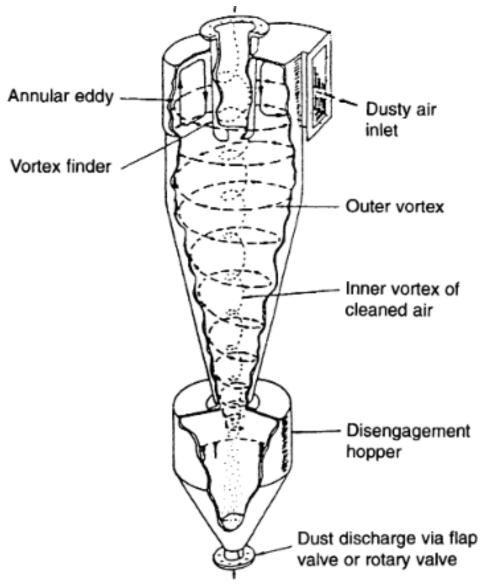


Figure 5-1: Schematic cyclone [8]

The picture above shows a reverse-flow cyclone, which is the most used type of inertial separator in industrial use. The vortex motion is generated by gas introduced tangentially into a cylindrical section ("Cyclone barrel"). The gas leaves the cyclone through an axial pipe ("Vortex finder"). This pipe extends beyond the gas outlet. This leads to a helical outer vortex of the gas inside the barrel and the cone. Afterwards it is moving into the much narrower inner vortex and leaving through the vortex finder. This created force pushes the particles to the outer wall and the helical motion inside pushes them down towards the apex and into the discharge area. Most of the time, the cyclones are mounted vertically for an easier discharge and disengagement hoppers are also mostly used to control the discharge. [8]

5.2 Fabric filters

The name of this system originates from the material that is used to filter the dust particles. They operate similar to a vacuum cleaner. The dirty gas is blown or sucked through felted or woven fabric filter bags, on which the dust remains and builds up a layer of dust, the so-called "dust cake". Most of the time several bags are used to increase the possible gas flow [9]. The principle of FF operation is filtration, which is reliable, very efficient and economic. The most common type of bags for a FF is cylindrical, and the container in which the filters are is also called "baghouse". The bags are vertically hanged, so that gravity also leads to particles falling off from the bags. They are periodically cleaned, either by shaking them or by blowing compressed air in the opposite direction of the gas flow. This should lead to the dust cake falling off from the filter bags and land into the hopper. It can then be discharged whenever necessary or continuous with a screw conveyor. [10]

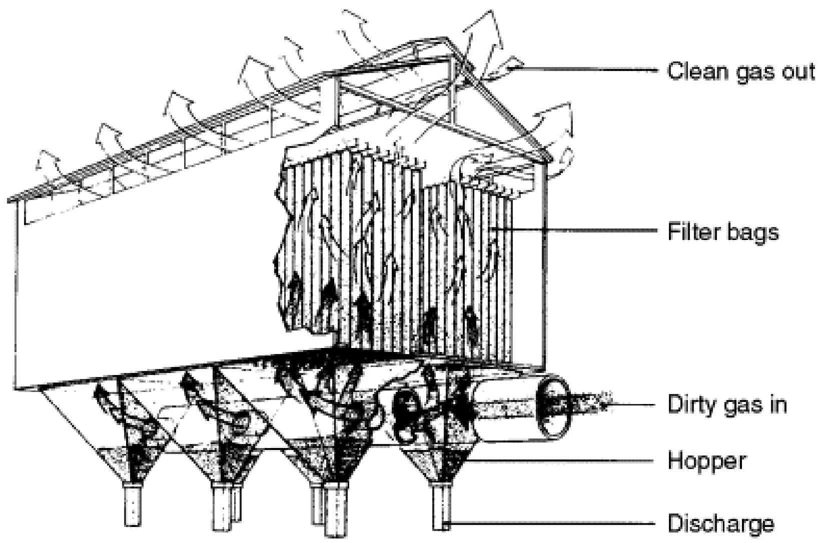


Figure 5-2: Schematic fabric filter [9]

Figure 5-2: Schematic fabric filter [9] shows a typical fabric filter. The whole construction is the baghouse, in which the different filter bags are hung.

Several different materials and filter sizes can be used for the filter bags, so that different advantages and disadvantages can be matched. For example: different temperatures, abrasion resistance and chemical resistance.

5.3 Wet scrubbers

The principle of wet scrubbers for dust removal is inertial impaction, interception and diffusion, as explained in chapter 3. Depending on the construction of the wet scrubber, they rely mainly on the spraying of water droplets, for example with a radial mixing impeller or an atomizer (nozzle). In Most cases the inertial impaction, which was already explained, is the dominant effect of how to bind the dust particle onto the washing droplet. Interception occurs when the relative velocity is lower than the required one for impaction and adheres to the surface of the droplet. Diffusion, which was also already explained, is only important for extremely small particles (<1mm) [11]. The most common types of wet scrubbers are the counter-flow and the Venturi scrubbers, as seen in the next figure.

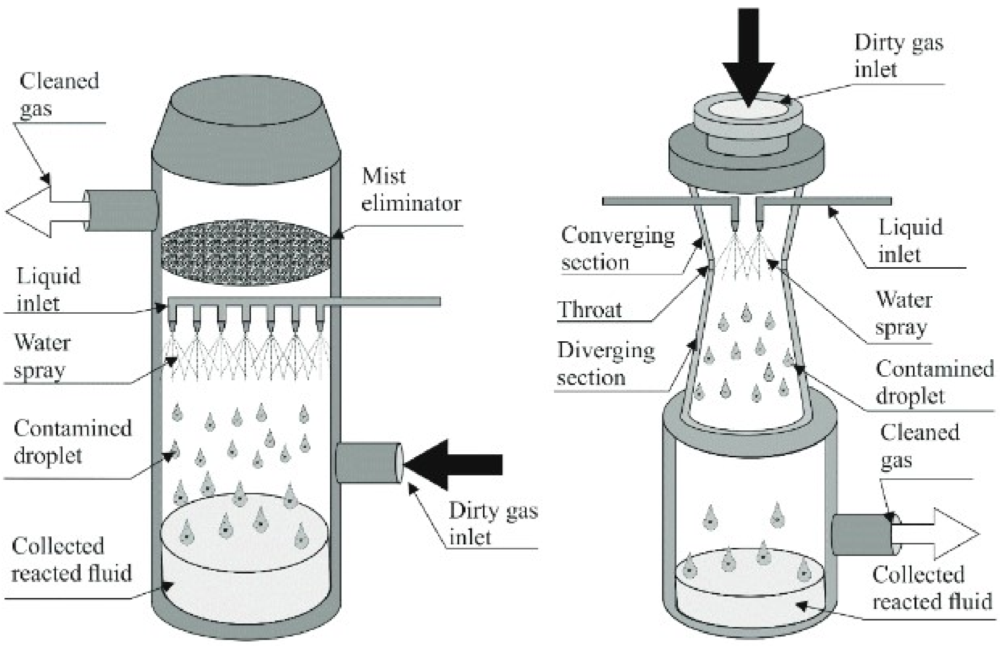


Figure 5-3: Schematic of Venturi scrubber (right) and counter-flow wet scrubber (left) [12]

On the left is a standard counter-flow wet scrubber displayed, where the mist is made by nozzles or radial mixing impellers. The droplets are falling down by gravitation, whereas the gas flows in the opposite direction upwards. The Interaction happens on the way from the top to the bottom. On the upper end, the cleaned gas needs to go through a mist eliminator, to reduce the water load of the gas stream.

On the right side is a schematic of a Venturi scrubber. The principle stays the same, as with all wet scrubbers, but here both particles flow in the same direction. The biggest advantages of a Venturi scrubber are that they allow much higher collection efficiency for particles above submicron size due to high gas velocity, a high inlet gas temperature, a compact design and high water temperature. The main disadvantage of this scrubber is that the pressure loss is very high and thus the energy consumption is way higher than compared to for example a counter flow-wet scrubber. [12]

EmiControls produces a special kind of wet scrubber. A water mist canon is used to produce a wide range of water particles and the main advantage of this process is that it can be used without a special housing, but the principle of the scrubber stays the same. The water mist is sprayed on the dust which should be caught and afterwards it will fall to the ground. That process is very useful on mining sites, construction sites and so on. The next picture shows a mist scrubber which is used to remove the dust from conveyor belts in the mining industry.

Figure 5-4: Dust suppression on conveyor belt [18]

5.4 Electrostatic precipitators

An Electrostatic Precipitator (ESP) is a scrubber that is used to collect the dust particles from a gas by using the force of an induced electrostatic charge. The electrostatic field is induced by a high voltage power supply unit connected to the discharge wires. This generates an electrical field between collecting plates and the wires. This also ionizes the gas around the wires to supply ions. A schematic is shown in the following figure. [13]

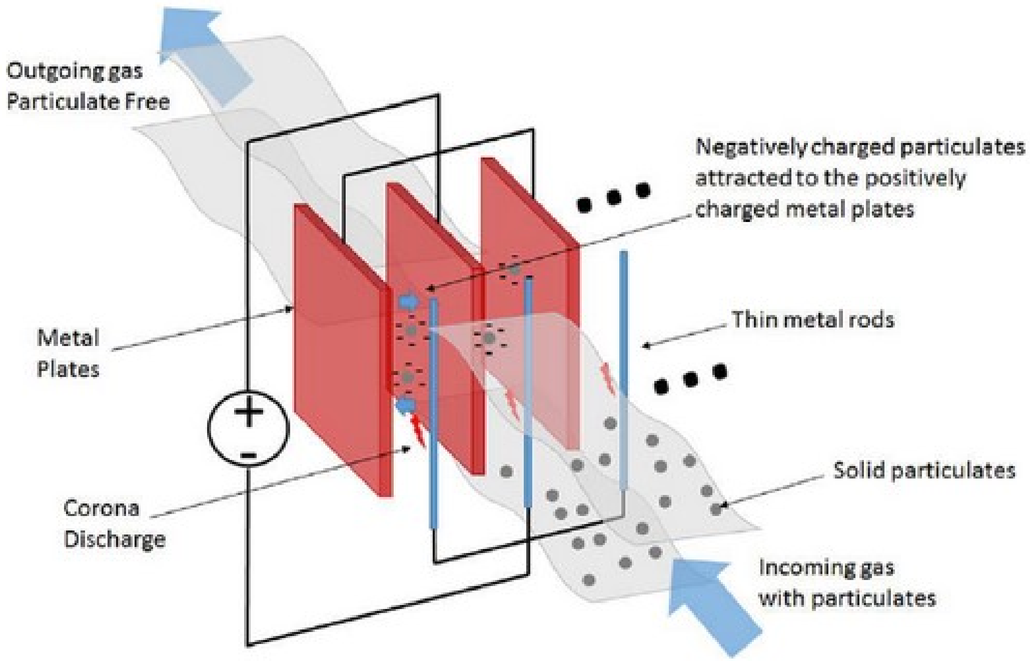


Figure 5-5: Schematic Electrostatic Precipitators [14]

When dust or mist polluted gas flows between the plates and the discharge wires, then the generated ions charge these particles. The electric field causes a Coulomb force, which causes the particles to get griped to the collecting plates, and the gas is purified.

ESP´s are highly efficient devices for filtration that minimally impede the gas flow through the device and work great with fine particulate matter. [13]

5.5 Unit collector

These are portable dust collectors, which can consist of different dust collection systems. As seen in the next figure, the schematic stays the same for the several different builds; the only thing that changes is the “air cleaning device”. This can either be a filter bag, a cyclone, or other forms of filters. Unit collectors are made for smaller workplaces like private workshops, warehouses in which several workplaces are present but don’t only need to be cleaned occasionally, or when workers need to travel with their equipment. [15]

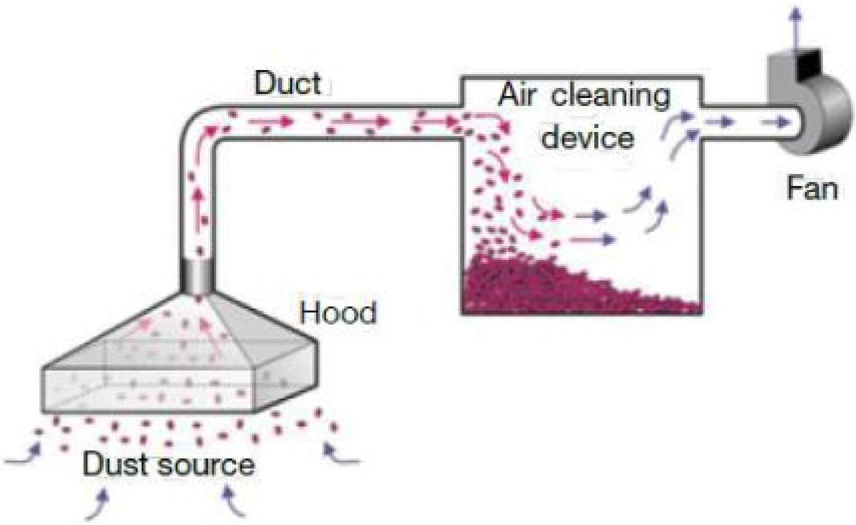


Figure 5-6: Schematic unit collection system [15]

As seen in the schematic above, the air can be cleaned, and the clean air will then be recirculated or blown out with the help of a fan. This system is working similar to a vacuum cleaner, where the filter is the “air cleaning device”. The hood is not necessary, but it makes the device more practical, because a bigger area can be cleaned and the airstream is not too high to become uncomfortable for the worker. Depending on the composition of the dust and location of operation for the unit collector, several adjustments can be made, for example a different hood, a temperature resistant filter, acid resistant filters and pipes. The biggest advantage of unit collection systems is that they can be very small in size, cheaper, and very flexible on working conditions. [15]

5.6 Comparison

The efficiency of a filter system is always directly linked to the particle size of the dust which needs to be collected. This fact makes it necessary to know the particle size distribution of the dust, before an optimal system can be chosen. The following figure gives a representation of this relation.

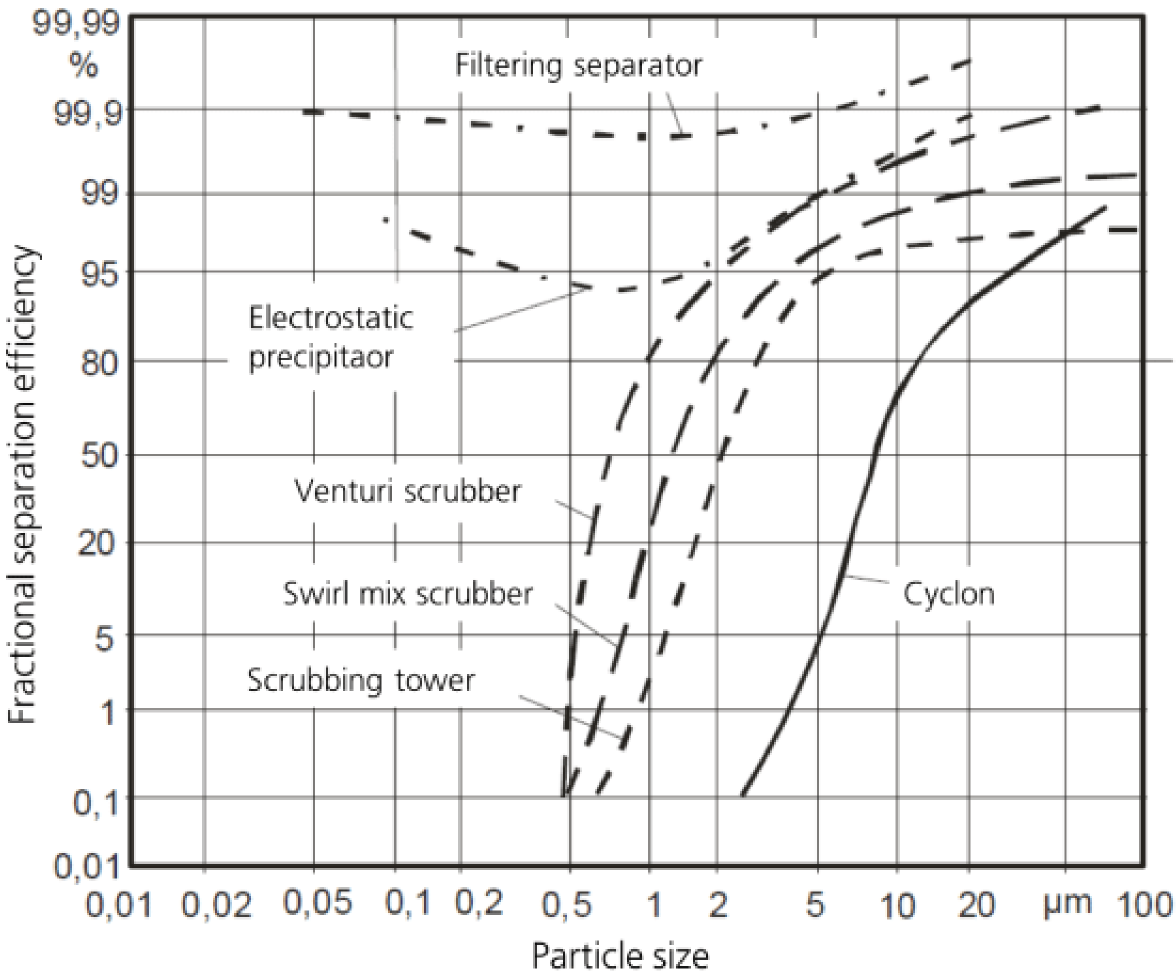


Figure 5-7: Separation efficiencies of different filter systems [16]

Several other factors can influence which filter system should be selected. For example if it is a hot gas treatment, then a filtering separator can either be not even used, or a special filter element needs to be installed, which makes it very expensive. The following table lists the major characteristics of the most common types of dust filter systems.

Characteristic data	Inertial separator	Wet scrubber	Electrostatic precipitator	Filtering separator
High separation efficiencies in the particle size range in µm	> 10	> 0,1	> 1	> 0,5
Crude gas dust content in g/m³	< 1.000	< 10	< 50	< 100
Achievable clean gas dust content in mg/m³	100 - 200	50 - 100	< 50	< 20
Pressure loss in Pa	500 – 3000	100 – 1000	30 - 400	600 – 2000
Max gas temperature in °C	450	300	450	260
Throughput in m³/h	3000 – 200000	3000 - 100000	10000 - 300000	1000 - 100000

Table 5-1: Comparison of different filters [1]

It is hard to compare the above stated filter systems with an open area water mist system, because they are all working in an enclosed area under optimal conditions, while a water sprayer system has to deal for example with different wind speeds. But to give an example on the efficiency of water mist dust binding systems the next picture shows the different efficiencies from the experiment on an ore pile from Yenn-Yi Lee 2022. A low wind velocity was between 2 - 3m/s and a high wind speed between 8 - 11m/s. [29]

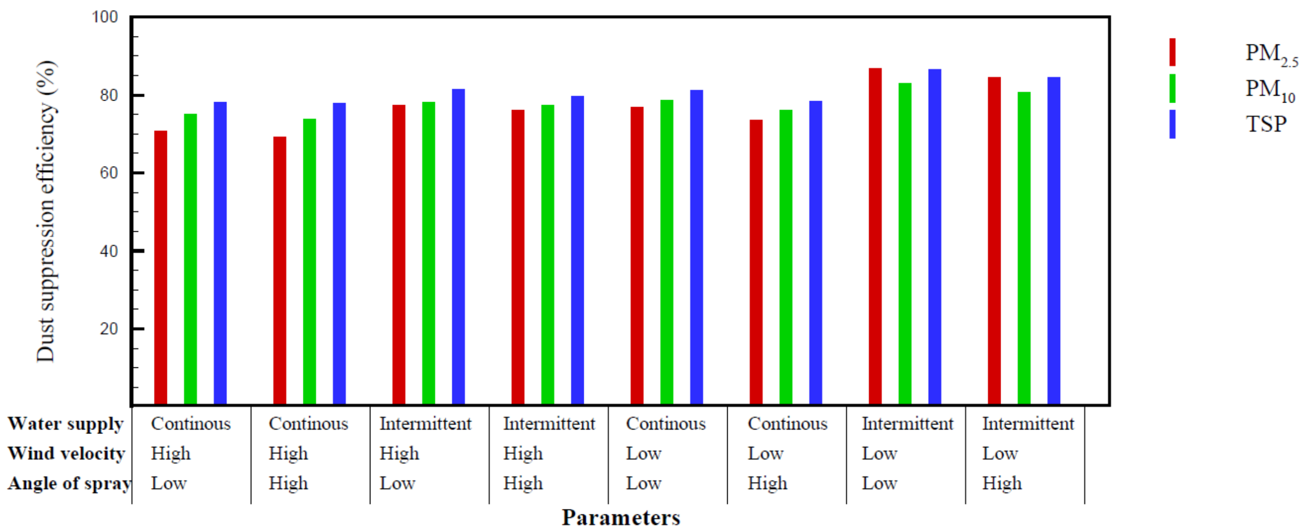


Figure 5-8: Suppression efficiency with mist generator [29]

As seen in the picture above, the efficiency of a dust compression system for the stated particle sizes is around 70% to 85% in an open field area.

6 Effects of dust on humans

The lungs are necessary for breathing, because they are responsible for insertion of oxygen into the body with the help of a series of branching air tubes and exchanging it for carbon dioxide, which is released back into the atmosphere. This chapter focuses on the damages from dust on the human health, especially the lungs. Also the influence on the workplace safety will be handled.

6.1 Breathing in dust

The most damage is done by breathing in harmful dust particles. This does not only mean the different carcinogenic substances, but the size of the particles is also crucial. But at first, the general function of the respiratory system needs to be explained. The structure of this system is shown in the next picture.

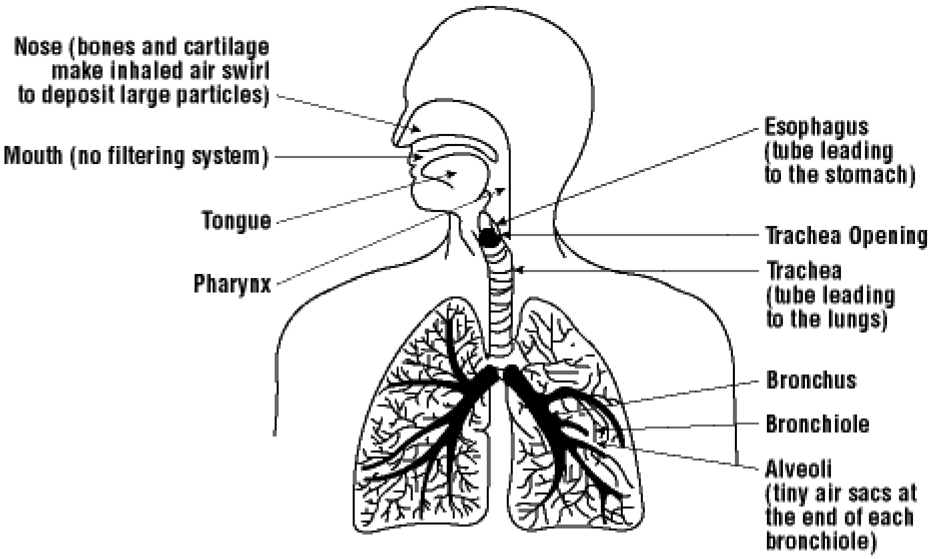


Figure 6-1: Structure of the respiratory apparatus [32]

The lungs are constantly exposed to danger from the dust particles in the air we breathe, but the lungs also have several defense mechanisms that remove the particles. The first filter of the body is the nose. When a person breathes in, air will be sucked through the nose, where most large particles are stopped in, until they get removed mechanically, by blowing the nose or sneezing, or by wandering into the back of the throat.

There it can be swallowed and become neutralized inside the stomach. This happens with the help of bones, hair, sticky mucus and cartilages. [32][

Smaller particles can reach deeper into the windpipe leading to the lungs, including the dividing air tubes. These tubes are called bronchioles and bronchi and both are lined by cells, which produce mucus. The mucus is a sticky fluid, which collects the particles by impaction, because of the high air velocity. When the particles are bound by mucus, tiny hairs called cilica move the mucus upwards into the throat, where it can be coughed up and afterwards be spat out or swallowed. [32]

The next station of the breathed in air are the air sacs, better known as alveoli, which is the inner part of the lungs. The air exchange happens though these alveoli. When dust gets to that point, then the next defense mechanism is activated. The small particles get attacked by special cells called macrophages. They “swallow” the particles and transport them with the help of the cilia in wavelike motions to the throat, where it can be again be spat out, coughed up or swallowed. [32]

If the dust contains germ-bearing particles, then the lungs do not only produce macrophages, but also a certain protein which attach to particles and neutralize them. Afterwards they get removed in the same way that “used” macrophages do. [32]

How far the dust can reach into the respiratory system and how harmful it can be, depends on the size of the dust particles and the composition of it, which will be explained in the next two chapters. [32]

6.1.1 Size of dust particles

Airborne particulate matter (PM) consist of a mixture of different particles. It persists of a mixture of solids and aerosols composed of dry solid fragments, solid cores with liquid coatings and small droplets. Particles are defined by their diameter to get standardization for regulations. Diameters of 10µm or less are called coarse particles as well as PM_{10} and the ones smaller than 2,5µm is fine particulate matter called $PM_{2.5}$. This means that $PM_{2.5}$ is a portion of PM_{10}. A size comparison of the two diameters to a human hair is shown in the next picture. [33] [36]

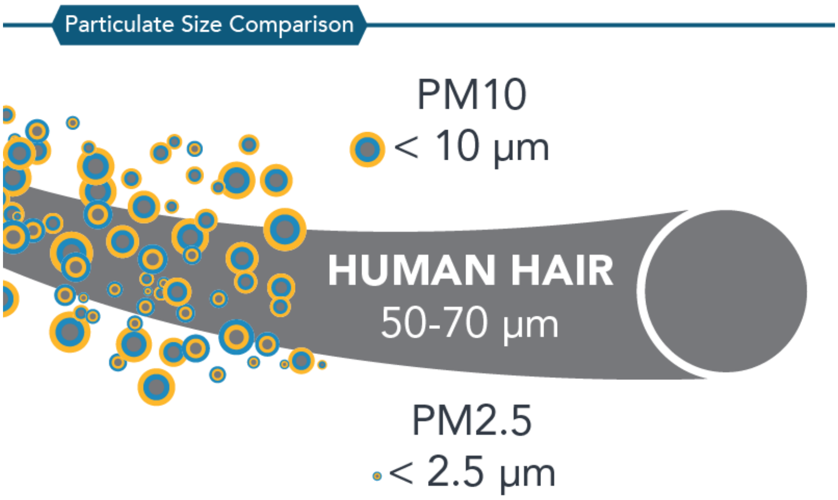


Figure 6-2: Particulate Size Comparison [33]

Particles with an aerodynamic diameter larger than 10µm are deposited in the nasopharyngeal region (nose, nasal cavity and throat). This happens through impaction because of the high air velocity, many turns in the air way, change of airflow direction and the mass of the particles when breathing in. [34]

Smaller particles with a diameter of 0,003 to 5µm are mostly deposited in the tracheobronchial and alveolar regions. This is due to the fact that the small particles entrained with the air flow deep into the lungs. [34]

Even smaller particles in the range of 1 to 100 nm can enter the bloodstream through the lungs and spread to other organs, causing severe damage depending on the composition and their toxicity. [34]

Because of the different deposition areas inside the lung, nose or throat, the American Conference of Governmental Industrial Hygienists (ACGIH) recommends different occupational exposure limits, which will be explained in the chapter 6.1.4. [34]

To summarize again which particle diameter can reach how far into the lungs, the next picture will be given.

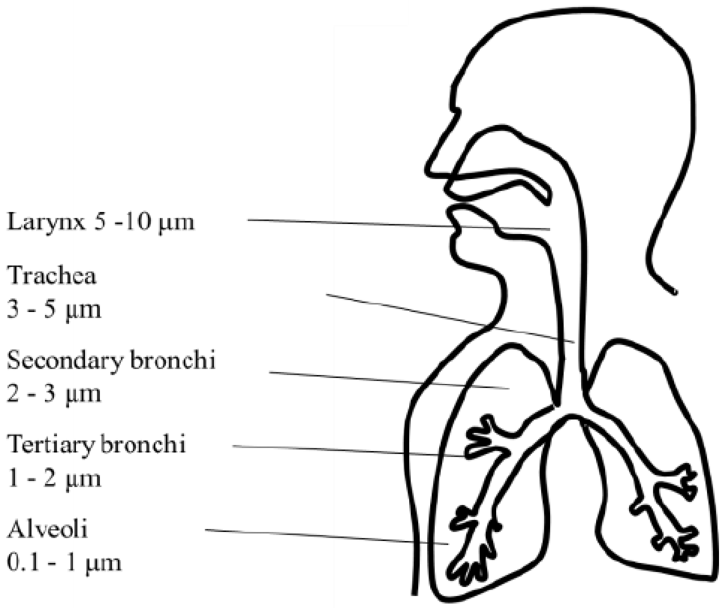


Figure 6-3: Penetration depth into the respiratory system [16]

6.1.2 Composition of dust

This chapter will handle the influence of the different compositions of dust. The body can be affected from many different illnesses caused by inhaled particles in their work environment. Since the main topic of this master thesis is dust, the cancerous substances will be ignored in this chapter and instead the effects of dust will be explained. A general term for lung diseases caused by inhalation is "Pneumoconiosis", or better known as "dusty lung". The changes inside the lungs depend on the different types of dust. Silica, for example, causes islands of scar tissue surrounded by normal lung tissue. The separated injured areas are still surrounded by normal tissue, which means that the lungs do not completely lose their elasticity. In contrast, the tissue produced by asbestos, beryllium or cobalt cover the surfaces of the deep airways completely and thus making the lungs stiff and loses their elasticity, which causes more damage. But not all particles produce scar tissue. Elements like carbon or iron will be absorbed by the macrophages until they die. When they die, they are then taken again by other macrophages. If there are more particles than macrophages, they get overwhelmed and the dust particles start to coat the inner walls of the lungs, but without causing scarring. They produce mild damage or maybe none at all. [32]

Some small particles can also become dissolved in the bloodstream and get carried away by it. They can reach and damage the brain, kidney and all other organs. [32]

In the following table, the most common lung diseases caused by inorganic and organic dust will be summarized.

Inorganic	Reaction of the lung	Type of Disease
Asbestos	Fibrosis	Asbestosis
Silica (Quartz)	Fibrosis	Silicosis
Coal	Fibrosis	Coal pneumoconiosis
Beryllium	Fibrosis	Beryllium disease
Tungsten Carbide	Fibrosis	Hard Metal disease
Iron	No Fibrosis	Siderosis
Tin	No Fibrosis	Stannosis
Barium	No Fibrosis	Baritosis
Organic		
Mouldy hay, straw and grain	Fibrosis	Farmer´s lung
Droppings and feathers	Fibrosis	Bird fanciers´s lung
Mouldy sugar can	Fibrosis	Bagassosis
Compose dust	No Fibrosis	Mushroom worker´s lung
Dust or mist	No Fibrosis	Humidifier fever
Dust of heat-treated sludge	No Fibrosis	Sewage sludge disease
Mould dust	No Fibrosis	Chesse washer`s lung
Dust of dander, hair particles and dried urine of rats	No Fibrosis	Animal handler´s lung

Table 6-1: Types of pneumoconiosis [32]

The most common form of pneumoconiosis associated with overexposure in mining is the silicosis, caused by the inhalation of respirable crystalline silica. [31]

The concentration and duration of exposure to respirable crystalline silica can lead to three different forms of silicosis: [31]

- Chronic: long-term and excessive exposure, first clinically apparent 10-30 years after first exposure
- Accelerated: exposure to higher concentrations, first clinically apparent 5-10 years after first exposure
- Acute: exposure to unusually high concentrations, first clinically apparent within weeks to 5 years after the initial exposure

6.1.3 Concentration of dust particles

The dust concentration describes the proportion of dust particles in a specific amount of air. Depending on the kind of dust or particles, it is given in g/m^3, mg/m^3 or $\mu g/m^3$. It is necessary to form a generally applicable standard, to develop limits for the amount of dust in the breathing air, and to get a number on a maximum allowable exposure to a dusty area. Like already explained, if the concentration of dust particles is higher, the risk of developing damage to the lungs is also higher. [35]

To gain a general understanding of what is described as a "normal" concentration of dust particles a person has to handle, the following figure shows the annual mean value of dust concentration (PM_{10}) in Austria from the year 2015. [37]

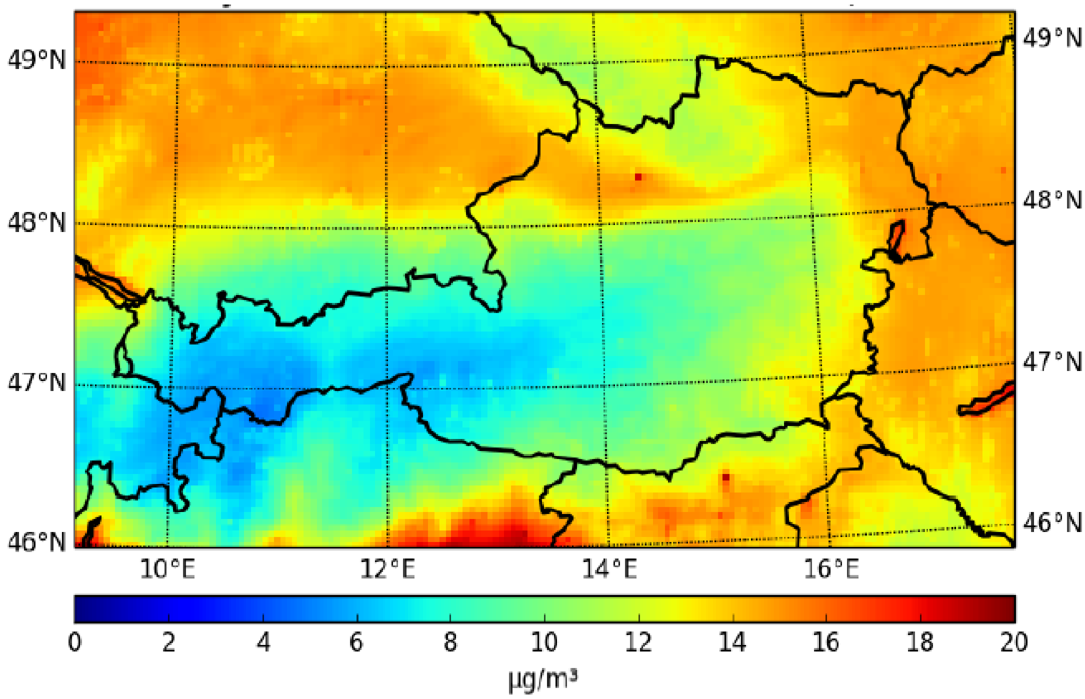


Figure 6-4: Annual mean value of PM10 (2015) [37]

6.1.4 Exposure time

The exposure time is the specific time, in which a worker is exposed to the dust.

The exposure time limit describes the maximum allowable time a worker can handle a specific exposure, without causing lung damage. The standard time for a limit is either 8 hours for a work day or 24 hours for a whole day.

6.2 Exposure limit & Legal requirements

With the help of the concentration of dust particles and the exposure time, it is possible to form legal requirements for different kinds of dust.

In the American region, there are three institutes which give recommendations on the exposure limits on dust. Two of them are recommendation and one is mandatory.

The mandatory one is the "*Occupational Safety and Health Administration"* (OSHA). This is also a federal agency in America. It was created to enforce the federal occupational safety and health.

The first institute which gives recommendations is the "*American Conference of Governmental Industrial Hygienists*" (ACGIH). It is a professional association of industrial hygienists and its goal is to advance worker protection.

Like already explained, the ACGIH states three different Threshold Limit Values (TLVs) for the American region on the exposure limit on different particle sizes. Three different terms are used for TLVs describing hazardous particles when they are inhaled: [34] [57]

- Inhalable particulate Mass TLVs (In German: E-Fraktion): inhaled into mouth or nose, hazardous as soon as they are deposited in the respiratory wing
- Thoracic particulate Mass TLVs (In German: Th-Fraktion): penetrating beyond the larynx, hazardous materials when deposited in the lung or lower airways
- Respirable particulate Mass TLVs (In German: A-Fraktion): penetrating to unciliated airways, small enough particles to reach lower airway passages and only hazardous if they reach that region.
-

The second institute which gives recommendations is the "*National Institute for Occupational Safety and Health"* (NIOSH). It is the United States federal agency for occupational health research and is part of the "*Center for Disease Control and Prevention*" (CDC).

The above named institutes give different recommendations on the maximum exposure to dust which are summarized in the table below. [38]

Compound	NIOSH	ACGIH	OSHA
	REL	TLV	PEL
Total dust	-	-	15 mg/m^3
Respirable dust	-	3,0 mg/m^3	5 mg/m^3
Inhalable dust	-	10 mg/m^3	-
Respirable crystalline silica	0,05 mg/m^3	-	0,05 mg/m^3

Table 6-2: US occupational exposure limits [38] [39]

The "Recommended Exposure Limit" (REL) is made to be protective over a 45-year working lifetime.

The TLVs are based on a 40-hour workweek with 8 hours per day.

The "Permissible Exposure Limits" (PELs) must be observed at workplaces by law. [38]

The exposure limits in the European region are made from the "*European Commission*", but the different countries can make stricter regulations. So the maximum values can vary a bit from country to country, but they stay roughly the same throughout Europe. [40]

To give an example, the occupational exposure limits for dust in an 8-hour workday will be given for Austria and Italy in the next Table.

Compound	Austria	Italy
	MAK	-
Respirable inert dust	5 mg/m^3	4 mg/m^3
Inhalable inert dust	10 mg/m^3	10 mg/m^3
Respirable crystalline silica (quartz, cristobalite, tridymite)	0,05 mg/m^3	0,1 mg/m^3
Talc	2 mg/m^3	2 mg/m^3

Table 6-3: EU occupational exposure limits [40]

The "Occupational Exposure Limit" (OEL) can have a specific name within different countries. In Austria it is called "Maximale Arbeitsplatz Konzentration" (MAK), which roughly translates to „maximum workplace concentration".

In occupational health and safety, the three terms mentioned above are used, but in environmental protection, PM terms are used. To establish a relationship between the two variants, the next figure is used.

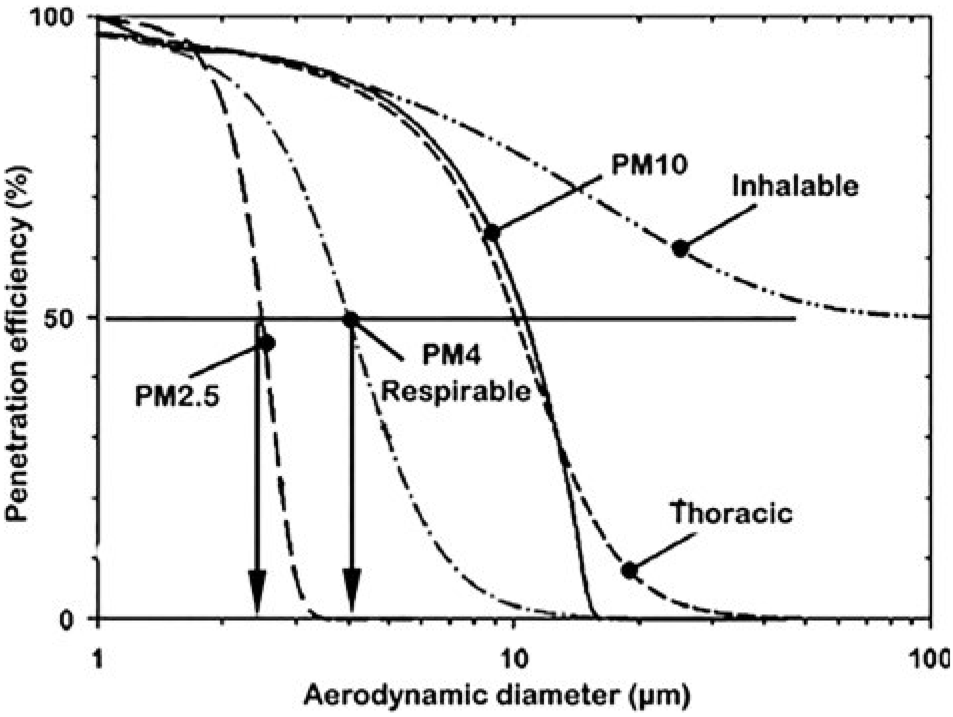


Figure 6-5: Relation TLVs and PM sizes [56]

When breathing in dust, only a fraction of the dust gets inhaled, depending on the particle size. If the particles are smaller, a larger fraction enters the mouth or nose. For example if the particles are larger than 50µm, then only about 50% of the airborne particles get breathed in. [56]

As seen in the picture above, the thoracic dust is typically measured with PM_{10} levels because this curves are almost identical and the respirable fractions with PM_4 levels, because there is a significant difference between the $PM_{2.5}$ curve and the respirable curve, so PM_4 is used instead. [56]

6.3 Other impacts on the safety of humans

This chapter focuses on other effects on the safety of workers. Not only the breathing in of dust can be harmful to people, but there are also other side effects like the visibility of other dangers or persons or the creating of a dust explosion. Two different examples will be given within this chapter.

6.3.1 Eye health and field of vision

The most hazardous effect of dust is on the lungs and the respiratory system, but other parts can be damaged too, for example the eyes. The ocular surface is a tissue and it is constantly exposed to the surrounding conditions. If dust gets onto the ocular surface, several eye symptoms can occur, for example eye redness, irritation and a sensation of a foreign body. There are even some diseases caused by PM exposure, including dry eye disease, blepharitis and conjunctivitis. This is another reason to reduce the dust as much as possible, wear safety glasses and limit the exposure to certain concentrations. [41]

Another impact of a higher dust concentration is the reduced field of vision. It is possible, that on certain points of a process, for example a conveyer belt or an unloading truck, a high concentration of dust can occur. This leads to a reduced field of vision which can lead to dangerous situations where workers cannot see machines or other workers, thus creating dangerous workplace conditions.

6.3.2 Combustion & explosion hazard

Combustible dust consists of fine particles suspended in air and can lead to a combustion and explosion hazard under certain conditions. Combustible dusts consist of distinct particles or pieces, which when suspended in air present a fire or deflagration hazard. This depends on the concentration of the particles. They are often either organic or metal dusts which are finely ground into chips, flakes, very small particles, fibers or a mixture of these. Dangerous are particles with an effective diameter of less than 420µm, but also larger particles can pose a deflagration hazard because while they are moved, they can abrade each other and thus creating smaller particles. Particles can also agglomerate due to electrostatics in the handling process and when they fall apart, they become smaller again and thus can create a combustion hazard when dispersed again. [42]

To create a flammable environment five parameters are necessary, whereas the first 3 are needed for a fire, which are also known as the “fire triangle”: [42]

1. Combustible dust (fuel)
2. Ignition source (heat)
3. Oxygen in air (oxidizer)

Two more parameters must be present in addition to the fire triangle to form the “Dust explosion pentagon” and enable dust explosions:

4. Concentration and quantity of particles is high enough
5. Confinement of the dust cloud

A Combustion hazard from dust can only occur if all the five stated requirements are met. [42] The next figure shows a representation of the dust explosion pentagon.

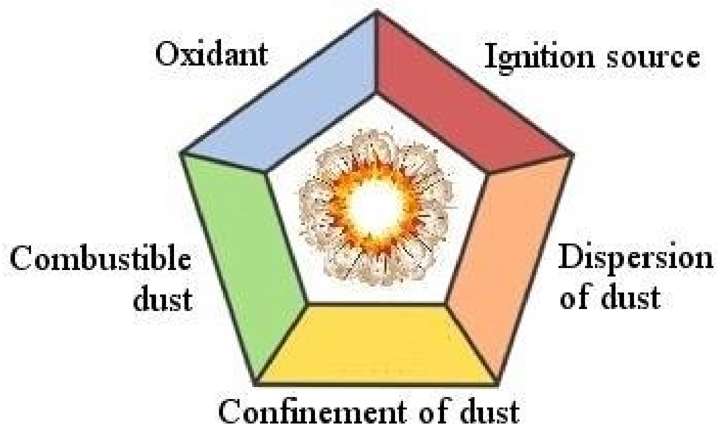


Figure 6-6: Dust explosion pentagon [44]

Dust explosions can be split into two different categories. The first one is the “Primary dust explosion”, where an explosion in processing equipment may shake loose dust or damage a containment system. This causes dust to become airborne again and this additional dust can create “Secondary dust explosions”. They can be more dangerous because not encapsulated and due to the increased quantity and concentration of the airborne dust. [42]

There are several influences on the combustion hazard of dust. The main factors are the particle size and the concentration, as well as available oxygen. Other influences are the particle shape, the moisture and the humidity of the ambient. [42]

To measure combustible dusts flammable hazards three physical properties are used: [42]

- Minimum Ignition Energy (MIE): likelihood of ignition
- Minimum Explosible Concentration (MEC): minimum concentration of dispersed dust
- K_{st}, dust deflagration index: relative severity of explosion compared to other types of dusts, higher number means a more severe explosion.

A few K_{st} values for different dusts are given in the next table:

Dust explosion class	Characteristic	K_{st} [bar*m/s]	Typical material
St 0	No explosion	0	Silica
ST 1	Weak explosion	>0 and ≤ 200	Charcoal, sulfur, zinc and sugar
ST 2	Strong explosion	>200 and ≤ 300	Cellulose, wood flour and poly methyl acrylate
ST 3	Very strong explosion	>300	Aluminum, magnesium

Table 6-4: K_{st} Values for different dusts [42]

To get a better understanding of the strength of the explosions, the next figure shows the difference in pressure versus time behavior with different ST classes.

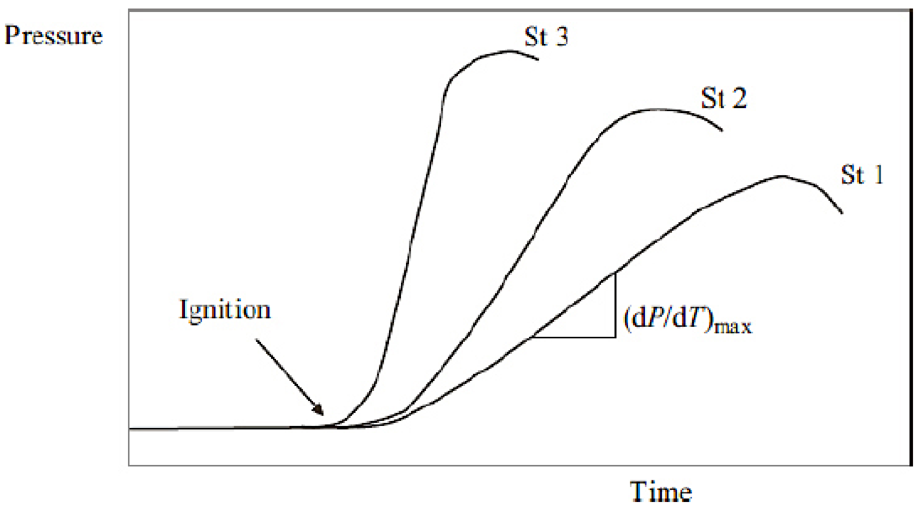


Figure 6-7: P versus time of ST classes [43]

Since the main topic of this master thesis is the binding of dust with water mist, the influence of the humidity must not be neglected. The following figure shows moisture content on a coal dust particle.

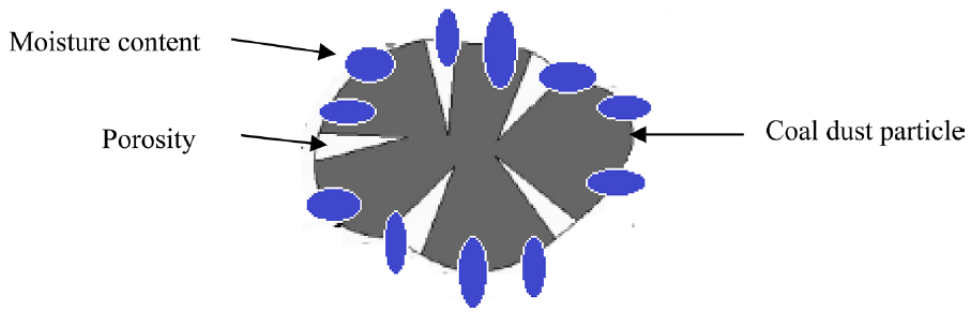


Figure 6-8: Moisture content on coal particle [43]

When a dust explosion happens, then two different phases occur. At first, the moisture is absorbed by the surrounding environment, meaning that if a flammable energy is present, the moisture gets absorbed directly into the coal particles, and then more heat is applied. This is followed by the transformation of the liquid into a gaseous state. If wet dust is exposed to fire, then at first the heat is consumed by evaporation and afterwards the burning of the coal particles can occur. Following this statement, it can be assumed that higher moisture content also raises the MIT and lowers the explosion pressure. Another advantage of higher moisture content is the agglomeration of the dust particles. If the small particles start to stick to one another and former larger clumps of dust, they are less likely flammable. [43]

The next figure shows a variation of the explosion index based on increased content of moisture.

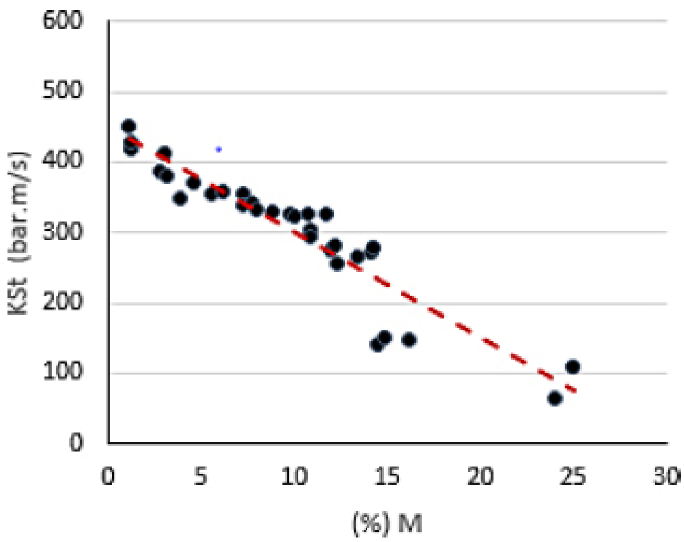


Figure 6-9: Explosion index based on moisture [43]

7 Effects of dust on the environment

Dust mainly influences the ecosystem of the planet in two different ways. The first one is the direct influence by reflecting and absorbing solar radiation; the second is the indirect way by affecting cloud formation and precipitation patterns. Another important part is the composition of the dust, which can affect the biodiversity. Mineral dust, which consists of wind-borne soil particles, has a typical diameter smaller than 30µm. To give an example on these effects, the next illustration shows the different influences as well as how they are measured. Explanations will follow in the next subchapters. [7] [45]

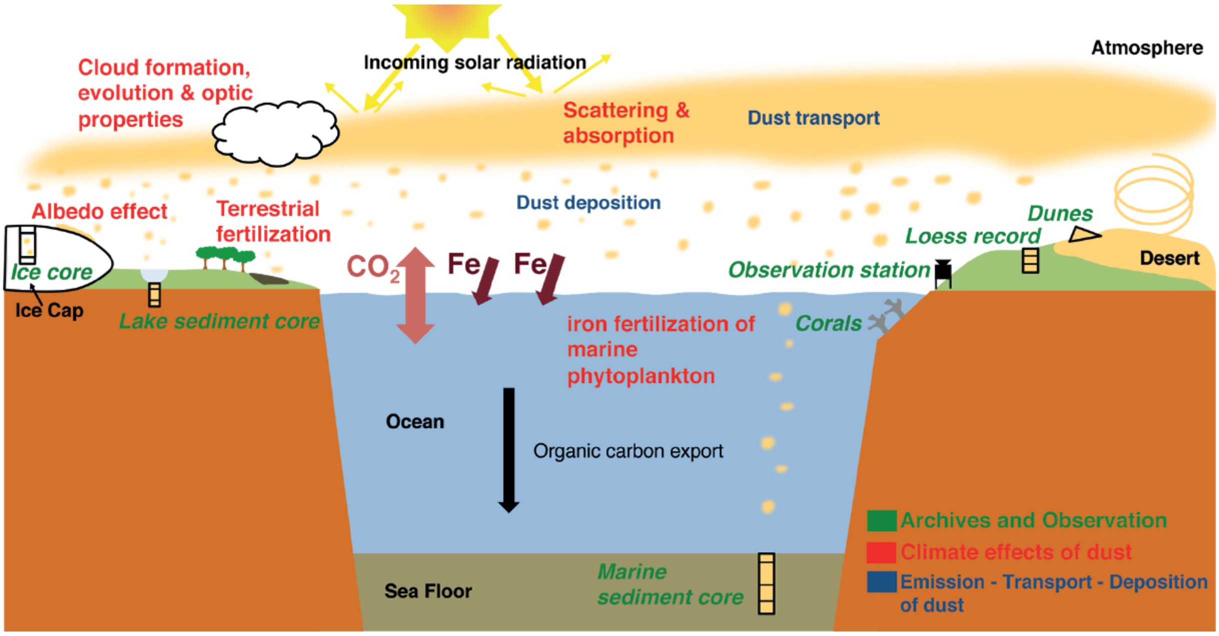


Figure 7-1: Schematic interactions between mineral aerosols and climate [7]

Atmospheric particles have different sources, but most of them originate from the emissions of the earth's surface, followed by industry. Primary aerosols are directly emitted from a specific source. The smaller ones are hot gases in the beginning, but quickly condense to become particles, for example from fires. The secondary aerosols are gaseous emissions, which undergo a chemical reaction in the atmosphere to be converted to aerosol particles. These particles can be cloud condensation nuclei in the later process and this occurrence is called “gas-to-particle conversion. [49]

Including in the next picture, the different reactions depending on the particle size and where they occur are named. These reactions will be explained in the chapter 7.2.

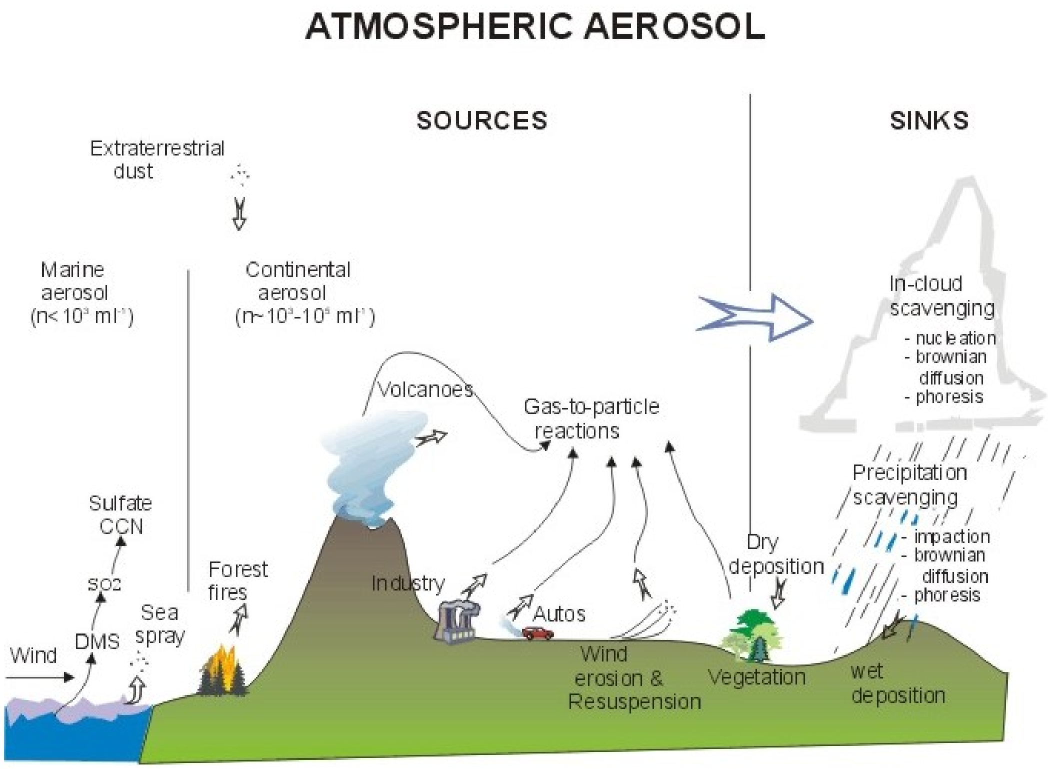


Figure 7-2: Sources and sinks of atmospheric aerosol [49]

There are two different sources of aerosols. The first is natural, which means they occur without human fault, and the second one is anthropogenic, which means that it is made by humans. Natural occurring particles come from volcanoes, forest, forest fires and gas to particle conversions (for example naturally occurring SO_2). Anthropogenic sources are for example the industry, transportation, power plants and also the gas to particle conversion, but with the help of anthropogenic gases. [48]

7.1 Reflecting and absorbing solar radiation

The direct impact is by affecting the reflecting and absorbing of the solar radiation from the sun. It attenuates radiative fluxes at solar and terrestrial wavelengths and is largely influenced by the layering of dust and clouds in the atmosphere and the amount of hematite present on the surface or within the particles. The next two pictures show a comparison on dust layer locations, consisting of Saharan dust. [45]

Figure 7-3: Dust below cloud level [45]

Figure 7-4: Dust above cloud level [45]

Figure 7-3 shows the dust cloud below the cloud level and the second figure shows it above cloud level. In the past, dust particles were handled as spherical scatterers with globally uniform composition, but recent studies show that different minerals react different on radiation and are also influenced by the underlying surface. For example if the dust cloud is over the ocean, it is comparatively bright and it reduces the incoming sunlight, which would be absorbed by the ocean surface otherwise. On the other hand, if the dust cloud is above a bright cloud, then the dust layer absorbs more solar radiation than it would under the cloud. To give another example of different reflectance values of a clean and a polluted cloud, the next picture shows the different reflectance values on certain wavelengths. [45]

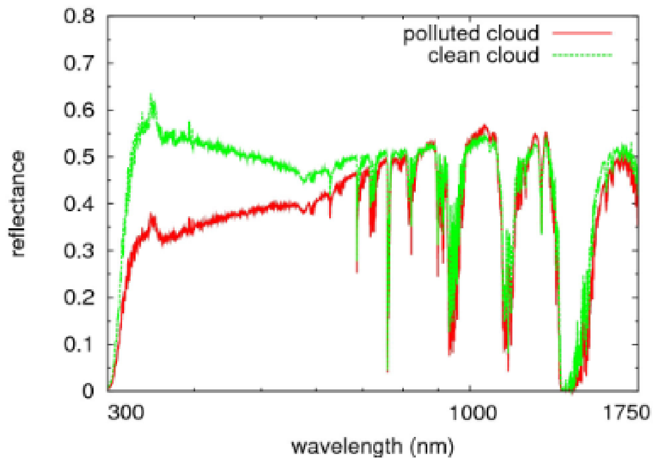


Figure 7-5: Reflectance spectra of polluted and clean cloud [46]

As seen in Figure 7-5, the polluted cloud has a lower reflectance value at short wavelengths but is converging toward the clean cloud spectrum at larger wavelengths. This can be explained by assuming that the smoke layer is placed above the cloud layer, because smoke has a gray absorption spectrum in the visible light. Smoke aerosols consist of small particles with an optical thickness depending on $\lambda^{-1,5}$, where λ represents the wavelength, thus resulting in the largest optical thickness at short wavelengths. Because the scattering is happening multiple times between the dust layer and the cloud layer, the smoke layer is most efficiently absorbing at smaller wavelengths and this effect decreases the reflectance value of polluted clouds. [46]

These effects are the reason why the location of the dust cloud has a direct influence on the impact of dust. Another direct impact of dust particles is the scattering of light. This leads to an illumination of the earth´s surface in directions away from the original sunbeam. The redistribution of a “direct” beam into a “diffuse” radiation leads to a decrease of phytoplankton. [45]

7.2 Affecting Cloud formation and precipitation patterns

The indirect impact of dust on the atmosphere is by affecting the cloud formations and precipitation patterns. This happens due to various variables, for example the aerosol mass, cloud condensation nuclei (CCN) concentration, water phase partitioning or ice nuclei (IN) concentration. To start the chapter, a general schematic of the effects of a cloud of dust on a rainy cloud will be given in the next figure. [45] [47]

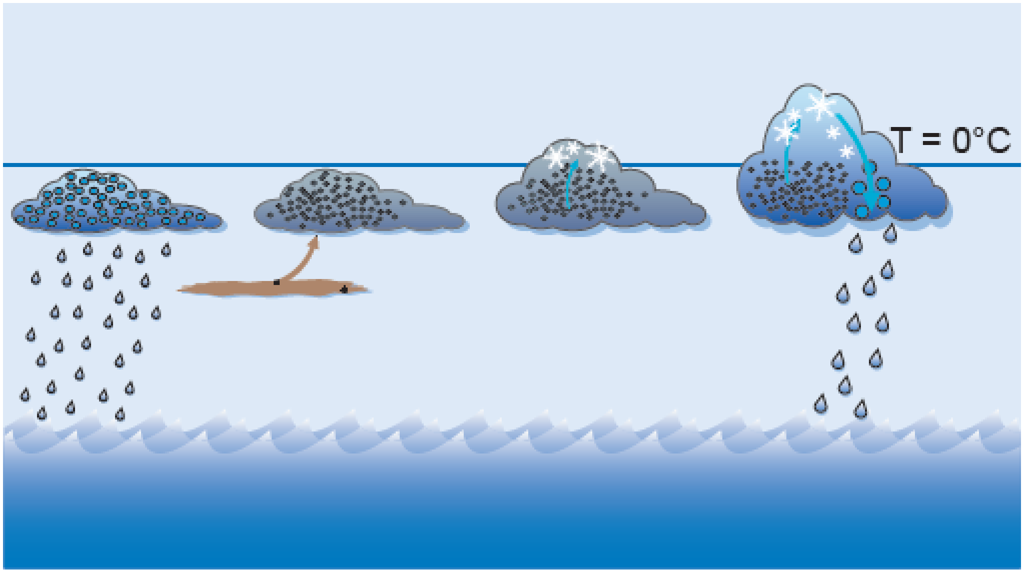


Figure 7-6: Example of cloud evolution due to dust [45]

The picture shown before explains the changes of a cloud due to increased dust inside of it. Starting from the left side, a rainy cloud is shown and in the next sector, it is exposed to a cloud of dust. When the two clouds collide, the dust initially inhibits rain by making the water droplets smaller. When they become smaller, they also become lighter, thus reaching higher altitudes, as seen in the third sector of Figure 7-6. If the top of the “dusty” cloud reaches altitudes above the freezing temperature level, then the dust particles and droplets provide nuclei for ice crystals. When they become too heavy to stay at that height, they start to fall. Since they started at a higher altitude as the “clean” cloud, the ice droplets can travel a longer distance inside the cloud and also an enhanced exposure to water. This effect leads to bigger drops than the ones from a dust free cloud. [45]

The first major indirect influence is the influence of an aerosol particle acting as a CCN, where it is depending on the size and the response of the particle to water. Dust particles can either be hydrophobic (it will show no reaction to the cloud), water – insoluble but hydrophilic (it can be wetted and activated at higher saturations), or have water-soluble components (it will activate at low saturations when given sufficient time). To generate an indirect impact, it is necessary that the particle is water-soluble or at least hydrophilic, which can include various compounds, for example sulphates, sodium chloride, other water-soluble salts and inorganic acids. These particles provide a surface, on which the water can condense on, and therefor start to form clouds, which wouldn't be there without CCN. The number of them influences the droplets as seen in the next figure. [47]

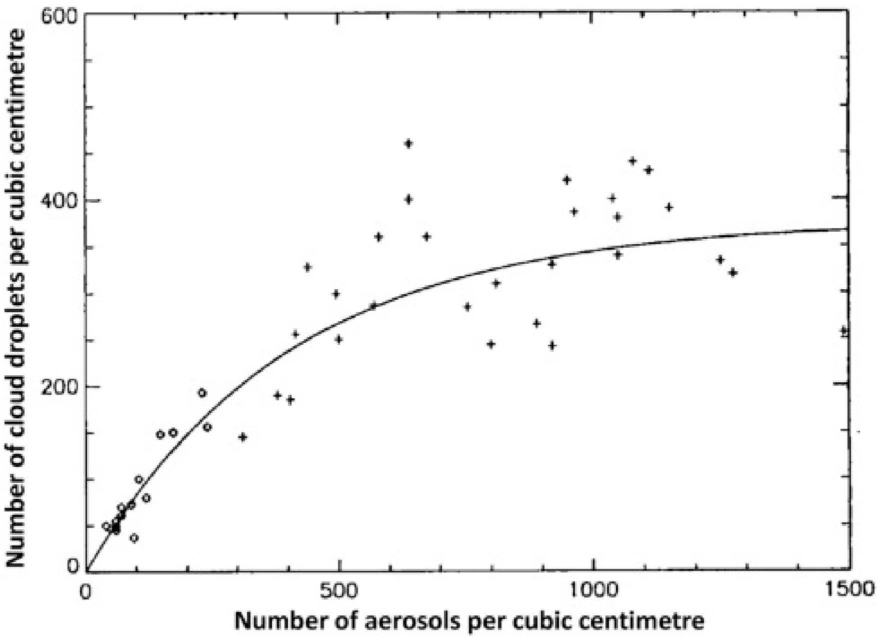


Figure 7-7: Connection between cloud droplets and dust particles [48]

The different particles sizes also depend on their source (as explained in Figure 7-2). The typical distribution of the particle diameters are shown in the next figure. The distribution has three bumps in it, which is dependent on how the particles are generated. [48]

- **Nucleation mode:** made by gas-to-particle conversion, quickly grow into accumulation mode particles.
- **Accumulation mode:** made when nucleation particles collide and agglomerate (coagulation), or by gases accumulating on a nucleation mode particle. Particles stay there for a few weeks.
- **Mechanically-generated mode:** consist of coarse particles, made by mechanical processes, particles settle pretty fast.

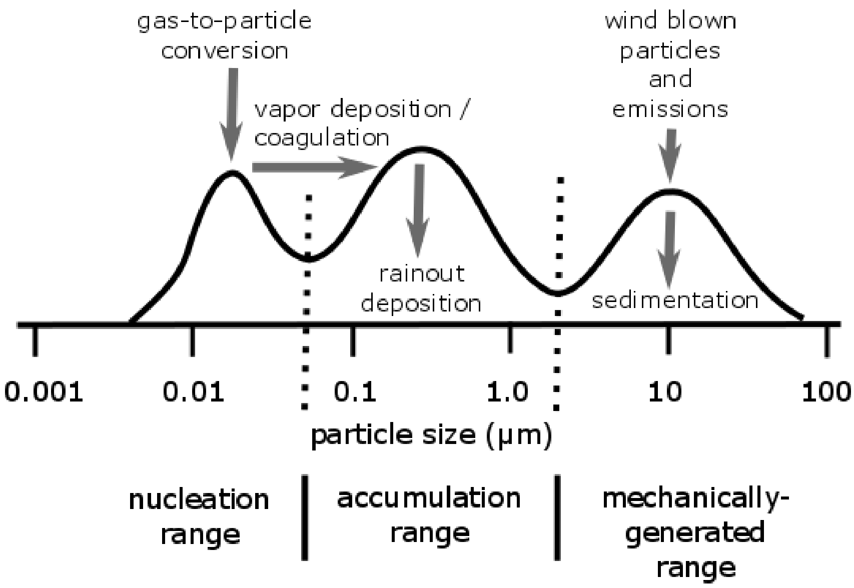


Figure 7-8: Typical aerosol size distribution with sources and sinks [49]

The second major influence is the increase of the cloud droplet number concentration. The rise of CCN from small dust particles also increases the number of small drops, thus increasing the concentration of drops. There can be different methods to make a correlation between aerosols and droplet numbers, but a detailed explanation would go beyond the scope of this master thesis. To summarize it, there are 2 empirical treatments and one mechanistic treatment of this effect. [47]

Empirical:

- Jones (1994)
- Boucher and Lohmann (1995) (B+L)

Mechanistic:

- Chuang and Penner (1995) (PROG)

The effect of sulphate aerosols will be shown in the next figure.

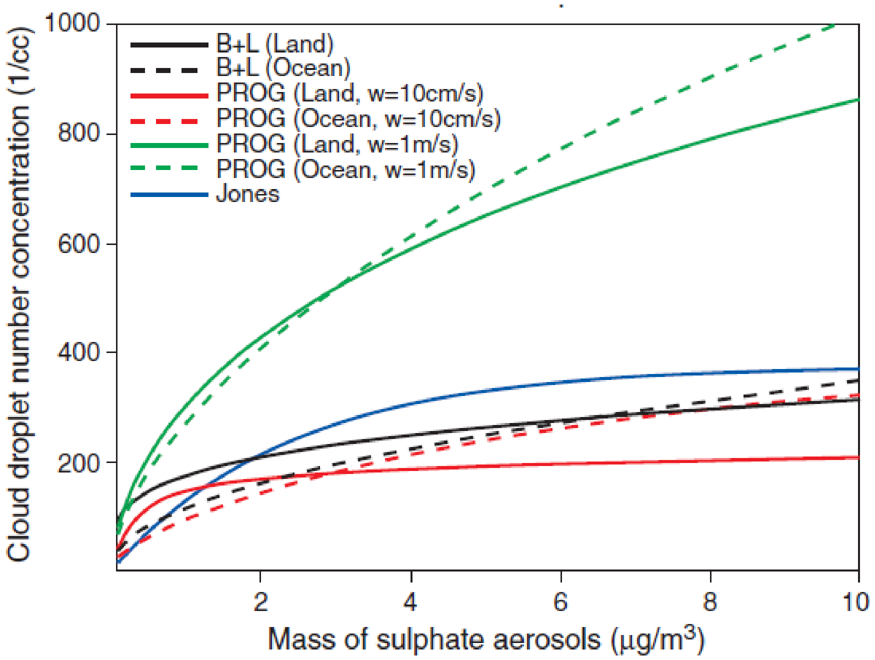


Figure 7-9: Droplet concentration depending on sulphate [47]

Another major influence is the influence from aerosols on liquid water content and cloud amount. This is also strongly associated with the development of precipitation patterns and therefor influencing the lifespan of individual clouds. A cloud is a sensible balance between sources and sinks for condensed water. This can include heat fluxes, radiate cooling, dry air flows and other effects. Like explained in the influence before this one, a higher concentration of aerosols leads to more droplets, but more droplets result in smaller droplets, because the cooling rate is limited. In warm clouds the most dominant precipitation process is the collision-coalescence process initiated by a large number of droplets above a certain size. Since the droplets cannot reach this diameter and start the falling, the precipitation rates are attenuated. This leads to a longer lifetime of clouds. [47]

The last big influence is the building of ice crystals, but this effect was already explained with the help of Figure 7-6.

7.3 Composition of the dust

There are not only direct and indirect effects of dust on the environment by influencing the radiation and clouds, but also the composition of the dust has an impact on vegetation and marine biodiversity, because it is falling to the surface when it starts to rain. This chapter should take a closer look on this subject.

7.3.1 Effects on Vegetation

The effect of dust on vegetation can happen in various ways, while most of them occur simultaneously or one after another. They can suffer for example from stomatal closure leading to cell changes, pigment loses, chlorosis and leave necrosis. The effects are listed and explained as followed: [50]

- Deposition on plants
- Effect on leaf morphology
- Effect on photosynthesis
- Effect on pigment content
- Interference with stomata functions
- Interaction with cuticle
- Effect on sugar
- Effect over the soil
- Soil nutrition
- Soil texture

Deposition on plants

Plants can filter coarse particles more easily than fine particles and a greater surface roughness of the leaves further increases the deposition rate, especially at higher wind speeds or higher surface humidity. Different particle sizes lead to different reactions of the plant, for example charcoal dust reduces the growth parameters while other kinds of dust can act as fertilizer. If a plant has a lot of smaller leaves, it acts as a counter to the dust load. Small dust particles can also reduce photosynthesis due to stopping the sunlight, increase leaf temperature due to radiation absorbance or even clog stomatal openings. [50]

Effect on leaf morphology

Fine dust particles can enter into the leaf and destroy individual cells and therefore reducing the efficiency of photosynthesis and reduce the amount of food production which the plant needs to survive. This effect is especially strong with exhaust fumes from cars, because they include heavy metals, which are extremely toxic (for example cadmium, oxides of nitrogen, hydrocarbon). Pollutants can cause different damages to the leaves like stomatal damage or a disturbed membrane permeability, which results in a decrease on the amount of leaves and the number of them. This can also influence the yield of some crops by reducing the leaf number and area. [50]

Effect on photosynthesis

Dust can also reduce the efficiency of the plants photosynthesis reaction. This occurs more with fine particles than with course ones. This results from the more dense coating that is possible with small diameters, resulting in a greater shading effect of the suns radiation. If not enough food can be produced by the plant, then it can lead to necrosis and a reduction on the number of leaves. Different types of plants can react differently to this effect. If they are adapted to low light conditions, they are less affected by dust depositions. [50]

Effect on pigment content:

By clogging the stomata of the leaves, the CO_2 availability is reduced, which inhibits a carbon fixation. This can lead to an increase in the temperature of the leaf and a retardation of chlorophyll synthesis. Afterwards the leaves become more and more yellow instead of green. [50]

Interference with stomata functions

The stomatal diameters of most plants range from 8-12 µm, which leads to the fact that particles with PM_{10} or lower are more dangerous than course particles. These are able to clog the stomata and influencing the transpiration rate. Like already mentioned, this can lead to a higher leaf temperature, but the metabolic functions can only operate in a certain optimal temperature range. For most plants the upper temperature is around 34°C. After this threshold, the photosynthetic enzymes begin to denature. [50]

Interaction with cuticle

The cuticle is the "skin" of a leaf. If dust has a strong lipophilicity and weak hydrophobic characteristics, it can get physically absorbed on the surface waxes of leaves. This damages the plant and results in a reduced photosynthetic rate.

Effect on sugar

Soluble sugar is the "Food" for a plant and provides it with energy. Sugar gets produced from the plant itself by photosynthesis and breakdown during respiration. The reduction on the efficiency of the photosynthesis leads to a reduction of the amount of sugar a plant can produce. Pollutants like NO_2, SO_2 H_2S are known to be responsible for this type of damage to the plant. [50]

Effect over the soil

Dust particles can have a fertilization effect on the soil. For example the dust from a coal power plant consists mainly of SiO_2, Al_2O_3, Fe_2O_3, as well as Ca and MgO. These trace elements are responsible for a higher pH value of the soil. The deposition of these elements is responsible for long-term effects on plants. [50]

Soil nutrition

The nutrition for plants consists of inorganic minerals. The uptake of these elements happens through ions, and gets strongly affected by the pH value of the soil. Most crop plants need a value between 5,5 to 6,2 or slightly acidic. If the pH is out of this range, the plant can get deficiencies or toxicities. For example a cement plant can create a lot of phosphorus and vanadium dust, which creates a pH value in the alkaline range. Another toxic element which was more present in the past was lead, because of the influence on photosynthesis, nitrogen fixation and NH_4 assimilation. [50]

Soil texture

Dust settles on the surface of the soil and only make up for a small fraction of the topsoil volume. But if the soil is artificially mixed by digging it up, the particles can reach deeper into the soil. If for example a coal fly ash is mixed into the ground, the water holding capacity in sandy soils will be increased. [50]

7.3.2 Effects on marine biodiversity

The deposition of certain trace elements in the ocean ecosystem can have negative or positive effects. The major influence is on the phytoplankton development and coral reefs. For example copper completely inhibits the development of phytoplankton. It is also known as “plant plankton”, which is a unicellular plant that lives in the surface waters. They produce oxygen with the help of photosynthesis, where they need sunlight, CO_2 and water. Another known negative impact is the correlation between Saharan dust and the decline of coral reefs in the Caribbean region. [45]

The growth of phytoplankton depends on its fertilization with trace elements. The most important one is iron. Also how the fertilization happens is important. For example the global warming is stratifying the upper ocean, which prevents mixing of the surface and the deep ocean. This leads to a nutrition shortage in the open ocean and therefor leading to a decreased productivity and lowered efficiency of CO_2 transfer. This effect makes the primary production dependent on external input of iron and phosphorus, for example by dust trapped in raindrops. [45]

From a global perspective, the input of trace elements into the ocean by dust is a rather small fraction. The discharge of rivers is the main coastal source. But it becomes more important in the open-ocean waters, because iron is scare in this region. Another note on the iron nutrition is that it needs to be in a soluble form to be assimilated by phytoplankton, which is depended on for example trace gases. This leads to the fact that the introduction of iron does not only have a short-term effect on the biodiversity, but it is transformed into a soluble form over a longer period of time (several months) and thus serves as a fertilizer in the long run. [45]

The summary of these effects is that a specific nutrition needs to be available for a good marine biodiversity and if some trace elements occur in higher number, it leads to a growth of specific plants and thus also leading to the dying of other plants, thus leading to a loss of biodiversity.

7.4 Legal requirements

The World Health Organization (WHO) is an agency specialized on international public health, which operates within the United Nations. It states a few air quality guidelines (AQG) for air pollutants as seen in the next table.

Pollutant	Averaging period	AQG 2005	AQG 2021
$PM_{2.5}$ [µg/m^3]	Year	10	5
$PM_{2.5}$ [µg/m^3]	24 h	25	15
PM_{10}[µg/m^3]	Year	20	15
PM_{10}[µg/m^3]	24 h	50	45

Table 7-1: Current WHO guideline values for air pollutants [51]

The different countries can adapt this guidelines and form laws or regulations out of it. For example in Austria, the guideline was adapted within the so called "Immissionsschutzgesetz- Luft (IG-L), which translates roughly to "Immission Control Act-Air". Within this law, all sources of pollutants are regulated to save the environment and the population.

The current limits for Austria can be seen in the next table.

Pollutant	Averaging period	IG-L 2022
PM_{10}[µg/m^3]	Year	40
PM_{10}[µg/m^3]	24 h	50

Table 7-2: Current IG-L limits [52]

The limit for $PM_{2.5}$ is the same within a year as the WHO states, but it is no law, just a recommendation. Austria states also a separate limit for the deposition limits on dust for the protection of health, which is 210 mg/(m^2*d). [52]

There are also separate limits for different production processes. For example the maximum value of dust emission for non-ferrous metals and refractory metals is 5mg/m^3 [53], and for the production of iron and steel the limit is 10 mg/m^3, or if the dust cannot be treated with a fabric filter dust collection system 20 mg/m^3 [54].

8 Conclusion

As explained in the chapters of this master thesis, there are a lot of different influences on the efficiency of water based dust binding. To recap the major mechanisms which are responsible for collecting dust particles, they will be listed once more:

- Inertial force
- Diffusion
- Condensation
- Interception
- Electrostatic force

These forces are responsible for the binding of the dust particle onto the water sphere. The inertial force is responsible for direct impacts because the particle is too heavy to follow the streamlines of the surrounding air. Diffusion is the act of catching via “random” collisions. Condensation leads to a growth of the dust particle and therefor better efficiency of the binding mechanism by the other forces. Interception is when a particle wants to travel around the droplet but the diameter of it is big enough to touch the surface of the droplet and it gets bound during this process. And the last force is the electrostatic force, which can happen when the particles and the droplets are charged oppositely.

All these forces depend on characteristics of the dust particle and the water droplet. To name a few major ones: Particle and droplet size, relative velocity between droplet and particle and the Reynolds number. All the listed influences within this master thesis should be taken into consideration when designing a wet scrubber and especially a water mist sprayer when operating them in an open field environment. The most important point is to know which dust should be collected and what the properties of this type of dust are. If the particle size distribution is known, then the sprayer can work in an optimum efficiency range, where it delivers droplets of the perfect size, so that a high degree of separation can be achieved. Or for example if the dust is water repellent, then the addition of surfactants should be taken into consideration. If the dust is known and the needed properties related to the specific particles, then the form and location of the nozzle should be discussed. Depending on the location, a few different forms can be chosen in which the droplets can be sprayed onto the aerosol or material. It also influences the droplet size and the volume of the water. The volume should be watched if the material is for example transported via a conveyor belt and is brought to the next production step, because the water adds moisture which needs to be removed if the material needs to be heated up again.

The different filter systems and their respective efficiencies were also discussed to get knowledge of the possible particle catching rates and to compare the different filters on different particle sizes and what are the major characteristics of the possible systems.

In the last two parts of this master thesis the effects of dust were discussed. These two chapters were necessary to gain an understanding of the reason why it is of such importance to reduce the dust in certain fields. Especially in the mining and ore processing industry, the workers are exposed to a dust load with particles in a very unhealthy particle size distribution. The most dangerous, non-toxic particles are PM_{10} and $PM_{2.5}$ which includes the particles smaller than 10µm or respectively the dust particles smaller than 2,5µm. These particles tend to reach deep into the respiratory area of the lungs and can therefor cause immediately and life long lasting damages, for example a fibrosis. The major influences on the hazardousness of dust are the particle size, the composition and concentration, as well as the exposure time. A higher exposition time in a dusty area equals a higher risk of getting damaged by the inhalation. But not only the inhalation of dust can be dangerous to the health of the body, but there are also other effects like damages to the eyes or specific kinds of dust can create, with enough concentration, explosive conditions, which can lead to a sudden explosion and therefor damages to workers and the equipment.

The last chapter focused on the environmental damages of dust, which included the direct and indirect effects of dust, as well as the damages to the biodiversity. Dust in the atmosphere can interact with the clouds and change the size of the raindrops and the precipitation patterns. This also includes the change in the solar radiation caused by absorbing or reflecting different wavelengths within the atmosphere. But not only the sky gets influenced by dust, but also the ocean, the soil and all different kinds of plants. The effects on the water of the earth is of a short and long lasting effect because the phytoplankton can be influenced by the nutrition from dust storms or the contribution of trace elements, which can cause growth or reduction on the number of different plants. This also has an influence on the CO_2 balance of the earth because the phytoplankton performs photosynthesis to generate oxygen and reducing carbon dioxide. The effects on the soil are also from great importance. Dust particles can cover the leaves of plants and smaller particles are even able to clog the stomatal openings, thus leading to a reduced efficiency of the photosynthesis and leading to a necrosis of the leaves. Even a change on the morphology of the plants is possible. If the plants want to survive in a dusty area, they need to produce more but smaller leaves, so the coverage of the dust doesn’t interfere with the efficiency of the photosynthesis that much.

To summarize all of this, it is recommended to get rid of most of the dust in all parts of the industry to protect both the environment and humanity from short term and long-term consequences.

References

[1] Intensiv Filter : Know - How: Das große Intensiv-Filter Lexikon der Entstaubung.

[2] Ulrich Klenk (2014): Minderung von Feinstaubkonzentrationen mit Sprühdüsen. Bergische Universität Wuppertal

[3] EmiControls, Story and Philosophy, accessed 22.06.2022, https://www.emicontrols.com/en/story-philosophy/

[4] Ulrich Klenk (2012): Use of water droplets and additives for dust control. Bergische Universität Wuppertal

[5] H. T. Kim, C. H. Jung, S. N. oh, K. W. Lee (2001): Particle Removal Efficiency of Gravitational Wet Scrubber Considering Diffusion, Interception, and Impaction. In: Environmental Engineering Science, Vol 18, No 2, 2001

[6] Beate Lange, Till Markus, Philipp Helfst (2015): Impacts of Scrubbers on the environmental situation in ports and coastal waters. Ed.: Umweltbundesamt

[7] Gisela Winckler, Natalie Mahowald (2014): Dust impact on climate and environment. In: PAGES Magazine No2, October 2014, S. 61

[8] J.P.K. Seville (1997): Gas Cleaning in Demanding Applications. Ed.: Springer

[9] J. Jeffrey Peirce, Ruth F. Weiner, P.Aarne (1998): Environmental Pollution and Control. Ed.: Butterworth-Heinemann

[10] Yongsheng Zhang, Tao Wang, Wie-Ping Pan, Carlos E.Romero (2019): Advances in Ultra-Low Emission Control Technologies for Coal-Fired Power Plants. Ed.: Woodhead Publishing

[11] Hu S., Gao Y., Feng G. (2021): Experimental study of the dust-removal performance of a wet scrubber.In: J Coal Sci Technol 8, 228-239 (2021)

[12] Arkadiusz T. Sobczyk, Anatol Jaworek, Artur Marchewicz, Andrzej Krupa, Tadeusz Czech (2019): Particulate matter emission reduction from marine diesel engines by electrohydrodynamic Methods. In: Journal of KONES Powertrain and Transport, Vol. 26, No. 3 2019

[13] Ibrahim Adabara, Abdurrahman Shuaibu, Abdurrashid Hassan Shuaibu (2017): Design and Implementation of an Electrostatic Precipitator and Its Cleaning System for Small Scale Combustion

[14] Kurt Becker, Weidong Zhu, Jose L. Lopez (2017): Microplasmas: Environmental and Biological Applications. In: Encyclopedia of Plasma Technology, 791-805. Ed.: Taylor & Francis

[15] Zaman Bhulyan (2020): Design analysis of Dust collection system. University of Manitoba

[16] Martin Meiller, Julia Zach, Andreas Hornung [2015]: Development of an electrostatic precipitator for small scale biomass furnaces. Frauenhofer UMSICHT Institute.

[17] Michael J. Pilat, John C. Lukas (2004): Droplet Charging for Wet Scrubbers. In: Journal of the Air & Waste Management Association, 54:3-7, February 2004

[18] Environmental Protection Agency United States (2003): Air Pollution Control Technology Fact Sheet, EPA-452/F-03-010

[19] EmiControls, dust-suppression, quarries, accessed 20.06.2022, https://www.emicontrols.com/en/dust-suppression/areas/quarries/

[20] BETE, dust-suppression, accessed 23.06.2022, https://bete.com/application/dust-suppression/

[21] John H. Seinfeld, Spyros N. Pandis (2006): Atmosperic Chemistry and Physics: From Air Pollution To Climate Change. 2nd Edition. Ed.: John Wiley & Sons Inc. Hoboken

[22] Raymond Mcdonnell (2006): The Effect of Water Droplet Oscillations on the Scavenging Efficiency of Micron Sized Particles, All These, 13, Ed.: TigerPrints

[23] S.M. Greenfield (1957): Rain scavenging of radioactive particulate matter from the atmosphere. Journal of Meteorology, 14:115-125, April 1957.

[24] Michael J. Pilat (1975): Collection of Aerosol Particles by Electrostatic Droplet Spray Scrubbers. In: Journal of the Air Pollution Control Association, 25:2 176-178, February 1975

[25] Seymour Calvert, Nikhil C. Jhaveri (1974): Flux Force/Condensation Scrubbing. Journal of the Air Pollution Control Association, 24:10, 946-951

[26] Peter Werner Grundnig, Wilhelm Höflinger, Gerd Mauschitz, Zechang Liu, Guiqin Zhang, Zhiqiang Wang (2006): Influence of air humidity on the suppression of fugitive dust by using a water-spraying system. CHINA PARTICUOLOGY, Vol. 4, No. 5, 229-233, 2006

[27] David Blyth: A Practical Guide to Dust Suppression. Dust Control by Sealpump Engineering

[28] Spraying Systems Co. (2016): Spray Technology for Dust Control

[29] Yen-Yi Lee, Chung-Shin Yuan, Po-Hsuan Yen, Justus Kavita Mutuku, Chien-Er Huang, Chih-Cheng Wu. Po-Jen Huang (2022): Suppression Efficiency for Dust from an Iron Ore Pile Using a Conventional Sprinkler and a Water Mist Generator. Aerosol and Air Quality Research, Vol. 22, Issue 2, February 2022

[30] CF Blazek (2003): The role of chemicals in controlling coal dust emissions. Presented at the American Coal Council PRB Coal Use: Risk Management Strategies and Tactics Course. Dearborn, Michigan, June 2003.

[31] NIOSH (2019): Dust control handbook for industrial minerals mining and processing. Second edition. By Cecala AB, O'Brien AD, Schall J, Colinet JF, Franta RJ, Schultz MJ, Haas EJ, Robinson J, Patts J,
Holen BM, Stein R, Weber J, Strebel M, Wilson L, and Ellis M. Pittsburgh PA: U.S. Department of
Health and Human Services, Centers for Disease Control and Prevention, National Institute for
Occupational Safety and Health, DHHS (NIOSH) Publication No. 2019–124, RI 9701.

[32] Canadian Centre for Occupational Health & Safety(2022): What are the Effects of Dust on the Lungs?. Accessed 08.07.2022, https://www.ccohs.ca/oshanswers/chemicals/lungs_dust.html

[33] California Air Resource Board: Inhalable Particulate Matter and Health (PM2.5 and PM10). Accessed 08.07.2022, https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health

[34] Canadian Centre for Occupational Health & Safety(2022): How Do Particulates Enter the Respiratory System?. Accessed 08.07.2022, https://www.ccohs.ca/oshanswers/chemicals/how_do.html

[35] Bart Ostro, Yewande Awe, Ernesto Sánchez-Triana (2021): When the Dust Settles: A Review of the Health Implications of the Dust Component of Air Pollution. World Bank Group, Washington, DC.

[36] George Thurston, Yewande Awe, Bart Ostro, Ernesto Sánches-Triana (): Are All Air Pollution Particles Equal? – How Constituents and Sources of Fine Air Pollution Particles ($PM_{2.5}$) Affect Health. World Bank Group, Washington, DC.

[37] Wolfgang Spangl, Christian Nagl (2017): PM_{10} - und $PM_{2,5}$ – Exposition der Bevölkerung in Österreich. Umweltbundesamt

[38] National Institute for Occupational Safety and Health (2018): Flavorings Related Lung Disease: Exposure Limits. Accessed 22.07.2022 https://www.cdc.gov/niosh/topics/flavorings/limits.html

[39] National Institute for Occupational Safety and Health (2018): Silica, crystalline (as respirable dust). Accessed 22.07.2022 https://www.cdc.gov/niosh/npg/npgd0684.html

[40] Industrial Minerals Europe (2022): Dust and OELs. Accessed 22.07.2022 https://ima-europe.eu/eu-policy/health-and-safety/dust-and-oels/

[41] Soo Youn Choi, Youngsub Eom, Jong Suk Song, Hyo Myung Kim (2019): Fine dust and eye health. Department of Ophtthalmology, Korea University College of Medicine, Seoul, Korea. J Korean Med Assoc 2019;62(9): 486-494.

[42] OSHA (2009): Hazard Communication Guidance for Combustible Dusts. Occupational Safety and Health Administration. OSHA 3371-08 2009

[43] Hadis Moradi, Farhang Sereshki, Mohammad Ataei, Mohsen Nazari (2020): Evaluation of the effect of the moisture content of coal dust on the prediction of the coal dust explosion index. In The Mining-Geology-Petroleum Engineering Bulletin 01.2020. pP.: 37-47

[44] Richard Kuracina, Szabova Zuzana, Pavol Cekan (2015): Determination Of The Maximum Explosion Pressure And The Maximum Rate Of Pressure Rise During Explosion Of Wood Dust Clouds. Research Papers Faculty of Material Science and Technology Slovak University of Technology. 23(36) 2015-0006.

[45] Santiago Gassó, Vicki H. Grassian, Ron L. Miller (2010): Interactions between Mineral Dust, Climate, and Ocean Ecosystems. In Elements – An International Magazine of Mineralogy, Geochemistry, and Petrology. ELEMENTS, Vol. 6, PP 247-252

[46] P. Stammes, L.G. Tilstra, R. Braak, M. de Graaf, E.A.A Aben (2009): Estimate of Solar Radiative Forcing by Polluted Clouds Using OMI and SCIAMACHY Satellite Data. In AIP Conference Proceedings, vol. 1100, pp.: 577-580

[47] J.E.Penner, M. Andreae, H. Annegarn, L. Barrie, J. Feichter, D. Hegg, A. Jayaraman, R. Leaitch, D. Murphy, J. Nganga, G. Pitari (2001): Aerosols, their Direct and Indirect Effects. In Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, pp.: 289-348 (2001)

[48] Jim Haywood (2021): Atmospheric aerosols and their role in climate change. In Climate Change (Third Edition) 2021, pP.: 645-659

[49] William H. Brune (2020): Where do cloud condensation nuclei (CCN) come from? College of Earth and Mineral Sciences. Accessed 03.08.2022 https://www.e-education.psu.edu/meteo300/node/671

[50] S. Kameswaran, Y. Gunavathi, P. Gopi Krishna (2019): Dust pollution and its influence on vegetation – a critical analysis. Research Journal of Life Sciences, Bioinformatics, Pharmaceutical and Chemical Sciences 5(1). pP.: 341-363

[51] WHO (2021): Global air quality guidelines. Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Accessed 04.08.2022 https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

[52] Umweltbundesamt (2022): Grenz-, Ziel- und Schwellenwerte. Accessed 04.08.2022 https://www.umweltbundesamt.at/umweltthemen/luft/daten-luft/luft-grenzwerte

[53] Bundesministerium für Wirtschaft und Arbeit (2008): Begrenzung der Emission von luftverunreinigenden Stoffen aus Anlagen zur Erzeugung von Nichteisenmetallen und Refraktärmetallen – NER-V. Accessed 04.08.2022 https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20005736

[54] Bundesministerium für Wissenschaft, Forschung und Wirtschaft (2016): Begrenzung der Emission von luftverunreinigenden Stoffen aus Anlagen zur Erzeugung von Eisen und Stahl 2016 (EiST-V 2016). Accessed 04.08.2022 https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20009485

[55] K. Ardon-Dryer, Y.-W. Huang, D.J. Cziczo (2015): Laboratory studies of collection efficiency of sub-micrometer aerosol particles by cloud droplets on a single-droplet basis. In Atmosperic Chemistry and Physics. Vol 15. pP.: 9159-9171

[56] Wilhelm Hoeflinger, Thomas Laminger (2019): PM2.5 or respirable dust measurement and their use for assessment of dust separators. Journal of the Taiwan Institute of Chemical Engineers, Volume 94, 2019, pP.: 53-61

[57] John Cherrie, Robert John Aitken(1999): Measurement of human exposure to biologically relevant fractions of inhaled aerosols. Occupational and Environmental Medicine. Volume 56(11), pP.: 747-52