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Improvement of air quality in laying hens barn using different particle separation techniques

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Abstract

Air quality improvement within laying hens barns using different particle separation techniques

Poultry production is increasingly regarded as a source of air pollutants which can be environmentally harmful. The air in animal housing contains gases, odours, dust and micro-organisms. These pollutants could directly attenuate poultry health which has major consequences on productivity. Moreover, they could also have a drastic influence on the general health of the people living close to poultry enterprises and the labourers working inside these enterprises. Generally dust can be considered as one of the most important sources for air contamination in poultry houses, where it may be generated from feed, litter, dried manure, feathers and building materials. According to environment protection laws and the maximum acceptable dust concentration in the workplace, dust concentration inside poultry houses must be controlled to provide adequate air for the labourers and the animals inside these buildings.

The aim of this investigation was to increase the air quality by purifying the recirculating air inside the animal barn. The experiments have been done inside laying hen houses with the aviary system. Dry and wet filter techniques have been tested to reduce the indoor dust concentration inside the laying hen houses. Laboratory experiments have been done to select suitable materials for designing dry filter systems and choose the process conditions suitable for laying hen buildings.

In small scale barn measurements the designed dry filter achieved the highest dust reduction efficiency in comparison to the cyclone and wet filter system. Resulting from these experiments the designed dry filter has been recommended for testing in a commercial scale farm. The reduction efficiencies of the designed dry filter under commercial scale barn measurements were 55 and 72 % for indoor concentration and dust emission rate, respectively.

Kurzfassung

Verbesserung der Luftqualität im Legehennestall durch unterschiedliche Partikeltrennungstechniken

Die Geflügelhaltung wird in zunehmendem Maße als eine Quelle umweltrelevanter Schadstoffe betrachtet. Die Stallluft enthält Schadgase, Gerüche, Staub und Mikroorganismen. Diese Komponenten können die Tiergesundheit beeinträchtigen und somit die Produktivität mindern. Außerdem haben diese Stoffe einen negativen Einfluss auf die allgemeine Gesundheit der Mitarbeiter und direkten Anwohner eines Geflügelbetriebes. Der Stallstaub entsteht aus Futter, Einstreu, Stallmist, Federn und auch aus Baustoffen. Entsprechend der Umweltschutzgesetze und der maximal zulässigen Staubkonzentration am Arbeitsplatz muss die Staubkonzentration innerhalb der Geflügelställe eingehalten werden, um ausreichend saubere Luft für die Arbeiter und Tiere innerhalb dieser Ställe zur Verfügung zu stellen.

Ziel dieser Untersuchung war es, die Luftqualität durch Rezirkulation und Filterung der Luft innerhalb eines Stalls zu verbessern. Die Experimente wurden im Inneren eines Legehennenstalles mit Volierensystem durchgeführt. Trocken- und Nassfiltertechniken wurden hierbei überprüft. Durch verschiedene Laborexperimente wurde zunächst geeignetes Filtermaterial für ein Trockenfiltersystem bestimmt und die Mess- bzw. Arbeitsbedingungen den Ställen entsprechend angepasst.

Der entwickelte Trockenfilter zeigte die beste Staubreduzierung im Vergleich zu Zyklon- und Nassfiltersystemen. Basierend auf den Ergebnissen dieser Untersuchungen sollte im zweiten Schritt, das Trockenfiltersystem in einem typischen Legehennenstall eingesetzt werden. Die Staubreduzierung dieses Filtersystems betrug in den abschließenden Praxis-messungen für die Innenraumkonzentration 55 % und für die Staubemission 72 %.

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List of abbreviations

AC	Peak area count
AU	500 kg body weight (Animal unit)
CEN	The European standards
CFU	Colony forming units
DM	Dry matter content
EC	Thoracic fraction
EI	Inhalable fraction
ESCS	Electrostatic space charge system
EU	Endotoxin unit
FVC	Forced vital capacity
ICRP	International commission on radiological protection
IDI	In duct ionizer
IOM	Institute for occupational medicine
ISO	International organization for standardization
IUPAC	International union of pure and applied chemistry
KCl	Potassium chloride
MAC	Maximum acceptable concentration
NAAQS	National ambient air quality standards
NH_3	Ammonia
OAS	Optical aerosol spectrometers
OEL	Danish occupational limit
PM	Particulate matter
PTFE	polytetrafluoroethylene
PVC	Polyvinyl chloride
RD	Respirable fraction
RH	Relative humidity
RIS	Room-Ionizer-System
TEOM	Tapered element oscillating microbalance
TSP	Total suspended particle
USSU	Ultra sonic sprayers unit
VDI	Verein Deutscher Ingenieure

1 Introduction

Poultry production can be considered as a one of the most feasible sources of animal protein (eggs and meat). Poultry is kept in most areas of the world and provide an acceptable form of animal protein for most people throughout the world. During the last decade, many developing countries have adopted intensive poultry production in order to meet the demand for this form of animal protein. Intensive poultry production is seen as a way of rapidly increasing animal protein supplies for increasing urban populations.

Poultry is able to adapt to most areas of the world at relatively low cost as they reproduce rapidly and have a high rate of productivity. Poultry is housed in confinement with the aim of creating optimal conditions of temperature and lighting. Poultry production has a harmful effect on the environment during the breeding period, such as the emittance of dust, odour and ammonia into the surrounding environment through the ventilation system as well as its harmful influence on the hens and workers inside these animal houses. Particle matter reduces the air quality within the livestock buildings compromising the health and welfare of farmers and animals, **(Hinz et al., 2007).**

The improvement of the farm animal health is an important goal to ensure proper livestock production. Apart from management factors the internal environmental conditions play a key role for ensuring the well-being of intensively housed livestock and farm workers. Airborne dust is a nuisance and more importantly must be considered as a potential health threatening compound in terms of an internal environmental evaluation, **(Banhazi and Seedorf, 2007).**

Requirements for good management and ventilation in animal husbandry systems ensure that the quality of indoor air is acceptable for animals' and humans' health, **(Haeussermann et al., 2007).**

1.1 Objective

The main targets of this study are:

1. To find the effect of diurnal change and housing style such as cage and aviary system on dust emission and to correlate it with theoretical animal activity.

2. Reducing the indoor concentration of the particle matter released from layers to increase the air quality for the animals and humans inside the barn and reducing the emissions by different indoor filter systems.
3. Evaluation and optimization of the filter systems.

1.2 Stages of study

1. **Quantification of the emission rate and its influences.**

Measure the emission of particle matter from laying hen houses with different breeding systems (cage and aviary systems) during the whole day through the different seasons of the year.

2. **Dust characterization.**

Characterise the particle matter in order to find the particle density and shape. The dust must be characterized by sedimentation experimentation and microscopic analysis.

3. **Indoor dust concentration reduction.**

Form primary experiments by using three different filters to find out the best reduction efficiency of these filters and test it on commercial scale.

2 Review of literature

Dust is normally considered to be one of the contaminants in livestock buildings. The main environmental issue associated with dust concerns the air quality in livestock buildings. Commercial livestock production facilities are always associated with some level of airborne particles. High concentrations of airborne particles could affect the external environment, production efficiency, health and welfare of humans and animals, **(Banhazi and Seedorf, 2007).** Livestock farmers are exposed to dust concentrations inside their animal houses that are a factor of 10 to 200 times higher than those of the outside air, **(Aarnink and Ellen, 2007)**. Although the ventilation system of a building discharges dust particles into the environment, considering the high dilution rate with the outside air, the following discussion focuses on the dust level and control inside the livestock building.

2.1 Harmful effect of the dust on human and animal health

It is generally assumed that dust particles are capable of transporting different chemical compounds and microorganisms from one livestock building to the other, or from a livestock building to the farmhouse and to the neighboring houses. This may cause increased risks of airborne infections of animals and malodour problems. Farmers in animal houses are exposed to gases and a complex aerosol of bacteria, fungi, endotoxin and organic dust, which are linked to the development of respiratory diseases in farmers' lungs, **(Takai et al., 2002).**

2.1.1 Air quality requirements

According to the federal pollution control law people, animals, plants, soil, water, atmosphere and other cultural assets need to be protected from harmful environmental effects. This is determined in the administrative regulation **(TA-Luft, 2002)** (technical instructions for cleaning the air) by specifying limits for the emission mass flow and the mass concentration of harmful substances in concrete.

According to the statutory mandate it is a goal of **(TA-Luft, 2002)** to provide authorities with up to date information on nationwide guidelines in order to carry out an evaluation of the emissions and immissions especially within licensed facilities. In order to indicate the values in **(TA-Luft, 2002)** the terms emission and immission are defined with the pertinent defaults using standardized evaluation criteria. "Emissions are defined within these administrative rules as those of air pollution" **(TA-Luft, 2002)**.

The emissions are thus indicated on the one hand as the mass of the emitted substances or groups of substances related to the volume and mass concentrations. The mass indication of emitted substances or groups of substances is related to the unit time (emission mass flow). The dust contained in the exhaust emissions should not exceed a 20 mg/m³ mass concentration or 0.20 kg / h of mass flow. There are other values in the MAC list (**M**aximum **A**cceptable **C**oncentration) published from the senate committee of the German research council, **(DFG, 2006)**. The "maximum workplace concentration value" in **(GefStoffV, 1999)** defines the value of substances permissible in workplace atmospheres, in order not to affect the health of workers within an eight hour daily work schedule. This value differentiates between two groups of dust, the respirable (< 5 µm) and the alveolar dust (< 1.1 µm). The respirable group may not exceed a concentration of 4 mg/m³ and for the alveolar group the limit value is 1.5 mg/m³, **(DFG, 2004)**. In case of non-compliance with these limits in animal barns protective arrangements should be employed for the staff such as breathing masks, **(Scheuermann, 2004).**

Pedersen et al. (2000) observed under Danish conditions a consistent relationship between environmental exposure in livestock buildings, lung function changes and/or respiratory symptoms in workers and identified exposure-response thresholds for workers on the basis of exposure response thresholds for poultry and swine confinement buildings. The authors also showed that the limit recommendations for humans are 2.4 mg/m^3 of total dust, 0.23 mg/m^3 of respirable dust with a total of 800 EU/m^3 (EU = endotoxin unit) and 7 ppm of ammonia.

2.1.2 Particle influence on the respiratory system of animals and humans

Keder (2007) reported that the particles suspended in the air enter the human body by breathing. These particles include natural materials such as bacteria, viruses, pollen, sea salt, road dust, and anthropogenic emissions. The hazard caused by these particles depends on their chemical composition as well as where they deposit within human respiratory system. Hence, understanding the deposition of aerosol in the human respiratory system is critical to human health, so that the deposition of "bad" aerosol must be reduced. The respiratory system works essentially as a filter. The viscous surface of the airway wall almost guarantees the deposition without re-entrainment when a particle is in contact with it. The most important mechanisms are impacting, settling, diffusion and interception. A particle entering the respiratory system is subject to all the deposition mechanisms previously mentioned. The actual deposition efficiency of a given particle size has been determined experimentally. Several models have been developed to predict the deposition, based on experimental data. A widely used model was developed by the **I**nternational **C**ommission on **R**adiological **P**rotection (ICRP). For the purpose of this model, the respiratory system is divided into three parts, as shown in figure 2.1:

1. Head airways (HA)
2. Tracheobronchial region (TB)
3. Alveolar region (AL).

Regional deposition is more interesting because it is relevant in assessing the potential hazard of inhaled particles.

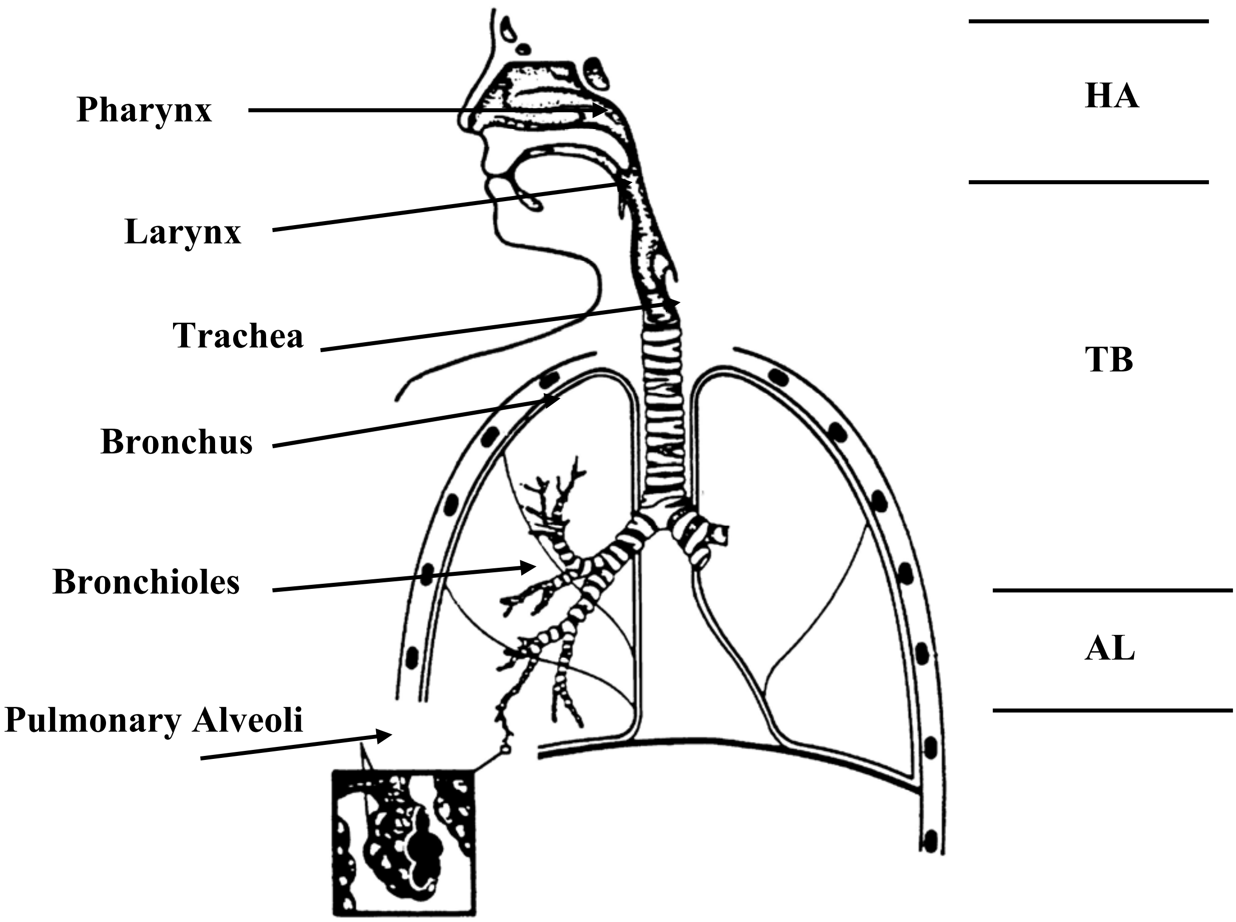


Figure 2.1: Parts of human respiratory system (after Nannen, 2007)

Radon et al. (2001) mentioned that the recent epidemiological studies have indicated a greater risk of respiratory disorders in farmers than in non-farming occupations. It is known that animal farmers are exposed to organic dust, endotoxins and hazardous gasses. These substances may affect one or more parts of the respiratory system and may induce diseases such as allergic and non-allergic rhinitis, organic dust toxic syndrome, bronchitis, asthma and asthma-like syndrome. Accordingly, the ventilation of the animal house might influence respiratory morbidity in farmers.

Rosentrater (2004) reported that over 700.000 people in the United States are exposed to hazardous levels of swine dust each year, and over 60 % of these suffer from various respiratory disorders including organic toxic dust syndrome, chronic bronchitis, hypersensitivity pneumonitis and occupational asthma. These primarily include confinement workers but also the family members of these workers and veterinarians. Swine dust particles are hazardous to human health because a substantial portion is smaller than 5 µm in diameter and is thus “respirable”. Their small size allows significant deep lung penetration, deposition, and consequent accumulation. Dust can also produce other problems including adverse health effects in the swines themselves. Because of the physical size and shape of the dust particles as well as the gas molecules that have been adsorbed from the air (e.g., ammonia, hydrogen sulfide, and carbon dioxide) airway irritation and respiratory diseases especially pneumonia can result. It has been estimated that between 35 and 60 % of all swine raised in confinement conditions suffer from pneumonia.

Seedorf and Hartung (2000) said that animal production is increasingly regarded as a source of air pollutants which can be both aggravating and environmentally harmful. The air in animal housing contains gases, odours, dust particles and microorganisms which are discharged by the ventilation system into the environment. There is an increasing concern within parts of the population that these compounds may affect the respiratory health of people living close to livestock enterprises. The authors also indicated that the effects of the dust on the animal’s health depend upon the nature of the dust (organic, not organic), the compounds the particles are carrying (bacteria, toxins) and the diameter of the particles. Particles with aerodynamic diameters smaller than 5 µm can penetrate deep into the lungs but the larger particles are deposited in the upper airways. The high dust concentrations can irritate the mucous membranes and overload the lung clearance mechanisms. Together with the dust particles microorganisms can be transported into the respiratory system causing infections. Endotoxins can trigger allergic reactions in the airways of susceptible humans even in low concentrations.

Eugenija et al. (1995) and Iversen et al. (2000) studied the prevalence of acute and chronic respiratory symptoms and lung function changes. **The authors** found that there are significantly higher prevalences of chronic cough, chronic phlegm, chronic bronchitis and chest tightness in poultry workers than in control workers.

Jay et al. (1994) reported that the particulate contaminants or more common dusts are not only a nuisance but can also contribute to worker and animal health problems. Particles are classified according to size: particles larger than 10 µm usually settle out of the air rapidly. If they are inhaled, they are trapped by moist tissue in the nose and throat. They may cause irritation of the nose and throat and cause sneezing. Particles 5 to 10 µm in size will reach the windpipe causing irritation of the lining and possible infection. Particles less than 5 µm called respirable particles may reach the bronchioles and alveoli. Theses particles therefore present the most hazards. The authors also mentioned that the dusts adversely affect health by directly irritating tissue and by causing allergic reactions in response to inhaled foreign particles. They also transport embedded microorganisms and adsorbed gases deep into the sensitive tissue of the lungs. Endotoxins are of particular concern to agricultural workers. They are substances found in the cell wall of Gram-negative bacteria and have a high biological potency. They have been linked with respiratory symptoms in workers.

Iversen et al. (2000) found that the work in swine and poultry units is associated with exposure to significant levels of organic dust and endotoxins. The highest concentrations were found in poultry houses whereas values found in dairy and cattle farming are much lower. **Alencar et al. (2004)** said that the inhalation of organic dust in broiler houses which has many microorganisms leads in general to respiratory allergic reactions in some individuals. For example asthma-like syndrome and mucous membrane inflammation syndrome which is a complex of nasal, eye, and throat complications. Furthermore, workers might have farmer’s hypersensitivity pneumonia which is a respiratory health risk with long-term exposure. The authors found from the study of restrictive function that lower FEV1 (the maximum respiratory potential, the forced expiratory volume in the first second of exhalation) and FVC (forced vital capacity) represented 24.32 % of the total of workers and severe obstruction represented 2.70 %. Other symptoms were found in 67.57 % of the workers as well. The results showed that those who work more than 4 years and within more than one poultry house, exceeding 5 hours per day of work, face higher pulmonary health risks. It is concluded that the activities within broiler houses may induce allergic respiratory reactions in workers. The use of IPE (individual protection equipment), besides special attention to the air quality inside the housing may be advised as a preventive method. **Hartung and Saleh (2007)** showed that the effects of the particles in livestock buildings on human and animal health cannot simply be attributed to dust levels or the concentration of microorganisms. Effects on health are related to the complex action of particles and gases as well as the physical and psychological environment. Particulates have effects which may be described as mechanical, infectious, immunosuppressive, allergic or toxic. Table 2.1 summarizes the possible effects of airborne dust, microorganisms and gases on animal health.

Table 2.1: Influences of dust and microorganisms levels on animal health (Hartung and Saleh, 2007)

Factor	**Effect on the animal**
High dust levels	Mechanical irritation: overloading of lung clearance, lesions of the mucous membranes.
Specific microorganisms	Infectious effect: infection by pathogens
Dust, microorganisms and gases	Non-specific effect: defence mechanisms stressed, reduced resistance
Microorganisms and dust	Allergic effect: over-sensitivity reaction
Microorganisms and dust	Toxic effect: intoxication by bacteria/fungal toxins

2.1.3 Transportation of harmful substance inside animal buildings

Particulate matter can be considered as a good media to absorb odour and other harmful gases such as ammonia. It can then transfer inside the animal buildings and to the environment by ventilation. **Mitchell et al. (2004)** reported that the airborne dust is one of the primary means by which disease-causing organisms are spread throughout a poultry house. Reductions in airborne dust levels have been associated with even greater reductions in airborne bacteria. Poultry (meat and eggs) contaminated with Salmonella continue to be important vehicles for Salmonella infections in humans. Pathogens, such as Salmonella can be introduced into the food chain at any point – from the breeder house to the processing plant. Interventions are best begun at the breeder house which is the first part of the chain. Airborne transmission of Salmonella is a major factor for the spread of Salmonella from bird to bird and hatching eggs in breeder houses. It has been shown to be a major factor in the spread of disease in hatching cabinets.

Koziel et al. (2007) found that total suspended particles (TSP) carried much more total odour than PM_1 and PM_{10} as shown in figure 2.2. When total odour was normalized with the PM mass and the total surface area the relative odour intensity of PM_1 was higher than that of PM_{10} and TSP.

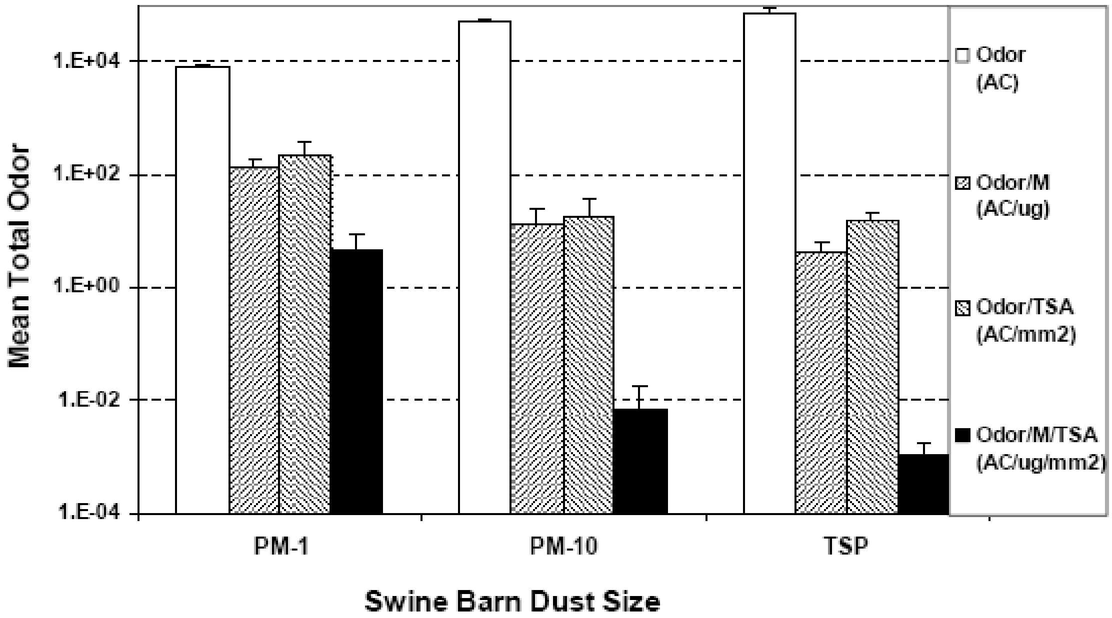


Figure 2.2: Characterization of odour for swine barn dust at PM_1, PM_{10} and TSP (Koziel et al., 2007)

Takai et al. (1998) indicated that dust can transport and amplify odour. **Robert (2001)** reported that the dust particles in swine buildings may be responsible for a considerable portion of odourant emissions from the buildings and odour perceptions by downwind neighbours of swine farms. Therefore, controlling the odour will require a reduction of dust emissions from buildings. **Reynolds et al. (1998)** indicated that a significant proportion (15 to 23 %) of airborne ammonia in enclosed livestock facilities is associated with dust particles. **Takai et al. (1998)** mentioned that ammonia and odours may be absorbed by the dust particles. Viable bacteria and viruses carried into the air by dust particles may have a greater ability to survive.

2.2 Particles in the poultry houses

Poultry houses have poor air quality because of the high concentrations of ammonia, inhalable and respirable dust and endotoxin. Percheries and caged laying houses have higher inhalable particle matter concentrations during the day than at night **(Takai et al., 1998)**. Another study which was done by **Kocaman et al. (2006),** showed the effects of the dust in animal housing that generally indicated potential for adverse effects on the health, growth and development of animals. Respirable aerosol particles within poultry housing have been shown to decrease bird growth and increase the diseases transferred within flocks as well as an increase of condemnation meat at processing plants.

2.2.1 Definition of the particle

MDHS (1996) defined three criteria for biologically-relevant size-selective of the dust as:

1. The inhalable fraction is the mass fraction of total airborne particles which is inhaled through the nose and mouth. The International Organization for Standardization (ISO) and the European Standards Organization (CEN) standards specify that samplers for this fraction should have the collection efficiency:

$$\mathbf{EI = 50(1 + \exp[-0.06D])} \qquad \mathbf{2.1}$$

Where D is the particle aerodynamic diameter and EI is expressed as a percentage.

2. The thoracic fraction ET is the mass fraction of inhaled particles penetrating beyond the larynx. The CEN and ISO convention for this fraction declines from 100 % at 0 µm with the shape of a cumulative log-normal curve with a median diameter of 11.64 µm and a geometric standard deviation of 1.5.

3. The respirable fraction RD is the mass fraction of inhaled particles which penetrates to the unciliated airways. The CEN and ISO convention for this fraction declines from 100 % at 0 µm with the shape of a cumulative log-normal curve with a median diameter of 4.25 µm and a geometric standard deviation of 1.5.

Pedersen et al. (2000) classified the dust into:

- **Total dust,** The fraction containing particles below 20 µm in aerodynamic diameter, collected by use of 38 mm filter cassettes with 5 mm downward inlets.
- **Respirable dust,** The fraction collected using a cyclone pre-separator (50 % cut-off effectiveness value of 5 µm)

- **Inhalable dust,** The diameter of these dust particles is slightly larger than 20 µm. The inhalable concentration will be about 25 % higher than the "total dust" concentration, but it depends on the particle size distribution.

ISO (1995) defined the Dust as small solid particles conventionally taken as those particles below 75 µm in diameter which settle out under their own weight but may remain suspended for sometime. On the other side, **IUPAC (1990)** defined it as a small, dry, solid particles projected into the air by natural forces such as wind, volcanic eruption and by mechanical or man-made processes such as crushing, grinding, milling, drilling, demolition, shovelling, conveying, screening, bagging, and sweeping. Dust particles are usually in the size range from about 1 to 100 µm in diameter, and settle slowly under the influence of gravity.

Sergio et al. (2005) defined PM_{10} as airborne particles with aerodynamic equivalent diameters less than 10 µm and currently regulated through the National Ambient Air Quality Standards (NAAQS). The primary concern for PM_{10} is on the issue of regional haze. **Zhang et al. (2005)** defined the particulate matters as solid or liquid particles of composition and size range.

Hartung and Saleh (2007) mentioned that, there are several relevant terms used to describe the particulates suspended in air:

Airosoals are solid or liquid particles which remain suspended in the air for longer periods because of their minute dimensions of between 10^{-4} and approximately 10^{2} µm. The aerosols can combine chemically with gases emitted into the air and these new compounds are inhaled by living organisms or can settle on them.

Airborne particulates can include both solid and liquid particles.

Viable particles are living microorganisms or any solid or liquid particles which have living microorganisms associated with them.

Dusts are dispersed particles of solid matter in gases which arise during mechanical processes or have been stirred up. Dust may cover a wide range of sizes and can be airborne or settled.

2.2.2 Particles characterization

2.2.2.1 Chemical properties of dust particles

Dust is analyzed according to its chemical composition into inorganic and organic (viable and non-viable) components.

Pedersen et al. (2000) referred, from the investigation which has been done to estimate the chemical composition of dust from different sources that the airborne and the settled dust have nearly the same concentrations of dry matter, ash, N, P, K, Cl and Na. The authors also referred to the high concentration of airborne microorganisms in the animal houses. The incidence of colony forming units (CFU) of bacteria was 6.4 log CFU/m^3 for poultry. In the same investigation the mean daily concentration of fungi was 4.01 log CFU/m^3.

Ellen et al. (2000) showed from the chemical analysis of the airborne and settled dust in broiler houses and pig rooms that the dust from broiler houses was higher in its chemical composition than that from the pig barns as shown in table 2.2.

Table 2.2: Chemical composition of dust in broiler and pig houses (Ellen et al., 2000)

Dust source		**DM g/kg**	**Ash g/kg**	**N g/kg**	**P g/kg**	**K g/kg**	**Cl g/kg**	**Na g/kg**
Airborne dust	Broiler	911	97.4	169	6.44	40.3	4.19	3.23
	Pig	4.4	16.1	2.3	0.29	1.4	0.44	0.34
Settled dust	Broiler	914	94.8	130	6.66	29.3	3.46	2.57
	Pig	3.1	1.9	2.4	0.13	0.3	0.32	0.07

Guarino et al. (1999) reported from the dust composition analysis for caged laying hens and from broilers housed in batteries or that ranged free on the floor that dust produced by laying hens was 92 % dry matter (60 % raw protein, 9 % fats and 4 % cellulose). The remainder was ash and hydrocarbons. The dust from the broilers was lower in fat but higher in protein. This was correlated with the down feathers from the 3rd to the 6th week.

Hartung and Saleh (2007) investigated the composition of dust sedimentation from a piggery and poultry house as shown in table 2.3.

Table 2.3: Compostion of the feed and deposited dust from a piggery & poultry houses (Hartung and Saleh, 2007)

Component	**Pig house Deposited dust, %**	**Pig house Feed dust, %**	**Poultry house Deposited dust, %**
Dry matter	78	88	89
Crude protein	24	19	50
Crude fat	4	4	10
Crude fibre	3	5	-
Crude ash	15	5	-

The dust from poultry houses contains the highest amounts of protein. This is caused firstly by the relatively high protein content in the feed which is usually between 20 and 25 %. Secondly the other proportion of up to 45 % comes probably from feathers and claw abrasion. Also in the pig house the dust percentage of about 20 % seems to come from the skin and the hair of the animals. **Takai et al. (2002)** found that the airborne dust in poultry houses contains a relatively large amount of ammonia as shown in table 2.4.

Table 2.4: Dust concentrations and ammonia contents in airborne dust, poultry houses (Takai et al., 2002)

Dust fraction	**dust concentration, mg/m^3**	**Ammonia content in dust, µg/mg**
Inhalable	2.50	3.48
Respirable	0.54	7.05

2.2.2.2 Biological properties of dust particles

Mårtensson and Pehrson (1997) concluded that there are larger amounts of airborne microorganisms in alternative housing systems of poultry houses. These high concentrations of viable fungi in the multiple level systems may be caused by using wood shavings in the bedding area that might have been contaminated with fungal spores. Also, the authors showed that there are high concentrations of airborne microorganisms in other poultry houses with the animals kept on the floor such as turkeys and broilers.

Wang et al. (2000) showed that the dust within livestock buildings has viable microorganisms, fungi and absorbed toxic gases.

Zhang et al. (2005) mentioned that the particles, especially large particles, act as carriers of other air pollutants such as bacteria, viruses, odour and gases.

Bakutis et al. (2004) showed that the dust and microorganisms with different admixture are abundant in the air of livestock houses. On the other side the amount of endotoxins is related to intensive microbial pollution of the environment.

Rosentrater (2004) reported that the dust can carry and promote large aggregations of microorganisms including viruses and bacteria (both gram-positive and gram-negative), especially Salmonella, Staphylococcus, Micrococcus, Endotoxin, and Rotavirus. Dust also harbors odourous substances such as volatile fatty acids, phenols and carbonyl compounds.

Zhu et al. (2005) mentioned that dust particles may carry hayards such as pathogenic bacteria, viruses, endotoxins and other organic substances.

Seedorf and Hartung (2000) reported that the dust particles carry gases, microorganisms, endotoxins and various other substances such as skin cells and manure particles. Animal house dust consists up to 90 % of organic matter. **Takai et al. (1998)** mentioned that the dust particles may carry hazardous material such as pathogenic bacteria, viruses, endotoxin or other organic substances.

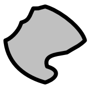
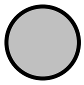
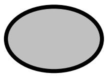
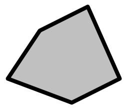
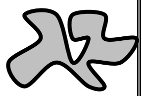
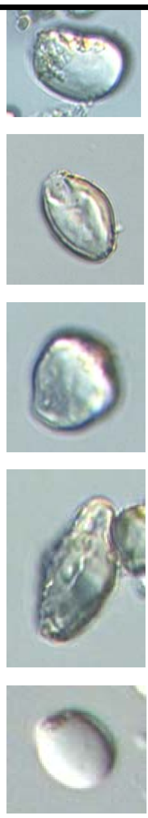
2.2.2.3 Physical properties of dust particles

There are several physical properties of the dust particles but this investigation will concentrate only on the shape and density of the particle matter.

Rosenthal et al. (2007) mentioned that the dust particles are subjected to a variety of physical processes according to their density, size and shape. The most important physical effects as the authors said are sedimentation, agglomeration, aerodynamics, adsorption and resuspension.

Nannen (2005) observed from the microscopic analysis of the dust particles which have been collected from two different fattening pig barns that there are differences in the particle shapes as shown in table 2.5.

Table 2.5: Classification of particle structure after shapes (Nannen 2005)

Shape	Shape1 	Shape 2 	Shape 3 	Shape 4 	Shape 5 	Shape 6 
Beispiele						

Schmitt-Pauksztat (2006) mentioned that there is a strong influence of the particle size, density, surface and shape on the distribution of airborne particles.

2.3 Sources of the dust inside the poultry houses

Wang et al. (1999a) said that the dust in enclosed swine buildings is primarily generated from feed grains, fecal materials, animal skin, hair, insects, and dead micro-organisms which are comprised of viable organic compounds, fungi, endotoxins, absorbed toxic gases and other hazardous agents. **Zhu et al. (2005)** indicated that the dust sources are feed, animal-derived dander, hair, urine, insects and excrements. **Seedorf and Hartung (2000)** mentioned that the dust in animal housing originates from the feed, bedding material and from the animals themselves. A small amount enters the animal house with the incoming ventilation air. **Hinz et al. (1999)** found that the dust concentration in turkey houses with 1.5 birds/m^2 was much lower than in the rooms with 3.5 birds/m^2. Consequently it can be concluded that the animals and their excrements are the main sources of dust in poultry houses.

Hartung and Saleh (2007) showed that the dust particles may originate from feed (80 to 90 %), litter (55 to 68 %), animal surfaces (2 to 12 %), feces (2 to 8 %) and from structural elements in the house such as the walls and floor.

Gustafsson (1997) showed in pig houses that the amount of dust released is proportional both to the number of animals and to their weights. The release of dust also increases with increasing age of chickens as presented in figure 2.3. This fact indicates that a considerable part of the dust can be generated from the animals themselves.

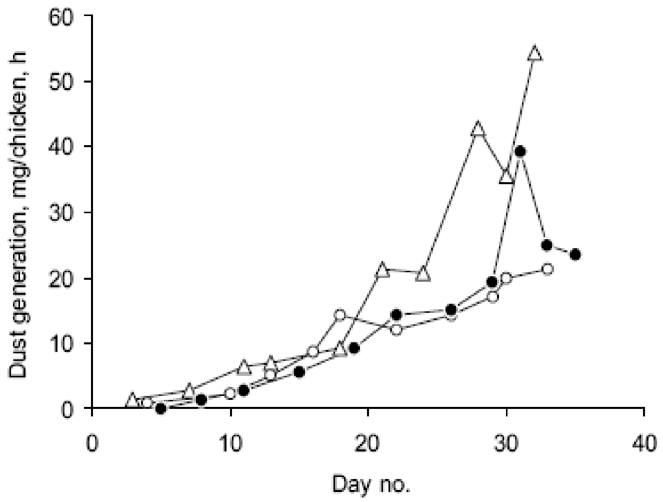


Figure 2.3: Generation of dust at different ages of chickens, determined during three production batches (Gustafsson,1997)

Ellen et al. (2000) performed microscopical analysis to estimate the sources of the dust inside the broiler houses during three weeks by collecting samples from the litter, food, floordust and elsewhere in the house. The results from this microscopical analysis are shown in table 2.6. Down feathers and crystalline dust are the main sources of the dust. The crystalline dust seemed to have originated mainly from urine components.

Table 2.6: Sources of the dust in the broiler houses (Ellen et al., 2000)

Source	Airborne dust	Settled dust
Feed	+/-	+
Down feathers	+++	+++
Excrements	-	+/-
Microorganisms/mould	+/-	+
Crystalline dust	+++	+++

+++ = more than 10 %; + = 1 to 3 %; +/- = < 1 %; - = not found.

Takai et al. (1998) mentioned that the organic dusts in livestock buildings are comprised of grain and other plant-derived particles, animal hair, urine, faeces, microorganisms and other particles. **Robert (2001)** mentioned that the dust in intensive animal housing is primarily composed of feed components and dried fecal material but can also contain dander (hair and skin cells), molds, pollen, grains, mites, insect parts, mineral ash, floor-reared poultry litter and feathers. **Jay et al. (1994)** reported that dusts may be composed of dried fecal material, feed, animal dander, feathers, mold, pollen, grain mites, mineral ash, gram-negative bacteria, endotoxin, microbial proteases, ammonia adsorbed particles and infectious agents.

Aarnink and Ellen (2007) summarized in figure 2.4 the different dust sources in poultry houses, the effect of their attributes, processes and activities leading to dust formation.

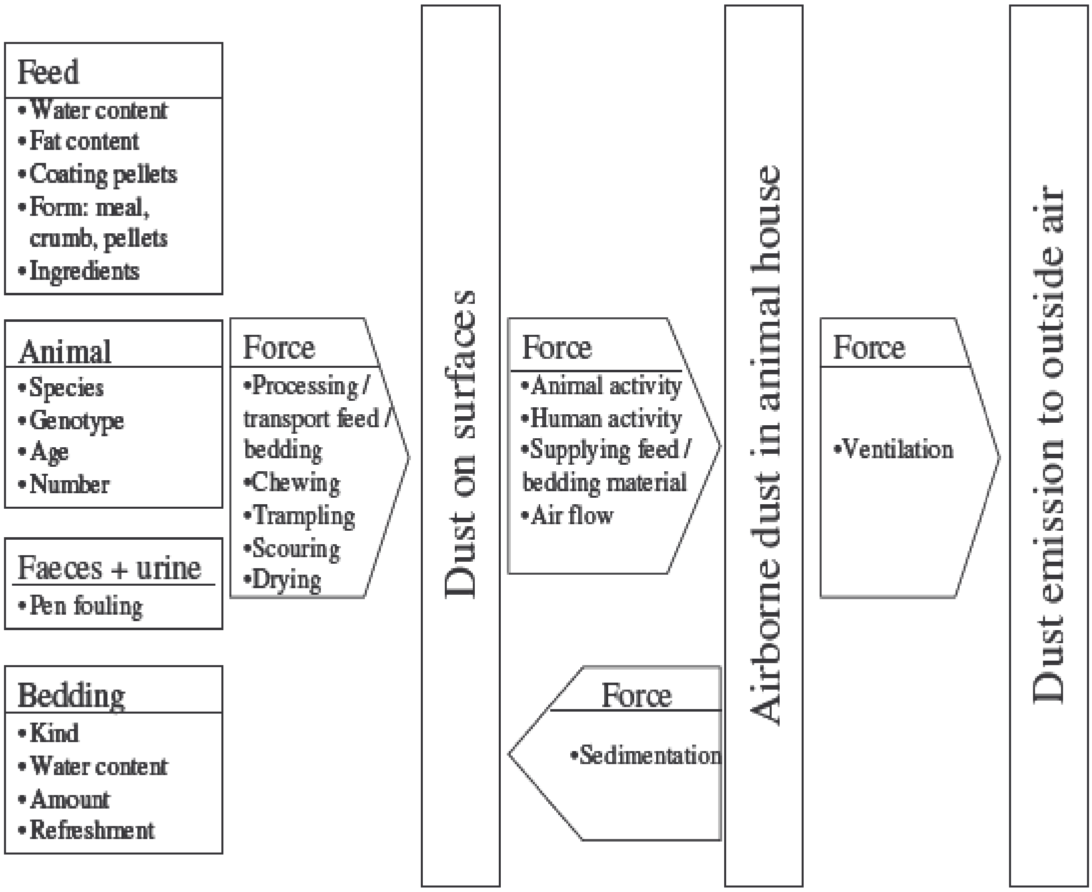


Figure 2.4: Dust sources with attributes, processes and activities (forces) that influence dust formation and dust emission from animal houses (Aarnink and Ellen, 2007)

2.4 Poultry housing systems

Jacky and Lymbery (1999) classified the Laying hen housing systems into:

1. The battery cage system

Rows of metal and wire cages are arranged up to 8 tiers high. Each cage measures 50 x 50 cm in area and up to 5 hens are kept in each one giving a legal (in Europe) minimum space per hen of 450 cm^2. The minimum cage height is 40 cm over 65 % of the cage and 35 cm over the rest. The cage floor is sloping wire mesh and each shed can contain between 10.000 and 90.000 hens, figure 2.5. There are big group cages up to 30 animals per cage.

Figure 2.5: Breeding style with cage system

2. The non-cage systems

1) **Perchery (also called aviary) systems**

Hens are kept in loose flocks in sheds with raised perches or platforms. Littered flooring has to provide 15 cm of perch for each bird and the maximum stocking density is 25 hens per square meter of floor space, figure 2.6.

Figure 2.6: Breeding style with aviary system

2) Deep litter systems

Hens are kept in sheds on the floor and perches are not usually provided. Part of the floor is littered and a part contains a droppings pit covered with wire. The maximum stocking density is 7 hens per square meter of floor space which is 1425 cm^2 per hen, figure 2.7.

Figure 2.7: Breeding style with floor system

3) Free-range system

Hens are kept in perchery or deep litter type houses but have access to the outdoors during the day. They can also be accommodated in small groups in small moveable houses. The maximum density is 1 hen per 10 square meters of outdoor range and the floor must be (mainly covered by vegetation), figure 2.8.

Figure 2.8: Free range breeding system

Martensson and Pehrson (1997) showed that the Battery system for laying hens restricts the movement and behavioural repertoire of the animals. Thus, some countries in north-western Europe have banned it. However, the interior design of the alternative systems must permit the hens to move freely on the floor or on levels of net floor and into the laying nests. This new type of rearing system compared to systems with animals in cages involves a new type of work operations. The authors also investigated the air quality in the alternative systems and found that the concentrations of the dust and endotoxin in these systems are higher than the concentrations in the battery system.

2.5 Indoor dust concentration and emission rate in the poultry buildings

Takai et al. (1998) measured that the concentration of both airborne inhalable and respirable fractions was overall higher in pig and poultry buildings than in cattle houses. Dust concentrations and emissions were affected significantly by several things such as housing type, the season of year and day/night time.

2.5.1 Effect of building style on dust concentrations and emission rates

Takai et al. (1998) measured the inhalable and respirable dust concentrations in the poultry buildings and found that the dust concentrations were 3.60 and 0.45 mg/m^3 respectively. The authors also estimated the dust emission rates on a 500 kg AU in Germany which were 2118 and 248 mg/h for inhalable and respirable respectively. This study also proved that the inhalable and respirable dust concentrations and emission rates in buildings for caged layers were much lower than in percheries.

Nimmermark and Gustafsson (2005) mentioned that the air in floor housing systems for laying hens may be more polluted than in traditional cage systems. Regarding laying hens, floor housing systems are being re-established in Sweden since animal welfare legislation stipulates that systems for laying hens must provide laying nests, perches and access to litter. Compared to traditional cage systems the air in floor housing systems may be more polluted since gases are emitted from large exposed surfaces of manure and litter.

Gustafsson (1997) mentioned that the air pollutants in buildings for laying hens have shown large differences in dust concentrations between cage systems and different alternative housing systems. The concentration of dust is generally higher in alternative systems probably due to increased activity. **Ellen et al. (2000)** mentioned that houses with caged laying hens show the lowest dust concentration with less than 2 mg/m^3 while the dust concentrations in the other housing systems such as perchery and aviary systems were often four or five times higher. **Van der Hoek (2007)** reported the dust emission and dust concentration for poultry houses in Netherlands as shown in table 2.7.

Table 2.7: Effect of breeding system on dust concentration and emission rates (van der Hoek, 2007)

Housing type	Dust concentration, mg/m^3			Vent. rate, m^3/animal/h	PM10 emission, g/animal/h
	TSP	PM_{10}	PM_5		
Laying hens, litter	8.4	3.78	1.25	2.3	7.0
Laying hens, cages	0.68	0.31	0.07	2.3	0.6
Broiler, litter	11.8	5.31	1.14	1.4	7.5

Table 2.7 shows the effect of the housing on dust emission concentration. The highest concentration and emission appeared among animals that are living in the floor system compared to the cage system.

2.5.2 Effect of the year seasons on dust concentrations and emission rates

Takai et al. (1998) measured the inhalable and respirable dust concentrations and found that they were 3.88 & 0.48 mg/m^3 in winter and 3.03 & 0.35 mg/m^3 in summer, respectively. It shows that the inhalable and respirable dust concentrations in poultry buildings were higher in winter than in summer. On the other hand, the mean inhalable dust emission rates in winter and summer were estimated to be 1590 and 2388 mg/h for 500 kg live weight basis, respectively. It shows the mean inhalable dust emission rates were higher in summer than in winter.

Guarino et al. (1999) indicated that the highest concentration of the total dust and respirable fraction in the laying hens houses were during June. This result can be explained by the fact that during this period the birds molted thus, increasing the amount of dust. Moreover, the increased ventilation due to the higher temperatures on the one hand helped extracting dust from the unit but on the other stirred up previously deposited dust. This indicates the enormous importance of the systematic general cleaning of the unit.

Kocaman et al. (2006) measured the dust concentration through the different seasons of the year and found that as shown in table 2.8, the dust concentration was the highest in summer compared to the other seasons.

Table 2.8: Means (±S.D.) of Temp., RH and dust concentration in laying hen houses (Kocaman et al., 2006)

Year season	Temperature, °C	Relative humidity, %	Total dust concentration, mg/m³
Winter	17.67±2.09	72.22±6.65	2.19±0.49
Spring	18.38±2.18	67.00±6.75	2.24±0.43
Summer	22.38±2.87	60.46±8.29	2.34±0.37
Autumn	19.92±8.77	66.58±8.77	2.02±0.39

David et al. (2002) measured the inhalable and respirable dust concentration in turkey houses as shown in table 2.9.

Table 2.9: Dust concentrations in turkey houses (David et al., 2002)

season	Mean total, (mg/m^3)	Mean inhalable, mg/m^3	Mean respirable, mg/m^3	Mean PM_{10}, mg/m^3
Winter	4.26	3.54	0.51	1.11
Summer	2.41	2.46	0.11	0.33

Table 2.9 proved the increase in inhalable and respirable dust concentrations in winter compared to summer. The authors also estimated the inhalable and respirable dust emission rates for 500 kg live weight in turkey houses as shown in table 2.10. The dust emission rates showed a higher level in summer than in winter with both inhalable and respirable dust.

Table 2.10: Inhalable and respirable dust emission in turkey houses (David et al., 2002)

season	Mean inhalable, mg/h	Mean respirable, mg/h
Average winter	413	59
Average summer	9628	332

Redwine et al. (2002) showed that the dust emission rates in the poultry building (27.500 birds) were high in the summer period compared to the winter period. The dust emission rates in summer ranged between 3.7 to 99 g/h but in the winter ranged between 0.58 to 57 g/h. **Hinz et al. (1999)** found that the dust concentration level in the winter period was at least higher than in summer, but never exceeded 6 mg/m^3. **Zhu et al. (2005)** proved that the mean airborne dust concentration in a swine gestation house was higher in cold weather than in warm weather. The average airborne dust concentration was 4.20 – 4.70 mg/m^3 in cold weather and 2.18 – 2.20 mg/m^3 in warm weather. The low level of dust concentration in warmer seasons was related to the high humidity and high exhausted ventilation. **Golbabaei and Islami (2000)** investigated the exposure of the workers to the total and respirable dust through the summer and winter season in both open and enclosed systems as shown in table 2.11.

Table 2.11: Means and standard deviations of poultry workers' exposure to total and respirable dust in poultry houses, mg/m^3 (Golbabaei and Islami, 2000)

Type of poultry		Summer				Winter	
		Open system		Enclosed system		Enclosed system	
		TSD	RD	TSD	RD	TSD	RD
Parent stock		**7.1±1.6**	**2.3±0.9**	**19.7±5.2**	**2.4±0.8**	**21.3±3.2**	**4.6±0.9**
Broiler		**4.2±0.5**	**1.6±0.2**			**3.7±0.4**	**2.2±0.2**
Laying hens		**10.5±1.7**	**1.7+0.8**	**15.0±3.6**	**2.3±0.8**	**15.8±1.4**	**2.5±0.6**
Control	With litter					**3.1±0.8**	**1.4±0.2**
	Without litter					**1.1±0.2**	**0.5±0.1**

The exposure of workers in the enclosed system parent stock barns in winter to total and respirable dust has been the highest as it exceeded the Danish Occupational Limit (OEL) of 3 mg/m^3 for organic dust by at least a factor of six.

Nannen and Büscher (2007 b) showed the particle mass concentration during the different seasons and air volume flow in two different fattening pig farms as shown in figure 2.9.

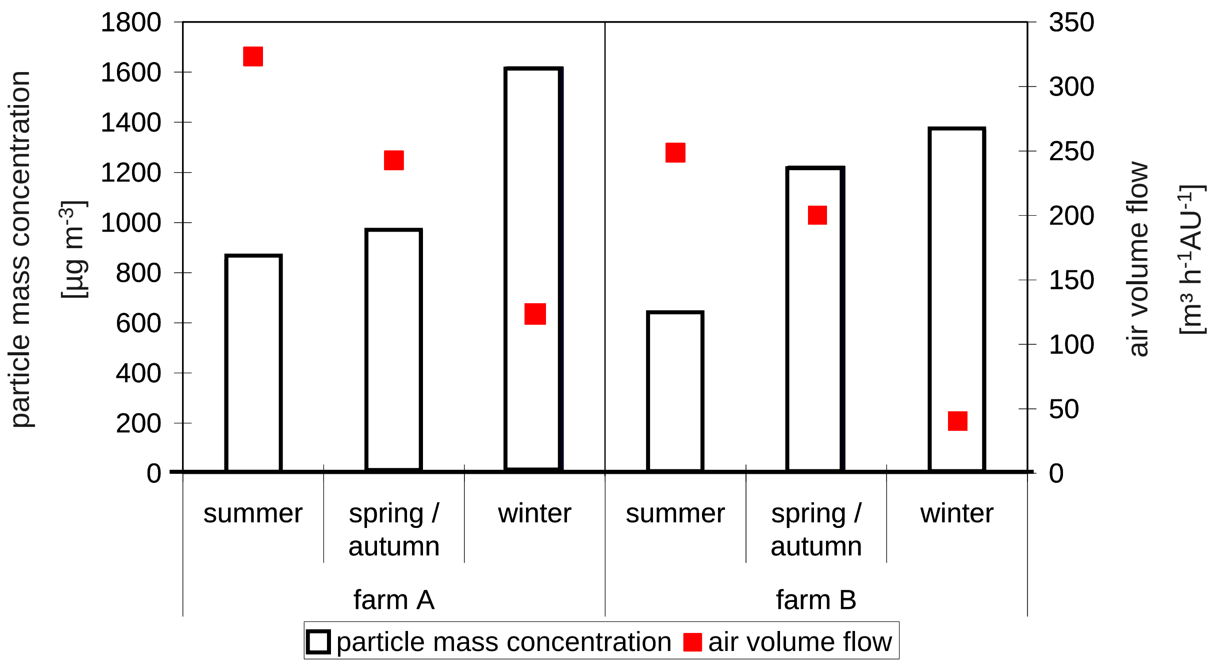


Figure 2.9: Particle mass concentration and air volume flow during different seasons of the year in two different pig farms (Nannen and Büscher, 2007 b)

Costa et al. (2007) measured the dust concentration and dust emission in a piggery with different rooms (wearing, pregnancy, farrowing and fattening) during different seasons (winter, summer and spring). PM_{10} concentration was monitored by a sampler either continuously or through traditional gravimetric technique and the mean value of the amount of dust collected on the membranes was utilized as a correction factor to be applied to the continuously collected data. The results of these measurements have been summarized in table 2.12.

Table 2.12: Data collected during different year seasons in piggery (Costa et al., 2007)

	Weaning room			Farrowing room			Fattening room			Pregnancy room		
	Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring	Summer
Nr. of animals	345	332	336	352	350	355	345	343	343	42	37	42
Internal mean temp.(ºC)	23.05	26.55	25.19	21.34	23.42	26	18.7	27	27.51	16.15	17	16.09
Internal relative Hum. (%)	43.27	51	50	37.14	48.71	48.51	71.13	57	56.89	73.85	67	53.24
External mean temp. (ºC)	3.81	16.43	14.46	3.06	11.88	23	7.11	24	24.39	3.13	8	24.39
External relative hum. (%)	80.74	70.87	72	52.35	69.96	69	69.45	55	55.5	73.37	67	55.5
Air volume flow (m^3/h)	4246	2810	5303	2873	5207	7167	7905	30692	27910	815	1615	4879
Dust conc. (mg/m^3)	0.123	0.089	0.11	0.322	0.165	0.108	0.423	0.121	0.146	0.321	0.315	0.30
PM_{10} emission with external dust (mg/h.LU)	8.8	15.2	7.1	125.8	56.06	32.95	28.15	79.85	40.875	23.8	24.9	31.75
PM_{10} emission without external dust (mg/h.LU)	19.6	18.05	42.6	154.05	65.15	58.65	54.35	132.6	89.5	40.5	34.35	87.4
PM_{10} emission corrected to gravimetric method (mg/h.LU)	20.38	18.77	44.30	147.89	62.54	58.65	63.58	155.14	104.7	38.47	32.63	83.03
Mean yearly PM_{10} factor (mg/h.LU)	27.81			88.91			107.81			51.37		
Mean yearly PM_{10} factor (g/d.LU)	0.67			2.13			2.59			1.23		

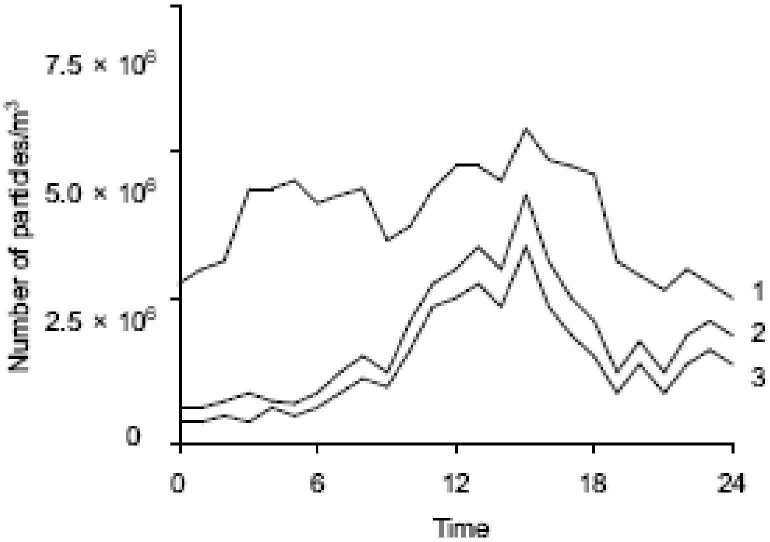
2.5.3 Effect of diurnal change and animal activity on dust concentration and emission rates

Hessel and Van den Weghe (2007) determined the influence of the daytime on the concentration of airborne dust (PM_{10}) in a commercial broiler house. The dust concentrations were twice as high during the light period (5542 µg/m³) compared to the dark period (2598 µg/m³). Concerning the diurnal dust concentrations highest concentrations were measured at 5:00 O'clock (8487 µg/m³). The lowest dust concentrations were found at 14:00 O'clock (1688 µg/m³). **Takai et al. (1998)** mentioned that there is a clear difference between day and night in percheries and caged layers buildings for inhalable and respirable dust concentrations as shown in table 2.13. Table 2.13 proves that the inhalable dust concentrations in percheries and buildings for caged layers were higher during the day than at night.

Table 2.13: Expected mean inhalable dust concentrations concentration in poultry buildings (Takai et al., 1998)

Sampling period	Housing	Inhalable dust concentration		
		Concentration (mg/m³)	Transformed mean concentration	Standard error
Day	Layers, perchery	7.33	1.99	0.108
	Layers, cage	1.51	0.41	0.110
Night	Layers, perchery	2.82	1.04	0.108
	Layers, cage	0.82	-0.15	0.110

Gustafsson (1997) observed the variation in number of different sized particles during the day with constant ventilation rate in a building for growing - finishing pigs which is presented in figure 2.10. The figure clearly shows an increase in the dust particle number during daytime when the activity is higher than at night. Similar situations have been observed with poultry. **Mitchell et al. (2004)** found that the dust levels in poultry houses were consistently low during the nighttime hours and highest during the afternoon suggesting a correlation to bird activity. **Lim et al. (2003)** measured PM_{10}, $PM_{2.5}$ and TSP during the whole day as presented in table 2.14.



Line 1. Particle size 0.5–1.0 µm, **Line 2**. Particle size 1.0–2.0 µm, **Line 3**.Particle size 2.0–5.0 µm

Figure 2.10: Daily variation in the number of dust particles at constant ventilation rate (75 m^3/pig,h) in a building for growing - finishing pigs (Gustafsson, 1997)

Table 2.14: Particulate matter concentration and emission in laying hen houses (Lim et al., 2003)

Sampling period	**Dust concentration, µg/m^3**			**Dust emission rates, mg/s**		
	PM_{10}	**$PM_{2.5}$**	**TPS**	**PM_{10}**	**$PM_{2.5}$**	**TPS**
Day	611±44	47±7.7	2268±718	179±27	13±2.5	719±133
Night	293±103	19±8.7	961±214	293±103	3.7±2.4	192±71
24-hr mean	518±74	39±8.0	1887±563	143±31	10±2.5	566±139

The large diurnal variations occurred as shown in figure 2.11, mean daytime concentrations were 2.51, 2.08, and 2.36 times higher than at night for $PM_{2.5}$, PM_{10}, and TSP, respectively. The combination of increased animal activitiy, operation of feed delivery equipment and worker activity (floor and equipment cleaning, etc.) were apparent causes of higher daytime concentrations.

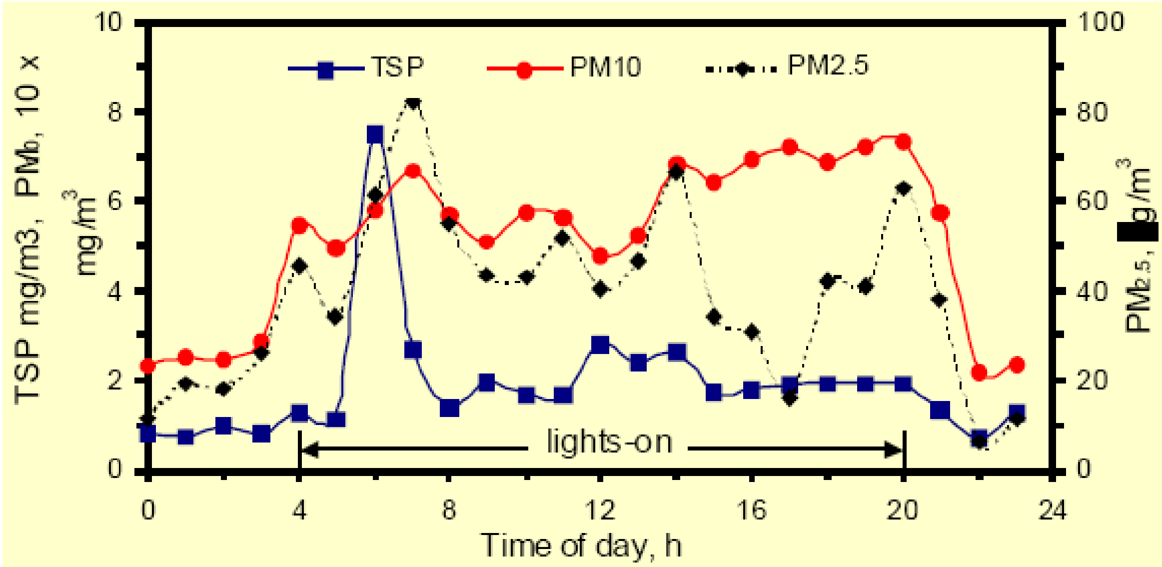


Figure 2.11: Average time-of-day hourly mean PM concentrations in laying hen houses (Lim et al., 2003)

Nannen and Büscher (2007 b) correlated between animal activity and particle mass concentration from the experiments which have been done in a piggery. As shown in figure 2.12, the dust emission increases drastically during the periods of animal activity.

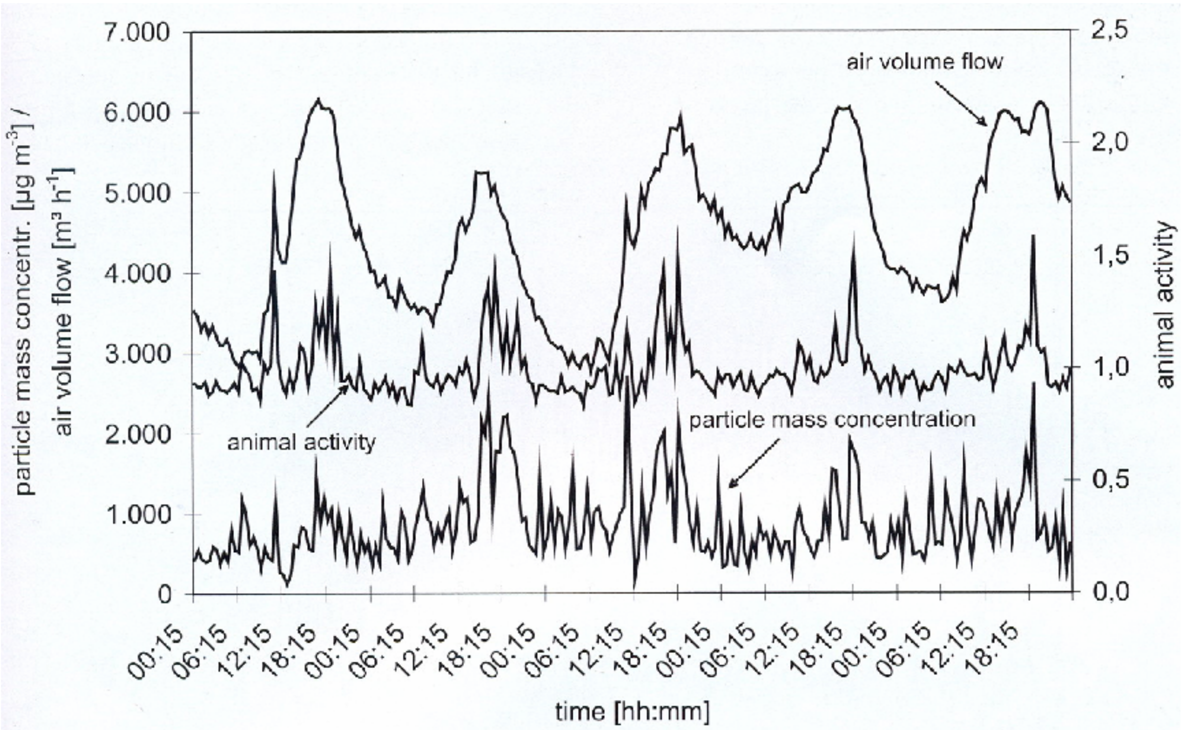
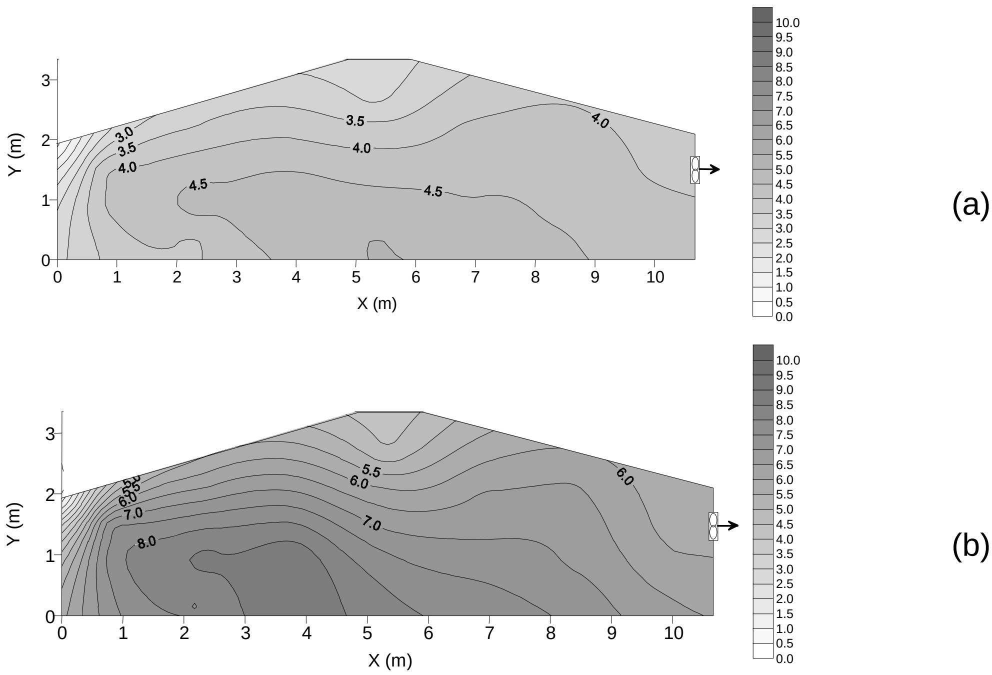


Figure 2.12: Particle mass concentration, air volume flow and animal activity (Nannen and Büscher, 2007 b)

Wang et al., (1999a) showed the spatial dust concentration changes with the diurnal change where as shown in figure 2.13 in a typical swine building. The measured spatial dust concentration show that the overall dust level during the daytime was much higher than during the night-time even though the daytime had a higher ventilation rate. This figure shows that there is a large variation in the overall dust level with the diurnal change. This overall dust level during day-time is much higher than during night-time likely due to the animal activity which changed the airborne dust production.



(a) Night-time in control room, average dust mass concentration in the entire room = 4.23 mg/m^3
(b) Day-time in control room, average dust mass concentration in the entire room = 7.14 mg/m^3

Figure 2.13: Iso-concentration lines of dust in a typical swing room (Wang et al., 1999a)

Hinz et al. (1999) found that the dust concentrations in force ventilated compartments for turkey production were up to five times higher during the day-time (light on) than at night-time (light off) as shown in figure 2.14.

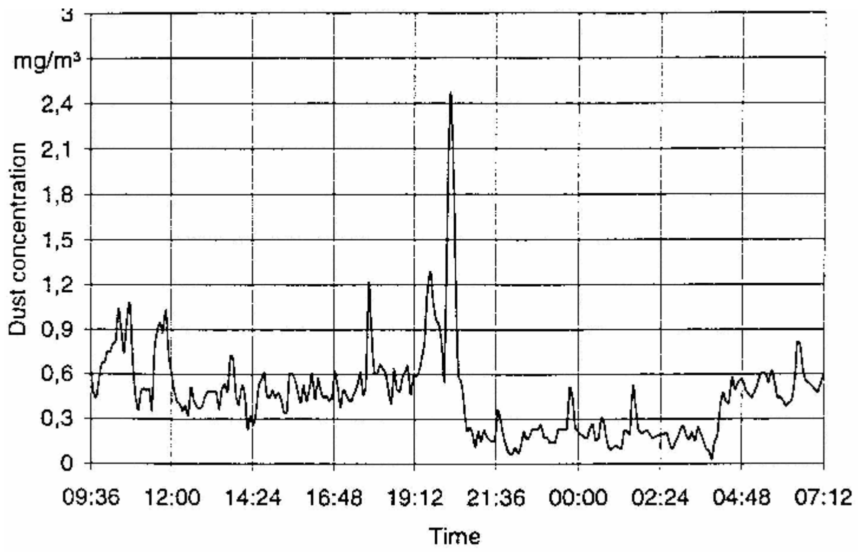
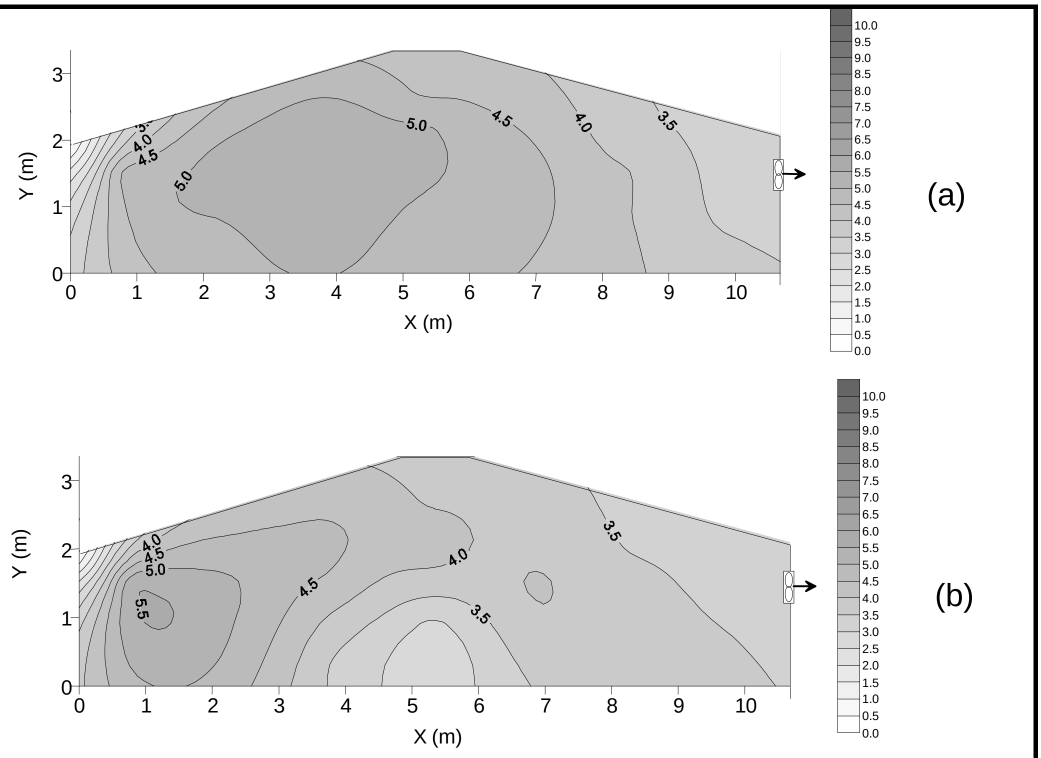


Figure 2.14: Dust concentration over the day in a turkey house (Hinz et al., 1999)

2.5.4 Effect of ventilation rate on dust concentrations

Pedersen et al. (2000) reported that there is a high variation in the pattern of spatial dust distribution in mechanically ventilated pig buildings. Thus, the ventilation systems have direct effects on the spatial dust concentration whereas the increase of the ventilation rate will not necessarily reduce the overall dust level effectivel because the dust production rate will increase with increasing ventilation.

Wang et al., (1999a) explained that the ventilation has an effect on the control and dilution of gaseous contaminants. It also has been widely believed that ventilation systems have a direct effect on the spatial dust concentration, where the ventilation will remove the dust from the airspace but at the same time ventilation may increase air movement and stir up dust and keep it in the air. Therefore, the authors measured the effect of ventilation on dust concentration using two systems (low ventilation rate at 26 % fan duty cycle and high ventilation rate at 68 % fan duty cycle) as shown in figure 2.15.



(a) Low ventilation rate, average dust mass concentration in the entire room = 4.56 mg/m^3
(b) High ventilation rate, average dust mass concentration in the entire room = 4.05 mg/m^3

Figure 2.15: Effect of ventilation rate on spatial dust concentration in a typical swing room (Wang et al., 1999a)

As observed from the figure 2.15, with the low ventilation rate there was a zone of higher dust concentration next to the feeder and dust was more symmetrically distributed across the swine building section. However with the high ventilation rate there is a zone of high dust concentration near the air inlet side which could be a dead ventilation zone. However, the measured overall average dust mass concentration had little difference between these two cases. Although the ventilation rate in the second case was 2.6 times higher than in the first case it refers to the increase of the dust production rate with the increase of the ventilation rate. This verifies that the ventilation rate has less effect on the overall dust removal. Therefore, the authors concluded that the ventilation system has a direct effect on the spatial dust concentration. Despite this increase of ventilation rate does not effectively reduce the overall dust level because the dust production rate increased with an increase of ventilation rate.

Redwine et al. (2002) compared the results of respirable dust concentration between European countries and the state of Texas in the USA and found that the dust concentration in European countries ranges in the literature from 0.4 to 9.7 mg/m^3, on the other side, the authors also measured the dust concentration in Texas and found it ranges from 0.1 to 0.3 mg/m^3, which is slightly less than comparable data from European studies. These results return to the warm climate of Texas as mentioned by the authors. This warmer climate requires a higher ventilation rate and the use of evaporative cooling systems. A higher ventilation rate may dilute the dust concentration and the evaporative coolers may suppress dust emission rates by maintaining a higher relative humidity in livestock buildings.

Gustafsson (1997) recommended increasing the ventilation rate as a method for reducing the concentration of air pollution in buildings. Unfortunately, the ventilation rate has a limited diluting effect on the total mass of dust at those ventilation rates recommended for insulated animal houses in temperate areas. The reason is that the settling of dust on different surfaces is a more important mechanism for removing large dust particles from the air than the ventilation rate. Figure 2.16 shows the effect of different ventilation rates on total dust concentration in a building for growing - finishing pigs. It should be noted that dilution of the dust by increased ventilation will increase the heating requirement in wintertime in temperate regions. The author observed almost the same results for laying hens. Measurements of the number of different sized particles in a pig house have indicated that increased ventilation rate mainly reduces the number of particles larger than 1.0 µm and had only a limited effect on the number of particles smaller than 1.0 µm.

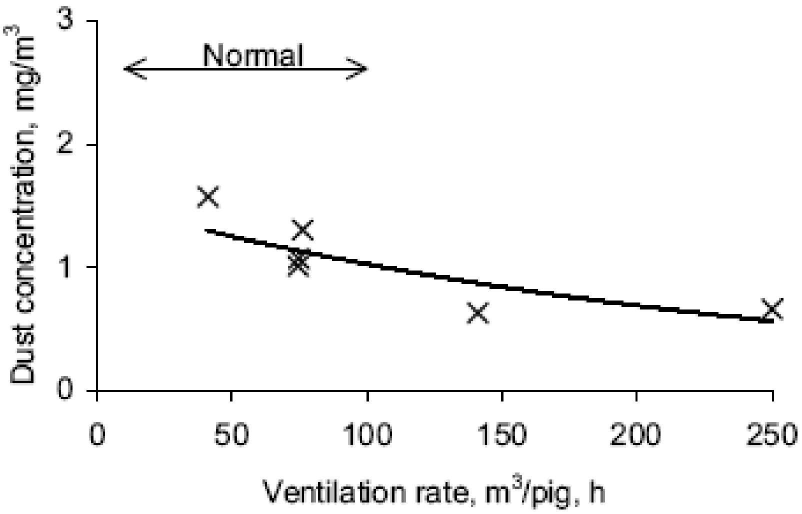


Figure 2.16: The influence of ventilation rate on total dust concentration in a building for growing - finishing pigs with an average body weight of 67.0 kg (Gustafsson, 1997)

2.6 Quantifications of dust concentration

2.6.1 Planning and preparation of the measurements

According to **(VDI 2066, 1975)** placement of the equipment and accessibility of the test points affect the dust determination. In new installations the requirements of the measuring sections and test points must be considered in the planning stage. These requirements are as following:

1. The flow in the measuring sections should be as undisturbed as possible.
2. The measurement cross section should be placed within a straight measuring section and have an inlet and outlet free of any interference.
3. The length of the inlet and outlet sections should be at least three times the hydraulic diameter of the measuring cross section.
4. The test place should be easily accessible by the measuring staff and for transport of the instruments.
5. The test place should be protected against external effects (rain, wind, heat, etc.) and it must comply with the accident prevention regulations.

2.6.2 Dust concentration measuring methods

The determination of dust concentrations with the help of filters has been explained by **VDI 2066 (1975) and VDI 2463 (1999).** Different procedures for measuring the particles in gases or liquids such as the Coulter Counter have been explained by **Cox and Wathes (1995).**

Schmitt-Pauksztat (2006) explained the different procedures to measure the dust concentration such as:

1. Aerodynamic procedures
   - Elutriator
   - Inertia impactor
   - Particle size analysis
2. Optical procedures
   - Mie theory
   - Laser particle counter
   - White light method
   - Influence of the particles form and structure

Gustafsson (1997) measured the dust concentration using the following methods:

1. Gravimetic measurements of the amount of total dust (mg/m^3) with 37 mm diameter Millipore filters at a flow rate of 1.9 l/min.

2. Gravimetric measurements of the amount of respirable dust (mg/m^3) with a millipore filter after separation of larger particles with a SKC cyclone.

3. Counting the number of different sized particles with a Rion optical particle counter.

4. Weighing the settled dust on 0.230 m^2 settling plates.

5. Measuring the ventilation rate with an Alnor hot wire anemometer in the exhaust air ducts.

Lim et al. (2003) measured the particulate matter (PM) in the ventilation exhaust air in a caged layer house using a tapered element oscillating microbalance (TEOM). The instrument draws aerosol through an exchangeable filter attached to a hollow tapered oscillating glass rod at a constant flow rate. The real-time PM concentration is based on a sample flow rate coupled with gains in mass on the filter measured by its effect on the oscillation frequency. Each TEOM system consists of controller and sensor units as shown in figure 2.17. The sensor unit contains a mass transducer and is heated to 50 °C to minimize moisture effects. The PM_{10} sample inlet is attached to the sensor unit and can be replaced with $PM_{2.5}$ inlets. Sample flow is split isokinetically into a main flow passing through the filter and a bypass flow each controlled by a mass flow controller.

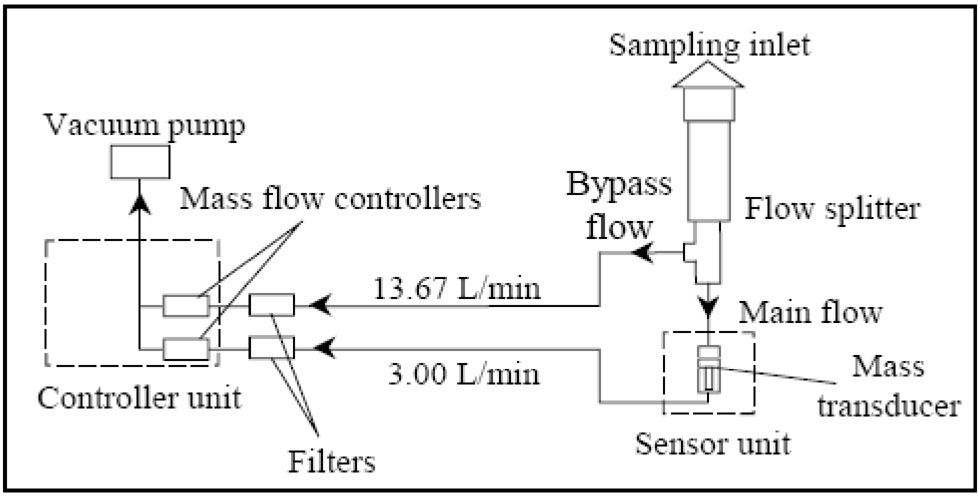


Figure 2.17: Schematic layout diagram of the tapered element oscillating microbalance (Lim et al., 2003)

Kosch et al. (2005) measured the total suspended dust (TSP) with a tapered element oscillating microbalance (TEOM 1400a). This equipment allows continuous gravimetrical data recording at a sampling point.

Zhu et al. (2005) determined total suspended particles using gravimetric measurement methods. The dust sampler used was a double air channel and timer dust sampler, Total dust was sampled using a 40 mm glass fibre filter.

Wang et al. (2000) and Wang et al. (1999a) developed a multi-point dust sampler to measure the spatial dust distribution at different ventilation rates in a mechanically ventilated airspace using an array of critical venturi orifices for controlling the airflow rate at each sampling point. A conceptual design of the multi-point sampler is shown in figure 2.18. It consists of a commercially available vacuum pump, a pressure monitor, a pressure regulator, an array of filter holders, filters, critical venturi orifices and sampling heads. When air is drawn through the sampling head and the filter the volumetric flow rate remains constant for all venturi orifices even though the pressure may vary as long as the pressure across the venturi orifices is higher than the critical pressure drop. Since the critical pressure drop of the venturi was below 11 kPa, the pump operated at a sufficiently high vacuum (approximately 35 kPa) and a constant flow through the filters was maintained. This multi-point sampler was used in this study to measure the dust mass concentration in a cross-section of the ventilated airspace.

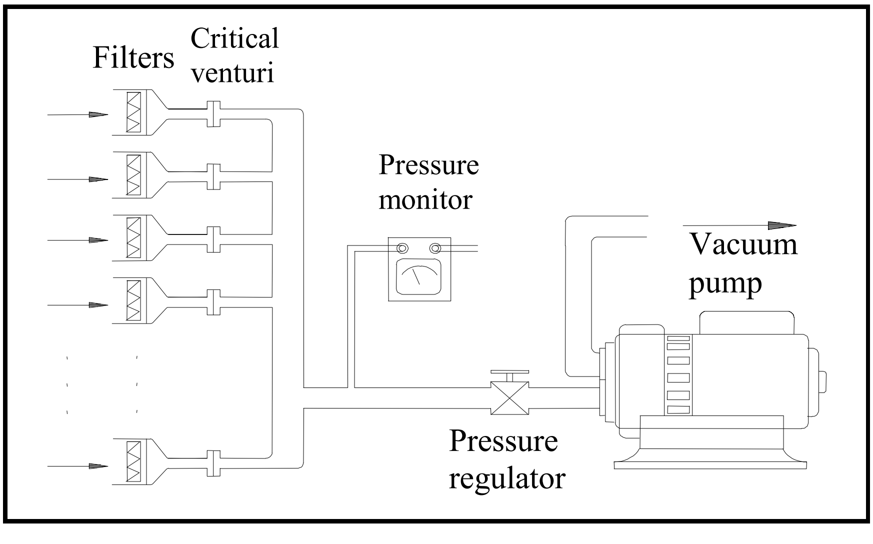


Figure 2.18: A schematic diagram of the multi-point dust sampler (Wang et al., 2000 and Wang et al., 1999a)

The results showed that there is a high variation in the spatial dust concentration within the mechanically ventilated buildings.

Mölter and Schmidt (2007) explained the technical set-up and measuring method of Optical Aerosol Spectrometers (OAS) including the device characteristics. The set-up principle of an OAS in forward scattering is presented in figure 2.19.

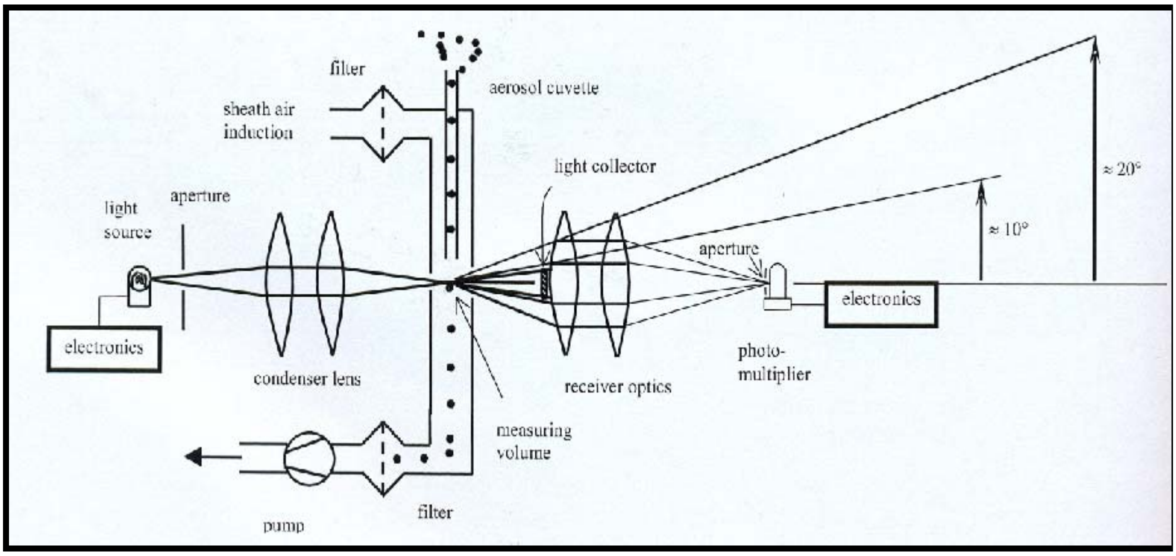


Figure 2.19: Optical aerosol spectrometer (Mölter and Schmidt, 2007)

During forward scattering, the light scattered by particles as shown in figure 2.20 towards 180º is collected by the light source with a light sensitive detector, e.g. a photomultiplier. At the 90º scattered light detection the photomultiplier is attached orthogonally to the image plane.

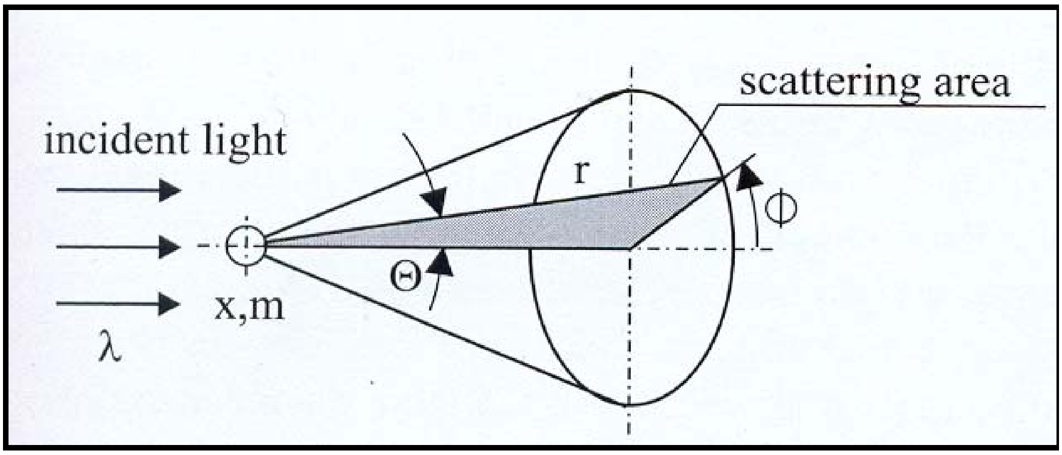


Figure 2.20: Principle of incident light scattering (Mölter and Schmidt, 2007)

The height of the scattered light impulse is a measure for the particle diameter, while the number of impulses supplies the information on the concentration since the volume flow is known. With the help of a lens system the light is focused on the desired measuring volume size. Before the receiver optics a light collector in forward scattering must be installed. This protects the light detector against direct irradiation. Due to diffraction actions of the light and of the scattered light the light collector leads to an ambiguous calibration curve also when using white light. However, a source of white light in connection with a 90º scattered light detection secures a clear calibration curve for many refractive indices.

Predicala and Maghirang (2004) evaluated the measurement of the emission rates of particulate matter from mechanically ventilated livestock buildings in the laboratory, using a test chamber and at the exhaust duct, using three air sampling methods:

- **Low-volume traverse under isokinetic conditions.**

This method used a sampling head with a 14 mm probe inlet diameter and a 37 mm filter assembly, as shown in figure 2.21a. The sampling head was attached to a 0.80 m long rigid tube which was connected by flexible tubing to a flow meter with a flow control and a vacuum pump. The sampling flow rate was adjusted to isokinetic condition. Isokinetic sampling was achieved by varying the sampling flow rate to match the air velocity at the inlet plane of the sampler with the air stream velocity outside the sampler. The required sampling flow rates for isokinetic sampling were determined by conducting a velocity traverse at the sampling plane prior to sampling.

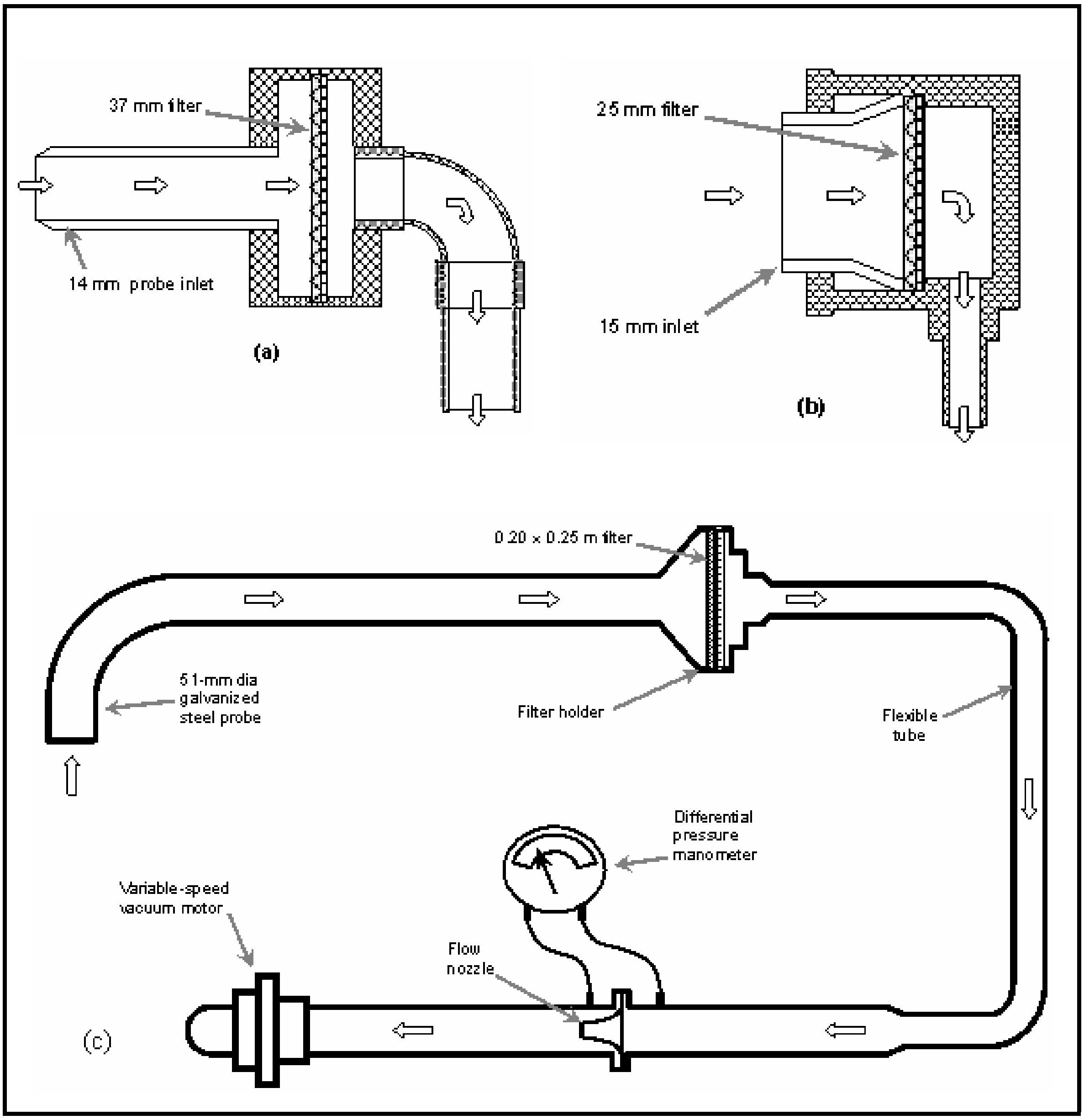
- **Fixed sampling at specific locations within the duct cross-section.**

This method used a 14 mm sampler and an Institute for Occupational Medicine (IOM) sampler, as shown in figure 2.21b. The 14 mm sampler was similar to that in the low-vol traverse method, while the IOM sampler was a commercially available inhalable PM sampler, operated under either isokinetic conditions or at the recommended flow rate of 2 l/min (sub-isokinetic sampling). The IOM sampler was typically used to assess occupational worker exposure in livestock buildings; thus, its possible application for measuring PM concentrations to determine PM emission rates was investigated. Sampling was sub-isokinetic when the actual sampling flow rate was lower than the required isokinetic sampling flow rate. A velocity traverse was also conducted prior to sampling to determine the required isokinetic sampling flow rate.

- **Hi-volume traverse under isokinetic conditions.**

This method is considered as the reference method for this study. The sampling train consisted of a 51 mm diameter probe, a 0.20 x 0.25 m filter holder, a flow nozzle and a variable-speed vacuum motor presented in figure 2.21c. Similar to the low-vol traverse method PM was also extracted isokinetically at specified sampling locations within the sampling plane. The sampling flow rate indicated by the differential pressure across the flow nozzle was adjusted by varying the speed of the vacuum motor. After sampling, the probe and the front part of the filter holder were rinsed with acetone to collect the PM deposited along the probe and filter holder walls. The acetone was allowed to evaporate and the residual PM was added to the PM mass collected on the filter. The sampling duration at each traverse point was determined by preliminary tests so the total collected PM mass was at least 100 mg.

The low-volume traverse and fixed sampling under isokinetic conditions agreed well with the high-volume traverse (mean difference ranging from 7 % to 14 %). Methods involving room sampling, fixed sampling at exhaust and high-volume traverse at exhaust were also compared in a swine finishing barn. Room sampling overestimated concentrations at the exhaust by an average of 30 % and PM concentration from fixed sampling did not differ significantly ($p > 0.05$) compared to the high-volume traverse method. It appears that fixed sampling under isokinetic conditions can be used as an alternative to the high-volume PM traverse method to accurately measure PM concentrations at the exhaust from which the PM emission rate can be determined.



a) The low-volume traverse method
b) The fixed sampling method
c) The high-volume sampling train

Figure 2.21: Schematic diagram of three air sampling methods (Predicala and Maghirang, 2004)

2.7 Means for reduction of dust in/from animal houses

Aarnink and Ellen (2007) summarized the most perspective options to reduce dust concentration and emission for animal houses as shown in table 2.15.

Table 2.15: Summery of most perspecive options to reduce dust emissions from animal houses (Aarnink and Ellen, 2007)

Option	Species	Estimated dust reduction
1. Sources approach:		
• Feed		
o Liquid feed	Pigs	-10-20 %
o Improved pellets	Pigs	10-20 %
o Coating pellets	Pigs	10-20 %
• Feces + Urine		
o Reducing pen fouling	Pigs	10-20 %
• Bedding		
o Kind	All	10-20 %
o De-dusted	All	10 %
o Refreshment	All	30-50 %
2. prevent dust formation		
• Prevent drying of faeces + Urine	Poultry	10-30 %
• Improve processes for making and transporting feed and straw	All	10 %
3. Prevent dust to become airborne		
• Reduce activity	Poultry, Pigs	10-30 %
• Improve feeding system	Poultry, Pigs	10-20 %
• Oil in animal	Pigs	60-80 %
• Spraying oil	Poultry, Pigs	50-90 %
• Spraying water	Poultry, Pigs	30-50 %
• Big layer of bedding material	All	30-70 %
• Optimal pen design	Pigs	20-40 %
4. prevent dust emission		
• Internal air cleaning		

Option	Species	Estimated dust reduction
o Filter	Poultry, Pigs	30-50 %
o Electrostatic filter	Poultry, Pigs	10-50 %
• External air cleaning		
o Scrubber	Poultry, Pigs	70-90 %
o Bio-filter	Poultry, Pigs	70 %
o Filter	Poultry, Pigs	95 %
o Electrostatic filter	Poultry, Pigs	20-70 %
o Water curtain/ Mist of water	Poultry, Pigs	20-40 %

Zhang et al. (2001) showed several methods for dust control. Such methods include spraying or sprinkling oil or oil-soap solution in the airspace accelerating dust sedimentation onto the floor by investigating the air ionization systems and separating dust from the air stream with air cleaning devices and ventilation. The authors also showed a number of mechanical methods for dust control. These methods include fiber filters, water or oil scrubbers, electrostatic precipitators and traditional cyclones (more particles smaller than 10 microns can't be separated by the conventional cyclones because of the strong turbulence associated with the high pressure typically higher than 500 Pa) but these methods may be associated with the ventilation system in the barns**.**

There are different methods used to reduce the indoor concentration and dust emission rate as following:

2.7.1 Dust Suppression with spraying oil and /or water

Aarnink and Ellen (2007), and Pedersen et al. (2000), showed the effect of reducing dust by spraying a mixture of oil and water. This method proved to be very effective to reduce dust in animal houses at relatively low costs. The main effect of oil/water spraying is preventing dust on surfaces to become airborne (again). With a good design dust reduction could be reach up to 90 %.When designing the system the following is important to be considered:

- Oil concentration should be at least 20 %. With this concentration the relative humidity inside the animal house slightly increased (< 2 %).

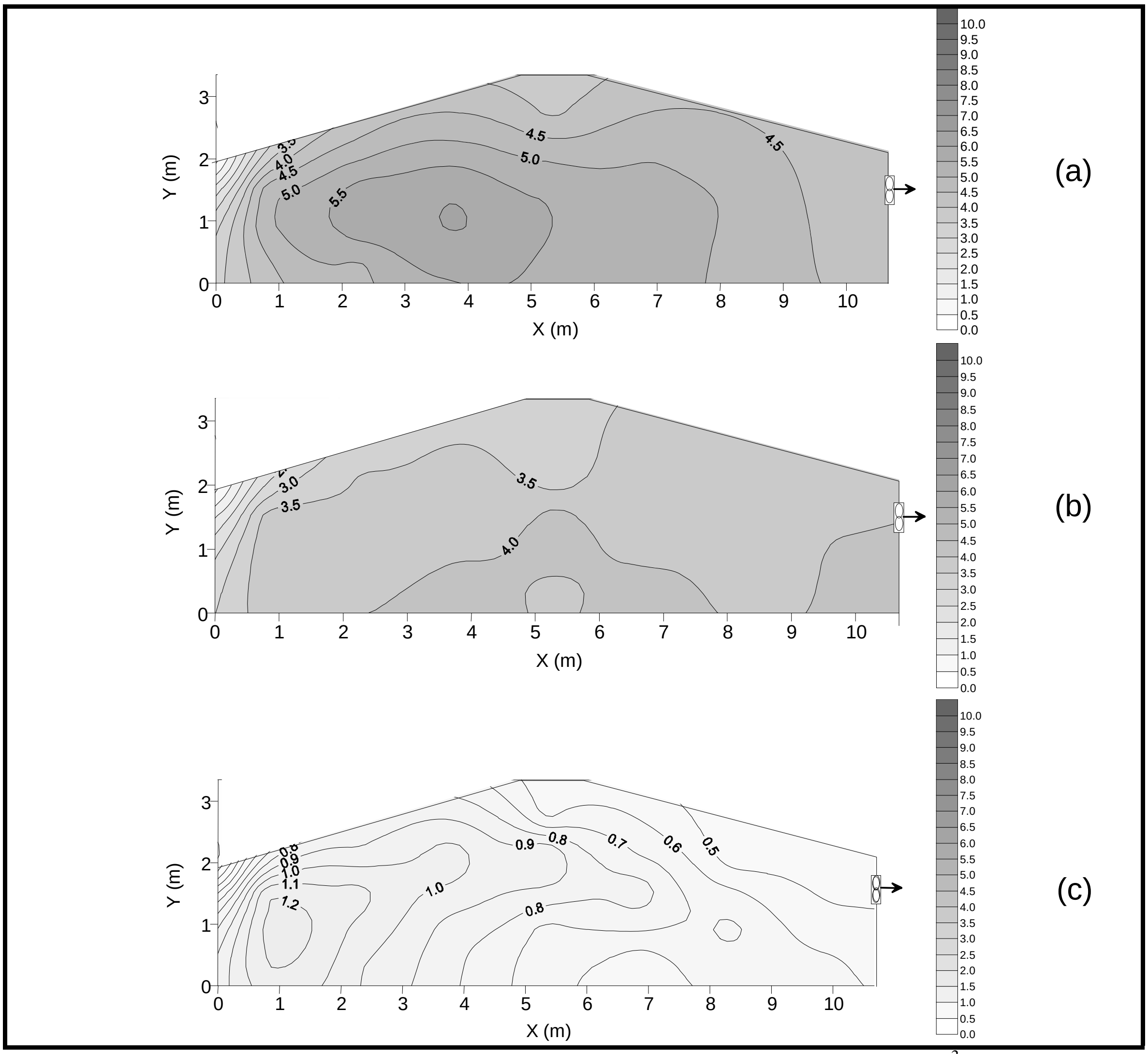
- Oil drops should be bigger than 150 µm to descend to the floor at a fast speed to increase efficiency. Furthermore, small droplets might affect the respiratory health of animals and humans when the small droplets are inhaled.
- Generally, all kinds of vegetable oils can be used although some remarks have to be made:
    - It is not necessary to use purified oil however the oil should be free of particles.
    - Oil with a strong odour is less suitable because of possible effects on animal behaviour.
    - Oil should contain a low concentration of Iodine.
- The dust binding effect of the oil is long lasting (some days). Frequent spraying is needed.

Ullman et al. (2004) used oil applications on the feeding materials for reducing dust concentrations by livestock industries in the Midwest and Canada. A variety of vegetable oils including canola, corn, sunflower, flax, soybean and rapeseed oils along with mineral oils have been used to control dust from feed sources and building floors. Soybean oil reduced dust counts by as much as 99 % following 0.5, 1.0 and 2.0 % additions to dry feed. Similar findings were obtained by the researchers of **Ullman et al. (2004)**, **Pedersen et al. (2000) and Takai (2007).** Although oil sprayed on birds is not recommended and application would be an incompatible practice with broiler rearing. Due to high bird density oil sprinkling may still hold promise as an effective dust control technique.

Takai (2007) focused on the technical parameters regarding the spraying of oil-water mixtures on surfaces in pig buildings to enable consistent dust reduction efficiency with the least possible oil application rate. The results have led to the following conclusions:

1. Number of treatments within the range of 1 and 14 per day does not have an influence on dust reduction efficiency.
2. Oil concentration in the oil-water mixture should be higher than 20 %.
3. Droplet diameter should be greater than 150 µm.
4. Further development of methods to prevent plugging in the spray system is desired.

Wang et al. (1999a) studied the reduction of dust concentration by suppressing the dust source using oil sprinkling in swine barns. The measurement of dust spatial concentrations with oil sprinkling treatment showed that the overall dust level is much lower than in the control room. This indicates that oil sprinkling at regular frequency can significantly reduce the dust level and also reduces most of the large sized particles, figure 2.22 c. The authors concluded that the clean air can reduce the dust level. To improve the overall dust removal efficiency it requires a large flow rate of the de-dusters. On the other side, the oil sprinkling at regular frequency is an effective measure to control the dust level.

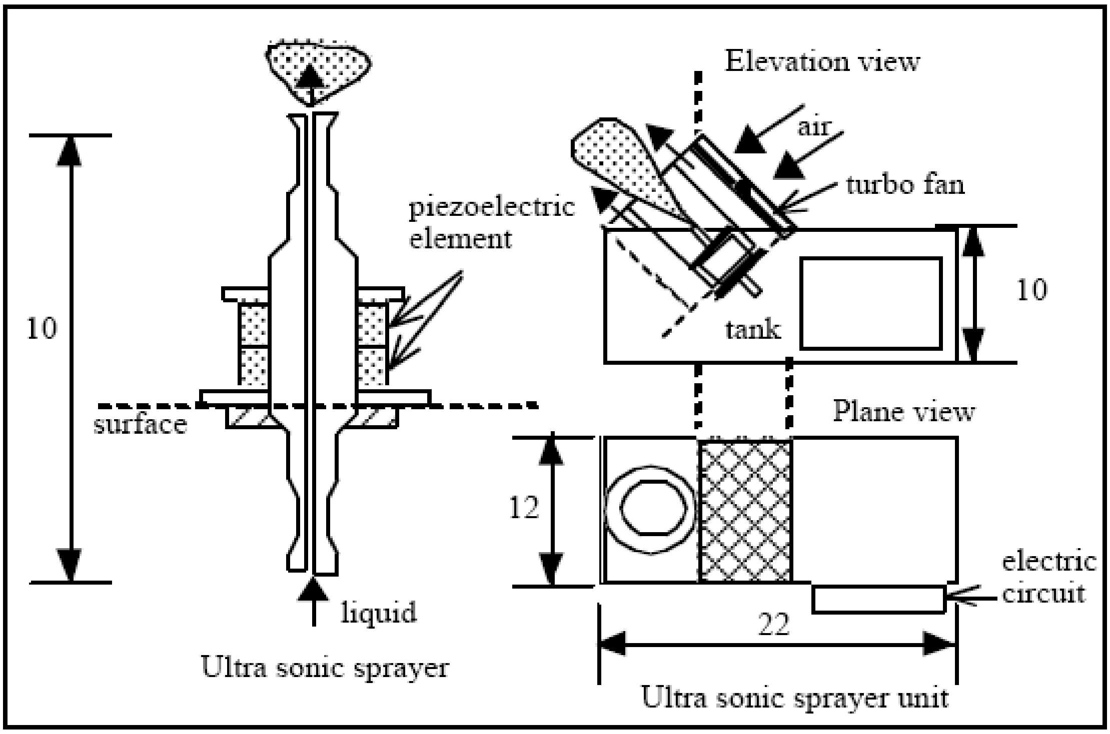


(a) Control room, average dust mass concentration in the entire room =5.02 mg/m^3
(b) Air cleaning (de-duster), average dust mass concentration in the entire room =3.82 mg/m^3
(c) Dust source control (oil sprinkling), average dust mass concentration in the entire room =0.82 mg/m^3

Figure 2.22: Comparison of dust spatial concentration in swing barns (Wang et al., 1999a)

Gustafsson (1997) proved that the spraying of mixtures from oil and water in pig houses reduced dust concentration by 75 – 80 %.

Atsuo (2002) used an ultra sonic sprayers unit (USSU) as shown in figure 2.23, to reduce the dust concentration in an enclosed experimental layer and floor feeding broiler house. For laying hens 1 and 2 % solutions of emulsified canola oil (weight base) were sprayed by (USSU) once a day after feeding. However for the floor feeding broiler house 2 % solutions of emulsified canola oil (weight base) were sprayed by (USSU) every hour for 10 minutes (75 g were sprayed) or when a dust concentration detector detected a threshold concentration which was 5.0 X 10^8 particles/m^3 with less than 5 μm. in aerodynamic diameter. The author found that spraying 2 % solution of emulsified canola oil with the ultra sonic sprayer unit in the enclosed layer house reduced the concentration of dust with 0.5 ≤ aerodynamic diameter < 2 μm and with 10 ≤ d < 30 μm to 58 by 51 %, respectively. On the other side, 1 % oil spraying in the layer house reduced the dust concentration to about 20 %. This spraying method could reduce the dust concentration to a daily average of 47 % in the floor feeding broiler room, but concentration itself was 100 times higher than in the layer house.



(All units in cm)

Figure 2.23: Ultra sonic sprayer unit (Atsuo, 2002)

Carey et al. (2004) demonstrated that oiling broiler litter with feed-grade canola oil reduced the dust levels by up to 32 %. Also, using evaporative cooling systems will control broiler house dust because if the litter is too dry increased dust concentrations may occur in the building. **Gustafsson (1997)** studied the effectiveness for manual spraying of a mixture of rape seed oil and water in pig houses. In order to see if the oil affected the release of dust from the skin one treatment has been administered outside the building so that no oil could cover any building surfaces. In this treatment the total dust concentration was reduced to 84 % of the reference level. The treatment caused a significant reduction of the settling rate (63 % of the reference level) and generation of dust (72 % of the reference level). It can be concluded that the treatment with oil reduces to some extent the generation of dust from the skin of pigs and functions as a dust binding agent on surfaces in the building. The reduction in total dust concentration with automatic spraying of different amounts of oil and water is presented in figure 2.24.

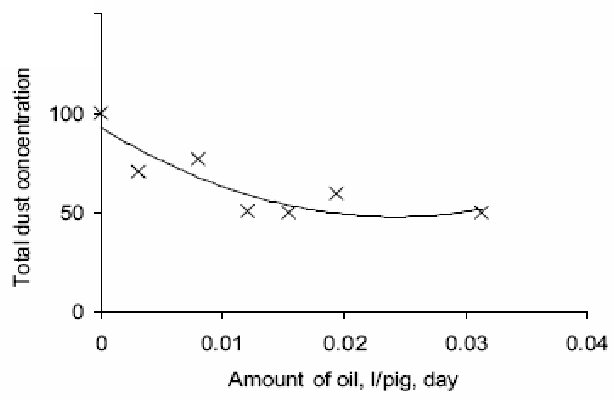


Figure 2.24: Relative changes in dust concentration when an automatic oil spraying system has been used (Gustafsson, 1997)

Ellen et al. (2000) performed experiments in two commercial broiler houses. In the first experiment pure water was used and in the second one a 3 % rapeseed oil-water mixture was used. Moreover, the capacities of the fans blowing water through the house were set at different levels. The duration of fogging varied from 1 to 10 min. The reduction of the dust concentration was determined by comparing the concentration just before and just after fogging. The dust concentration was measured by continuous registration. In table 2.16, the results from the experiments on fogging with pure water showed a small effect on the dust concentration. The maximum reduction achieved was about 12 %. The different durations of fogging and the different fan capacities did not result in changes in the dust reduction.

Table 2.16: Reduction in dust concentrations as a result of fogging with water (Ellen et al., 2000)

Duration of fogging, min	Capacity of fans, %	Mean dust concentration before fogging, mg/m^3	Mean dust reduction, %
1	10	0.98	1.8
1	100	1.53	2.0
5	10	2.37	5.9
5	50	0.65	6.2
5	100	3.24	8.6
10	50	5.70	11.9
10	100	3.33	3.3

The experiment with 3 % rapeseed oil-water mixture resulted in a reduction of about 11 %. An explanation for this low effect is the very small size of the produced water droplets (<10 µm). These droplets evaporate very quickly and there will be no interaction between dust particles and water droplets. The oil droplets are probably also too small to interact with dust particles. In this experiment as shown in figure 2.25, the spraying of an oil-water mixture and pure water gave good reduction rates of the total dust concentration. A mixture of oil and water reduced the concentration by about 50 %, and pure water reduced the concentration by a third compared to the reference period. Spraying with pure water gave an even better result than spraying with the oil-water mixture.

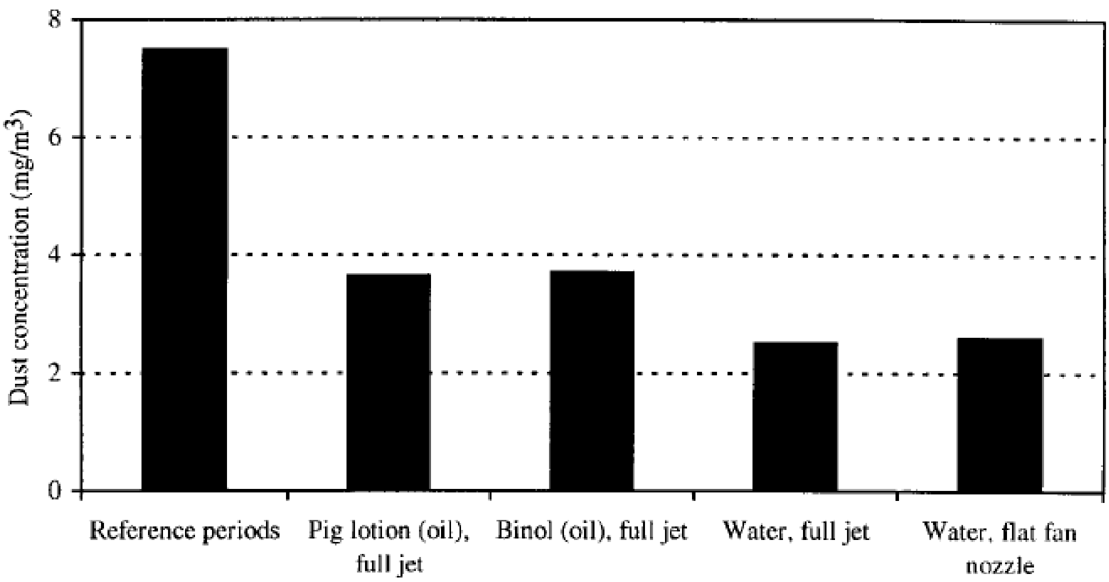


Figure 2.25: The effect of several treatments on the total dust concentration in an aviary system for laying hens (Ellen et al., 2000)

Gustafsson (1997) mentioned that showering water on the floor surfaces in the walking alleys reduced the total dust concentration with 9 % average and spraying salt solution (KCl) in the air with nozzles reduced the total dust concentration by 41 %. The author also found that spraying water droplets gave different results depending on the type of nozzles used. The use of high pressure nozzles (ultrasound nozzles) which created droplets in the size range of 5-10 µm resulted in a significant increase of both total and respirable dust. The reason for the increased dust concentrations was probably an ultrasound effect (frequency 30 kHz) created by the nozzles. The use of flat fan nozzles operated at a pressure of 0.35 MPa resulted in a reduction in both total and respirable dust concentrations as shown in figure 2.26.

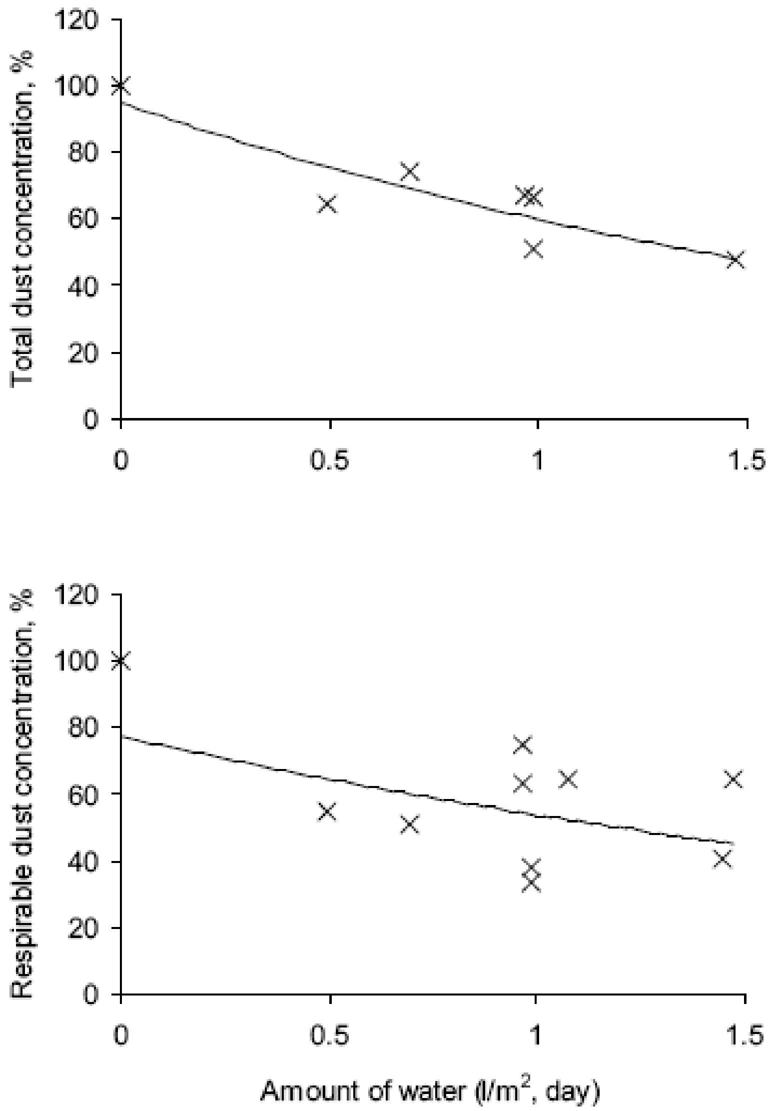


Figure 2.26: Relative levels of dust concentrations when flat fan nozzles were used (Gustafsson, 1997)

Zhu et al. (2005) reduced the dust concentration in swine gestation houses using spraying misting through the feeding time by about 75 % of average airborne dust concentration in the summer season.

Hölscher (2006) used an aerosol application unit to distribute an oil mixture-emulsion under high pressure inside a pig barn. The oil mixture contained different types of essential oils (to reduce airborne germs and fungi) and a carrier oil. By operating the aerosol application unit every 30 minutes, it was possible to obtain an almost continuous indoor air treatment within the barn. In comparison with the reference pig barn (same building, different compartment; ceteris paribus conditions), an average indoor concentrations were reduced to an average by 59 % for total dust and 54 % for PM_{10}. Emissions reduced to 68% for total dust and 65 % for PM_{10}

Gustafsson and van Wachenfelt (2007) evaluated from an investigation in a floor housing system for laying hens the influence of the following factors on dust concentration and generation:

1. Age of hens.
2. Storage of manure with conveyors below the draining floor and laying nests.
3. Ventilation rate was calculated from air velocities measured two times per trial in 5 positions of the cross section of the exhaust air duct (Φ 400 mm) by using a hot wire anemometer.
4. Bedding materials, namely: gravel, clay pellets, peat, wood shavings, chopped straw and chopped paper.
5. Fogging water droplets
6. Spraying a rape seed oil mixture.

The authors concluded from this study that the age of the hens and storage time for manure have no influence on the dust generation. The ventilation rate has a limit diluting effect on dust concentration as shown in figure 2.27.

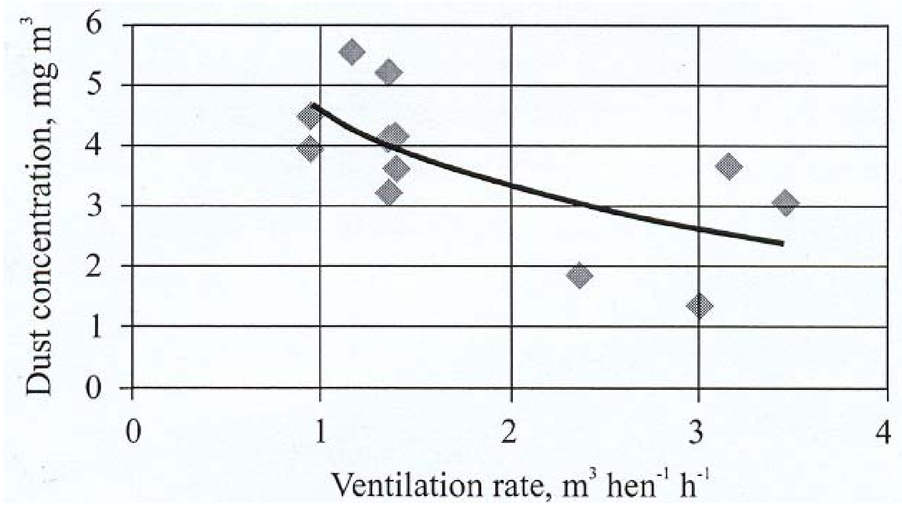


Figure 2.27: Total dust concentrations at different ventilation rates in a trial with gravel as bedding material for laying hens (Gustafsson and van Wachenfelt, 2007)

Bedding of clay pellets or peat generated the lowest concentration. On the other side the gravel has the highest dust concentration. Fogging water resulted in a considerable reduction of dust concentration in all trials. The reduction in dust concentration was improved when the amount of water increased which is exemplified in figure 2.28. Showering a mixture of 10 % rape seed oil in water reduced the dust concentration from 30 to 50 % as shown in figure 2.29. The feather conditions were very good when water droplets or an oil mixture were sprayed.

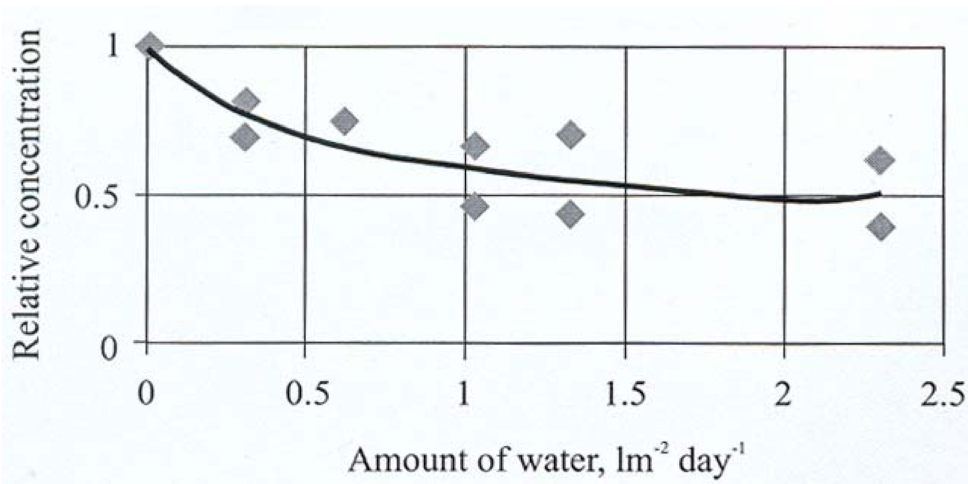


Figure 2.28: Relative dust concentration at different amount of water sprayed, wood shaving was bedding material for laying hens (Gustafsson and van Wachenfelt, 2007)

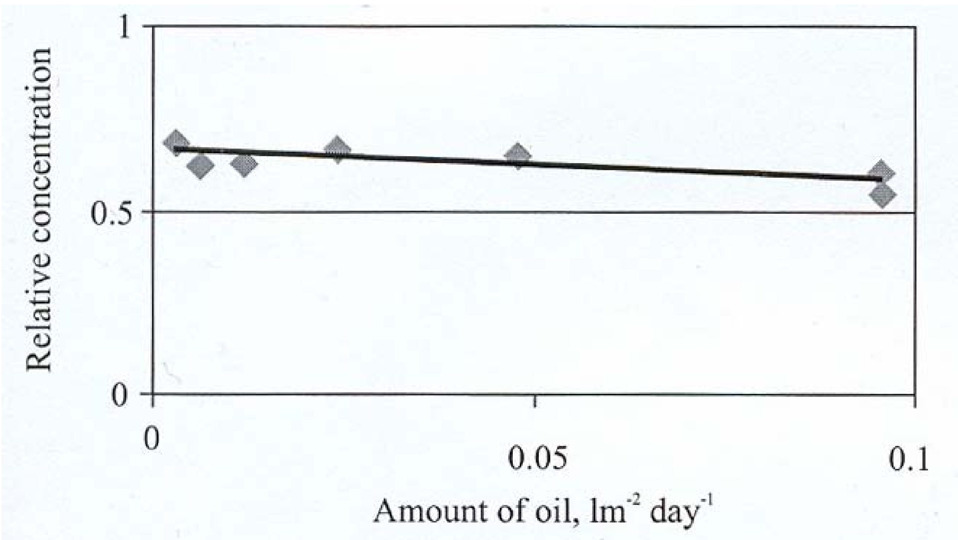


Figure 2.29: Relative dust concentration at different amount of a sprayed oil mixture for laying hens (Gustafsson and van Wachenfelt, 2007)

2.7.2 De-dusters

Zhang et al. (2001) developed two aerodynamic uniflow de-dusters (a cyclone type particle separator & gas remover with airflow capacity 188 l/s and 1,880 l/s) with low pressure requirement and high particle separation efficiency. This development is based on fluid dynamics, particle mechanics and sensitivity analysis.

- The small model de-duster employs a set of turbine-type vane guides, an involute separation chamber and a flow converging section to minimize turbulence and reduce the pressure loss. As shown in figure 2.30, dusty air is drawn from the air inlet passing through a set of vanes to establish a spiral flow pattern. The air then passes through the involute chamber and converges at the exit section above the dust bunker. Particles are collected in the dust bunker and clean air is exhausted through the blower. This device, as shown in figure 2.30, unlike the conventional cyclones, can remove respirable particles at pressures of 50 Pa.

- The large model de-duster contains three concentric de-dusters. The outer cylinder of the smaller de-duster serves as the inner cylinder of the bigger de-duster. Thus, the total cross sectional area is increased to allow air delivery and the volume of the unit is minimized as shown in figure 2.31. The fan speed can be varied via a frequency controller so that the performance at different airflow rates can be evaluated. An automatic dust flushing system was developed to periodically clean the dust in the dust bunker. The new design is aimed at reducing dust emissions for exhaust fans with large air flow rates. The dust mass concentration was measured at the inlet and the outlet of the de-duster using filter collectors during 24-h periods. The results showed that the dust mass removal efficiency was 91 % at the 60 % power level. The dust reduction efficiency was 89 % at 100 % power level.

Wang et al. (1999a) studied the reduction of dust concentration through cleaning the air using aerodynamic de-dusters and found that the ratio of air flow rate through the de-duster to the ventilation room is 32 % with a dust removal efficiency of 85 %. The large flow rate for the de-duster is required to improve the room air cleaning efficiency. The measured spatial dust concentrations with de-dusters show that the overall dust level is approximately 20 % lower than the control room, figure 2.22 b. The high dust concentration zone near the air inlet side disappeared. This indicates that some dust was removed from the dusty air.

Gustafsson (1997) mentioned that the effectiveness of air cleaning devices on dust concentration is dependent not only on the airflow through the device but also on the ventilation rate in the building. The reduction in dust concentration has therefore been determined at different airflow rates through an electrostatic air cleaner and at different ventilation rates in a pig house. The use of the air cleaner had a minor influence on the dust concentration in the air as presented in table 2.17. Although, it was proven that the equipment removed a large fraction of the particles from the air which had passed through it. Considering the mass balance of the dust it is obvious that the air cleaning equipment needs large airflow capacities if the dust concentration in the air is to be affected as shown in table 2.17. The airflow through an air cleaner has the same influence on the dust concentration as an equally large increase in the ventilation rate in the building.

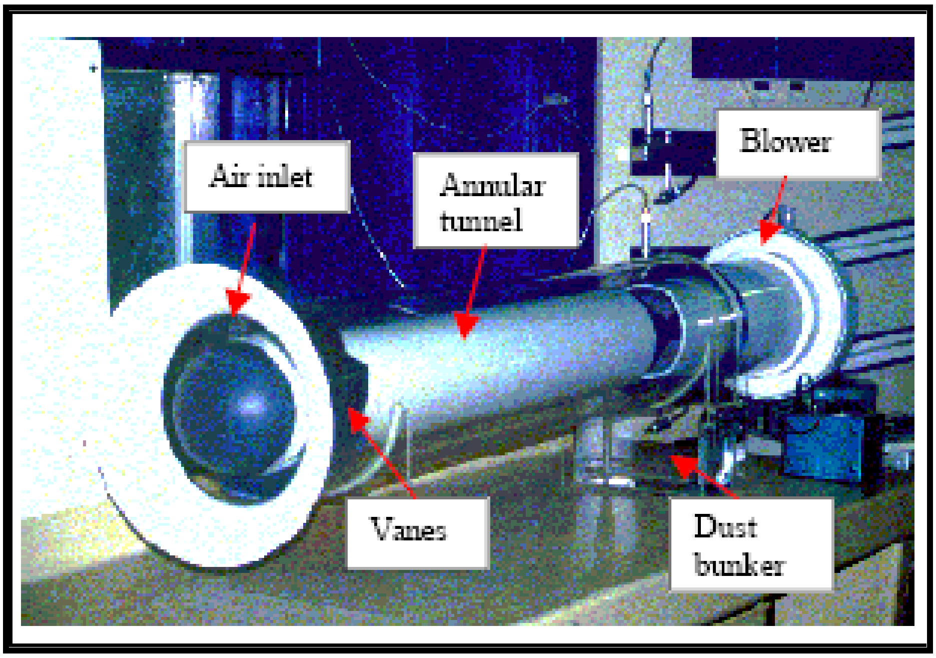


Figure 2.30: The prototype of the uniflow deduster fabricated based on the sensitivity analysis (Zhang et al., 2001)

The particle separation efficiencies of this de-duster were 50, 77 and 90 % for particles diameter of about 4, larger than 7, and larger than 10 µm respectively. In terms of mass concentration measured using mass samplers, the particles separation efficiency was 85 %. Because most of the dust mass is attributed to the larger particles, the number separation and mass separation efficiency agreed very well.

Figure 2.31: The large de-duster prototype (Zhang et al., 2001)

Table 2.17: The influence of air cleaning on total dust concentration (Gustafsson, 1997)

Trail Nr.	Total dust concentration			Airflow through air cleaner, m^3/Pig.h	Ventilation rate, m^3/Pig.h
	Air cleaner, mg/m^3	Reference, mg/m^3	Difference, %		
1	0.94	1.24	-24	17.3	12.4
2	0.92	1.28	-28	10.3	31.9
3	1.39	1.77	-21	10.3	46.2
4	1.21	1.45	-17	17.2	46.2
5	1.60	1.74	-8	11.6	36.4
6	1.09	1.41	-23	11.6	53.0

2.7.3 Ionization

Ionization is the physical process of converting an atom or molecule into an ion by adding or removing charged particles such as electrons or other ions. This process works slightly differently depending on whether an ion with a positive or a negative electric charge is being produced. A positively charged ion is produced when an electron bonded to an atom (or molecule) absorbs enough energy to escape from the electric potential barrier that originally confined it, thus breaking the bond and freeing it to move. The amount of energy required is called the ionization potential. A negatively charged ion is produced when a free electron collides with an atom and is subsequently caught inside the electric potential barrier releasing any excess energy.

Ullman et al. (2004) studied the reduction of dust concentration in animal buildings using an ionization system where the ionization of air imparts a negative charge on dust particles that can then be attracted to collection plates or rods. Ionization reduced dust concentrations by about 78 %, with reductions ranging from approximately 68 to 92 % for 6 different ranges. An electrostatic space charge system was shown to remove up to 91 % of artificially generated dust and 52 % of dust generated by mature White Leghorn chickens in a caged layer room. An apparatus consisting of 2 negatively charged needles located 0.25 m above the floor and a positively charged aluminium collector plate (0.76 m high by 1.4 m long) located in front of the door, charged at 12 and 8 kV, respectively, was tested at a livestock facility. Ionization was approximately 6 times greater at dust removal than gravity alone. Relative humidity had no apparent impact on reductions in dust concentrations. **Gustafsson (1997)** showed that the ionization in pig houses has resulted in a 20–30 % decline in dust concentration. **Rosentrater (2004)** reported that the electrostatic collectors are devices that impart electric charges to dust particles and then push them out of the air stream using electromagnetic force. They typically exhibit low operating costs and high removal efficiencies. The electrostatic ionization could produce airborne swine dust removal rates of up to six times greater than gravitational sedimentation alone. The author tested the ability of the electrostatic precipitator system in figure 2.32 to remove airborne particles. This electrostatic precipitator consisted of a discharge electrode which was constructed from a single strand of stainless steel wire and a grounded collection electrode pipe positioned 17.8 cm below the wire. The discharge wire and the collection pipe were supported by PVC end plates. Additionally, an ionization guard was located above the wire to direct electrons and charged dust particles down toward the collection electrode. The entire unit was 3.05 m in overall length. To charge the precipitator and provide negative ionization at the discharge wire (which imparts electrical charges to passing dust particles). The electrode wire was connected to a -20 kV, 50 mA, and rectified a.c. power supply unit.

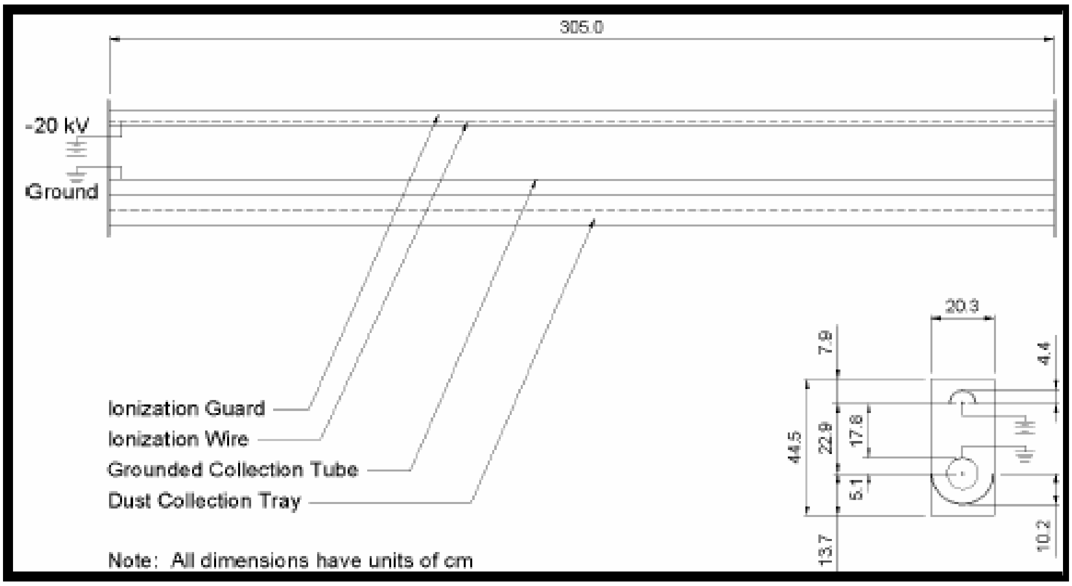


Figure 2.32: Schematic of electrostatic precipitator unit (Rosentrater, 2005)

This system reduced airborne particle concentrations exponentially, and produced removal rates between 8 and 13 times greater than gravitational settling alone.

Mitchell et al. (2004) used an electrostatic space charge system (ESCS) to demonstrate the effectiveness of this system in the breeder/layer farm environment for reducing airborne dust in a several month long study. The system as shown in figure 2.33 used ceiling fans to distribute negatively charged air throughout the room and to move negatively charged dust downward toward the grounded litter where most of it would be captured.

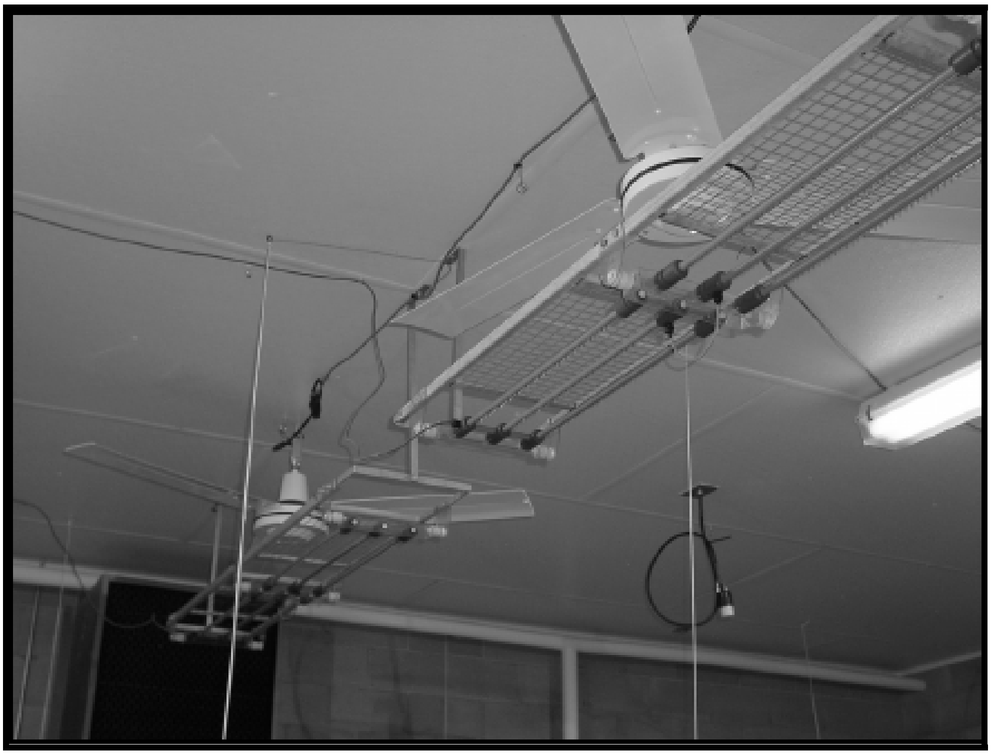
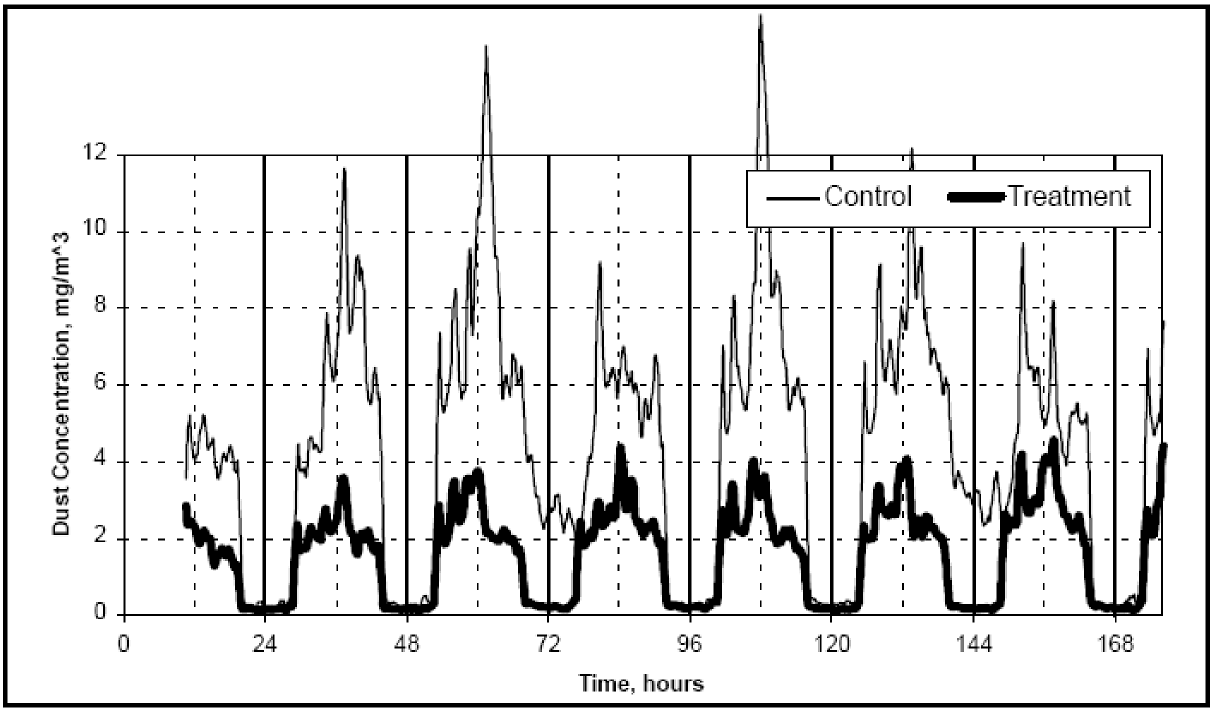


Figure 2.33: ESCS units suspended below the ceiling fans in the treatment room (Mitchell et al., 2004)

The dust concentration was reduced by an average of 61 % over a period of 23 weeks as presented in figure 2.34.

Mitchell and Baumgartner (2007) used previous ESCS for reducing the dust particle concentration in poultry production houses and a hatchery. The effectiveness of ESCS for PM_{10} dust reduction ranged from 78 % in commercial poultry hatchers to 47 % in commercial caged layer houses.



Note: the light timer turned on in the control room on the evenings ending at hour 72 and hour 144

Figure 2.34: Dust concentration in laying hens house for treatment vs. control rooms by cumulative hours for a typical week (Mitchell et al., 2004)

Mitchell (1997) studied the effects of airflow on the distribution of negative air ions using three types of ion generators as shown in figure 2.35, which have potential for dust reduction in animal house or hatchery applications. All of the devices used limited current power supplies which restricted the current to 2 mA or less for safety and the ozone output was limited to less than 0.1 ppm. The first type was a self-contained Ceiling Ionizer that was designed to hang from the ceiling in the middle of a room where a space charge was desired. The second was a Room-Ionizer-System (RIS) consisting of a metallic bar with external power supplies operated at –8 kVDC, or –15 kVDC. Both of these devices require an external air moving device. The third type was an ionizer which is designed to be used inline in a duct or with a self-contained air source to charge clean outside air prior to injecting it into a treatment area. This device will be referred to as the IDI (in-duct-ionizer).

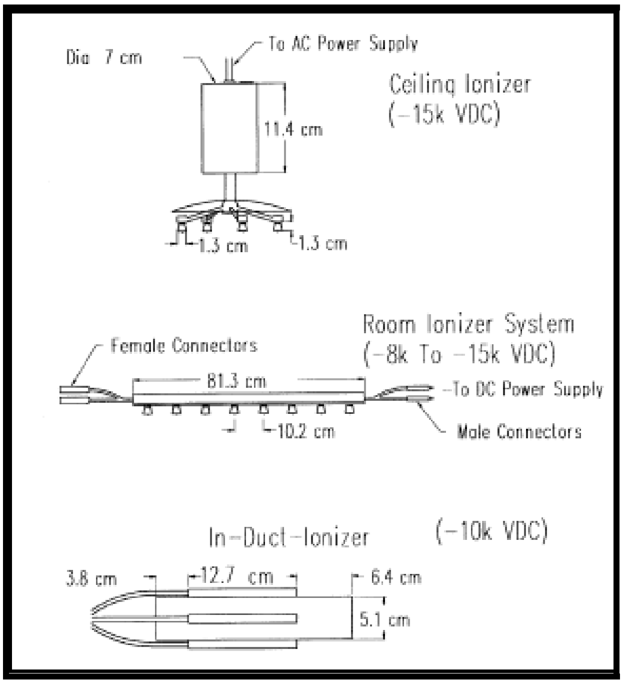


Figure 2.35: Ionizer configurations (Mitchell, 1997)

The author observed that these devices could be effectively used to reduce dust and microorganisms in a variety of applications with air moving devices.

2.7.4 Oxidants

An oxidant can be defined as a chemical compound that readily transfers oxygen atoms or a substance that gains electrons in a chemical redox (short for reduction/oxidation reaction) reaction.

Ullman et al. (2004) mentioned that cleaning the air by oxidation has been used for decades using oxidizing agents such as ozone, potassium permanganate, chlorine and chlorine peroxide. Evaluation of an indoor ozone system for dust control effectiveness proved that the total dust concentrations decreased by 60 % at the fan exhaust under maximum tunnel ventilation compared with a nearby building without any ozone treatment.

2.7.5 Windbreaks

A windbreak or shelterbelt is a plantation usually made up of one or more rows of trees planted in such a manner as to provide shelter from the wind.

Ullman et al. (2004) found that two hundred operations in Taiwan have constructed walls downwind of tunnel-ventilated poultry buildings and had seen reduced dust emissions off-site. The effectiveness of module walls constructed of 3 x 3 m pipe frames covered securely with tarpaulins was determined by collecting aerial dust particles and demonstrating airflow from exhaust fans using smoke. An increase in the vertical height of the smoke plume subsequent to reaching the windbreak demonstrated the potential for reduced dust concentrations downwind of animal facilities. Elbows placed on exhaust fans designed to redirect fan airflow upward produced some plume rise. However, dispersion models indicated that tall stacks may offer further effectiveness.

Pedersen et al. (2000) demonstrated that windbreak walls placed at 3 and 6 m, respectively, from the building deflected the airflow from the exhaust fans in the upward direction similar to other wind barriers, thus providing surfaces for dust deposition. The vertical height at which the plume would flow over a downwind lagoon under low wind conditions was increased by building a windbreak wall. As a result, the dust levels in the area downwind from the windbreaks were lowered.

2.7.6 Scrubbers and Filters

Ullman et al. (2004) studied the reduction of dust from the exhaust air using scrubbers. These scrubbers consist of towers packed with a contact media, gas or liquid-driven venturi systems. These venturis and spray towers offer a more instantaneous removal of dust particles. **Pedersen et al. (2000)** mentioned that the wet pad scrubber placed in the animal house 1.2 m upwind from the exhaust fans achieved modest reduction in dust emission from the piggery building in warm weather. The results demonstrated that these control methods did not substantially challenge the existing ventilation systems by causing excessive resistance to airflow and they would therefore be practical and useful emission control methods.

Kosch et al. (2005) used a bioscrubber system to perform at a higher level of efficiency to reduce emissions in consideration of the huge amounts of airflow in poultry production. The working principle of the exhaust scrubber as shown in figure 2.36 is the continuous spraying of the partition grill with a high specific area. The spraying is done with three pumps (1.5 kWh) which discharge 75 m^3/h of water at a height of 5 m. The cleaning water wets the synthetic partition grill evenly and causes the removal of dust particles. The efficiency of reduction for suspended dust is 45 %.

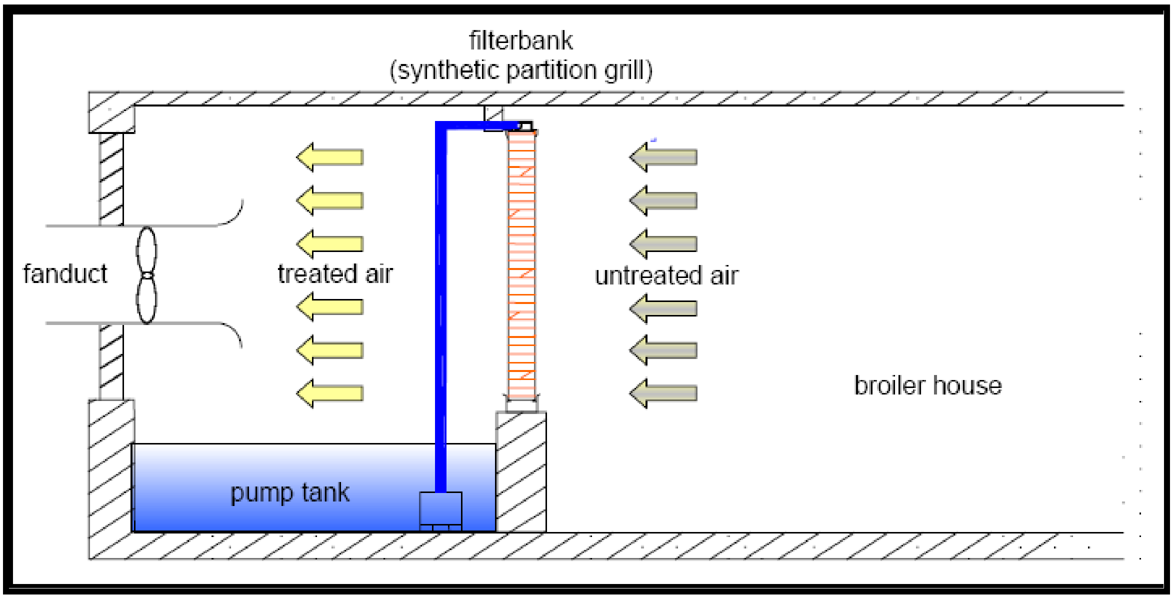


Figure 2.36: Schematic of the exhaust air cleaning system for a poultry house (Kosch et al., 2005)

Snell and Schwarz (2003) described the exhaust air cleaning system as shown in figure 2.37, based on a bioscrubber. The exhaust air flows horizontally to the house gable and passes through the fans to enter the filter which is located outside the stable. In the beginning the air is humidified and then flows into the first filter bank which consists of so-called pads. In this stage the dust is washed out of the air and transported downwards by the water and the air flows through the second filter bank. In this filter the ph value of the water is regulated by acid to eliminate NH_3, fine dust and odourous substances which cannot be washed out in the first filter bank. The water from both filters is collected and smoothed so the solid matter deposits on the ground of the basin and the water is then pumped up to flow over the pads again. The result of the dust concentration measurements as visualized in figure 2.38 shows that more than 80 % of the airborne dust was removed by the filter.

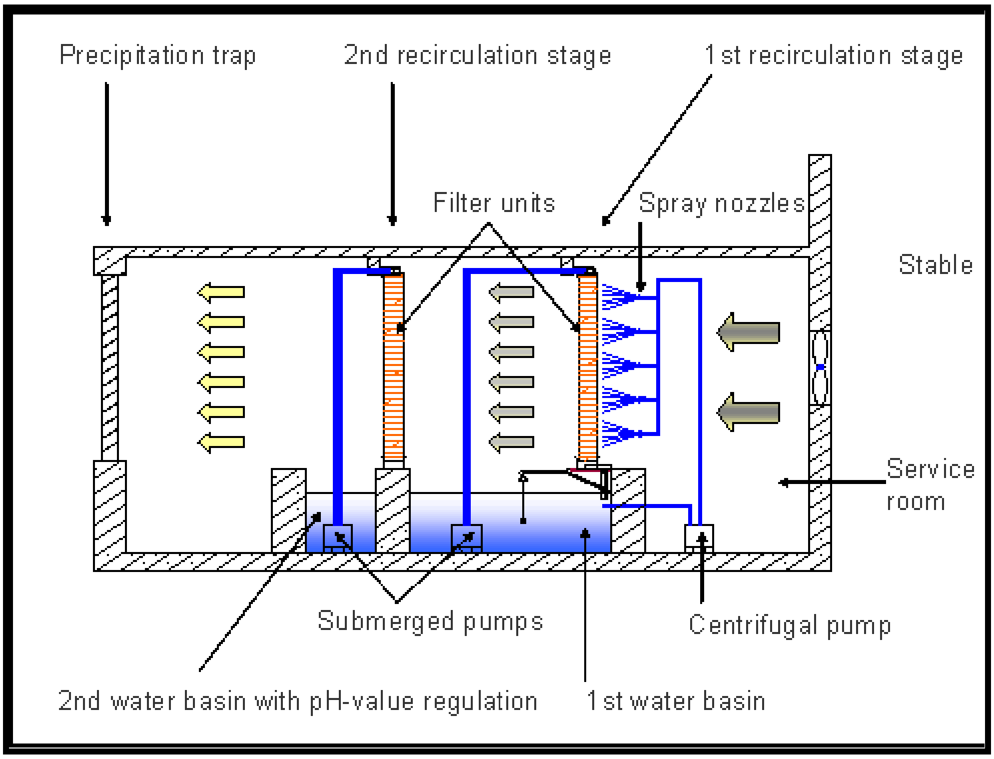


Figure 2.37: Schematic of the exhaust cleaning system (Snell and Schwarz, 2003)

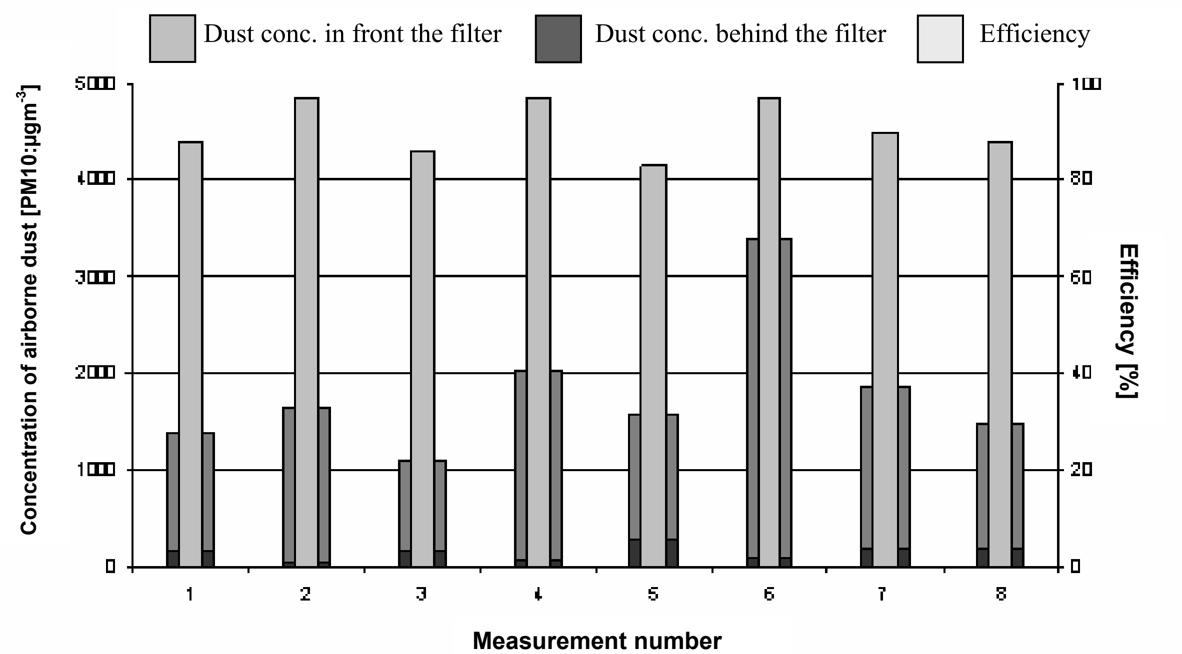


Figure 2.38: Concentration of airborne dust in the exhaust air (Snell and Schwarz, 2003)

Ullman et al. (2004) studied the reduction of dust concentration in animal buildings using a filter. This filter provides an alternative method to air scrubbers for broiler operations. Dust became entrapped in fibers through a number of physical mechanisms. The traditional filter systems used in broiler operations reduced the dust content by up to 50 %. Clogging of traditional filter systems by dust and feathers in broiler facilities became problematic to a point when poultry operators found to forego filters over airconditioning units rather than deal with the required maintenance. To overcome such problems filters should be placed in a series with the first (i.e., upstream) filter consisting of a fairly coarse strainer primarily intended to remove feathers. The authors also used the Biofilter which operates by forcing air through a moist packing material to provide an alternative to traditional filter systems for broiler facility dust emission reduction. It is recommended that biofilters used at poultry facilities should be installed with dust removal equipment as dust accumulates on fans.

Hölscher (2006) reduced the dust emission rate from a pig barn with 515 pigs using two air scrubbers by recycling the air inside the building. The measurements over a three month period indicated that emissions can be reduced on average by 54 % for total dust and by 51 % for PM_{10}, compared with a reference pig barn. Indoor concentrations have been reduced on average by 63 % for total dust and by 60 % for PM_{10}.

3 Material and methods

3.1 Poultry houses description

The field study passed through three different stages. The first stage was carried out in a big commercial farm to describe the dust emission rate from different housing systems for laying hens. There are two different breeding styles in this farm: aviary and cage system. This farm is located in Dülmen (North Rhine-Westphalia), Germany.

The second stage of the experiments was carried out in small scale in an experimental station of the university with a floor system to test the efficiency of different filter systems. This farm belongs to Bonn University and is located in Frankenforst (Königswinter), Germany.

The third stage has been done in a small commercial farm to test the filter system that gave the highest efficiency in small scale experiments. This farm is located in Düren, Nörvenich (North Rhine-Westphalia), Germany. The experiments have been done with a floor system.

3.1.1 Dülmen farm

3.1.1.1 Cage system

In the examined stable, 46.000 laying hens are accommodated in conventional cages. The total area for this stable is 1.820 m^2 (70 m length x 26 m width) with forced ventilation. The fresh air flows inside the barn through the side panels which are located in the stable walls. The exhaust air is sucked out with 26 fans aligned at the ridge axis of the stable, as shown in figure 3.1. The cage system consists of three floors with moving belts under each level which carries the excrement directly out of the stable. Chain feeding and tap watering stations supply the animals with fodder and water.

3.1.1.2 Aviary system

In the examined stable which accommodated 14.600 laying hens divided into separate functional areas, to be seen in illustration 3.2. The total area for this stable is 675 m^2 (90 m length x 7.5 m width). The fresh air flows through the side panels and the exhaust air is sucked out by 9 fans aligned at the ridge axis of the stable, as illustrated in figure 3.2. Conveyor belts have been installed under the slats making it possible to remove manure on demand. There is room in the system to incorporate feed and water lines. The eggs are laid in darkened nests and then collected automatically.

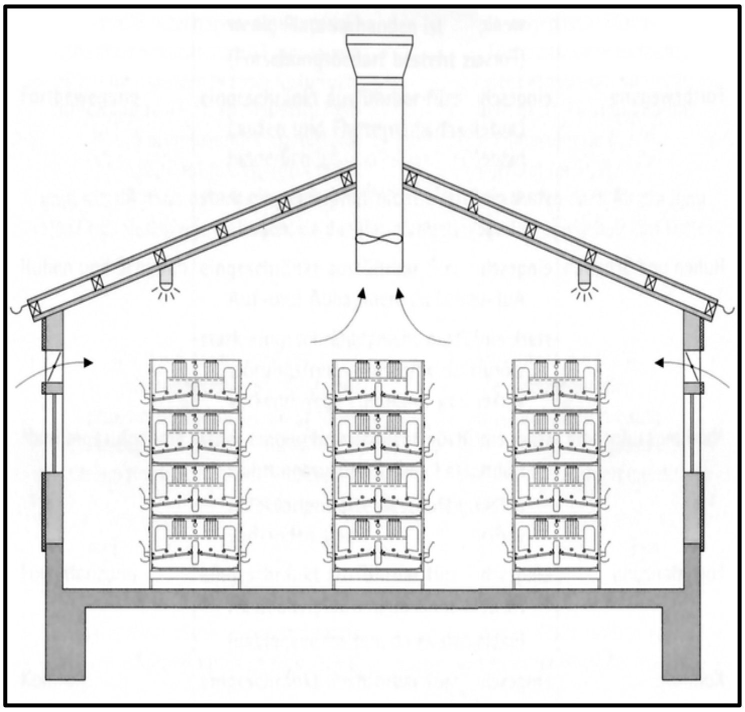


Figure 3.1: Laying hens stall with cage system and forced ventilation system (Nannen and Büscher, 2007 a)

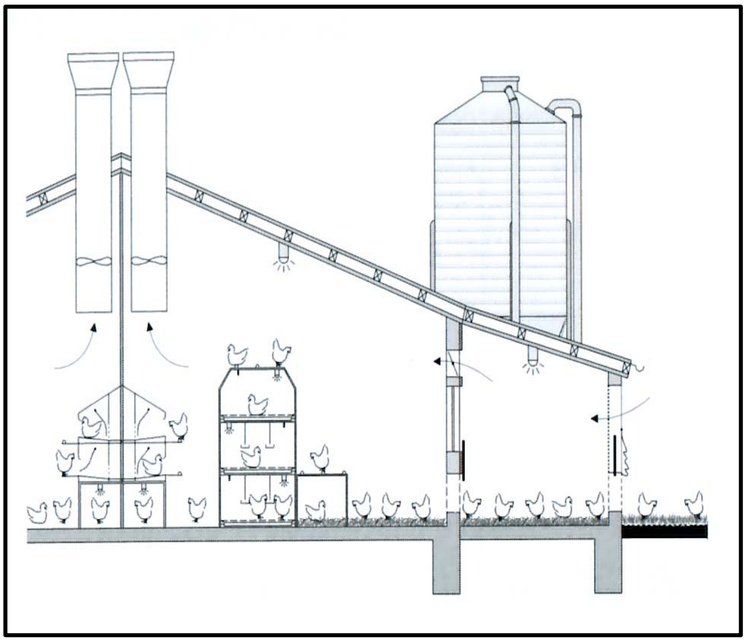


Figure 3.2: Laying hens stall with aviary system and forced ventilation system (Nannen and Büscher, 2007 a)

3.1.2 Frankenforst experimental station

This is a small scale experimental station for an aviary system. The total area for this compartment is 80 m^2 (8 m width x 10 m length). As shown in figure 3.3, 250 laying hens are housed in this location within four wire-separated rooms. These rooms have only one fan for the exhausted air and the fresh air enters through windows located in the walls from each side. Manure removal, water supply and feeding are done manually.

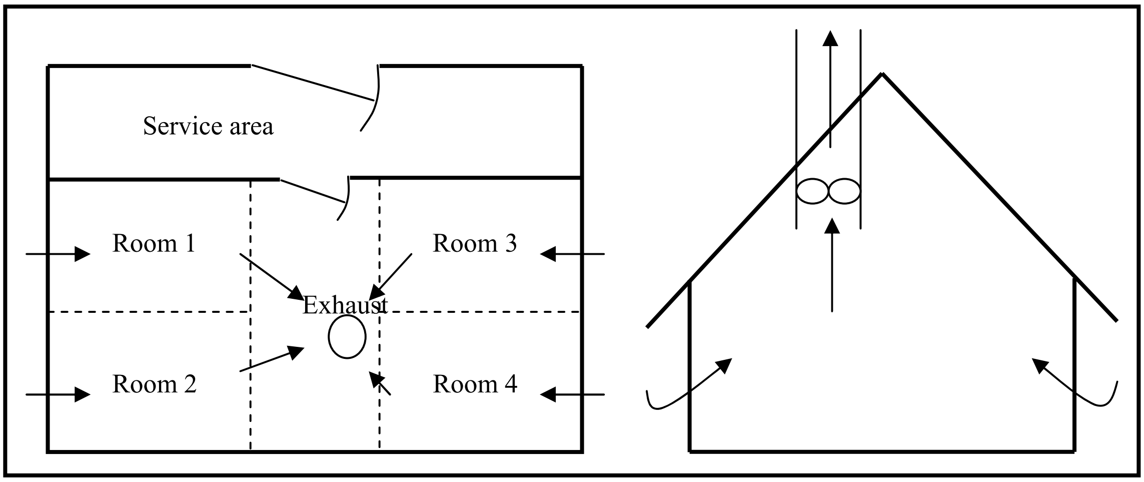


Figure 3.3: Schematic for laying hens stall in Frankenforst experimental station for aviary system (left top view, right cross view)

3.1.3 Düren farm

This is a large scale commercial farm for a floor system. The total area for this barn is 200 m^2 (10 m width x 20 m length). 1600 laying hens are housed in this barn with a breeding density of 8 hen / m². This barn has two fans for the exhausted air and the fresh air enters through windows located in the farm walls from each side. Manure removal is done manually but water supply, feeding, and egg collection are done automatically, as shown in figure 3.4.

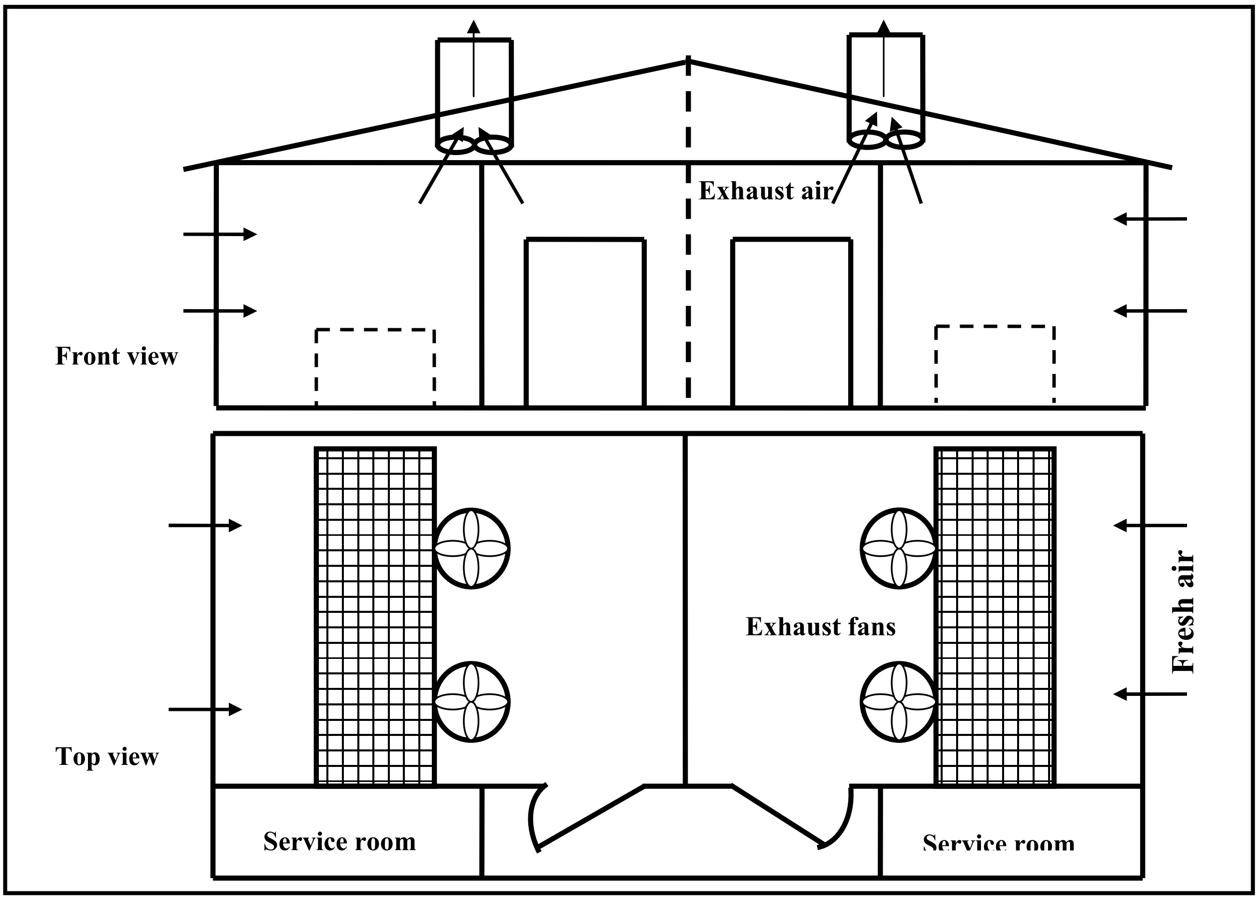


Figure 3.4: Schematic for laying hens stall in Düren barn for aviary system (above front view, below top view)

3.2 Dust characterization

Physical properties of particle matter have an influence on the penetration depth of the particles into the lungs and consequently have an effect on the health of animals and humans. Analysis of the physical properties of the particles has been done to describe the mass, size, shape and density of the dust. This goal has been achieved by microscopic analysis and sedimentation experiments.

3.2.1 Microscopic analysis

This microscopic analysis of dust particles has been achieved by the Institute of Plant Diseases, Bonn University, using a scanning microscope (Leitz DMRB company), figure 3.5. This microscope is supported by a digital camera to make microscopic pictures of the different particle fractions as shown in figures 3.6, 6.7.

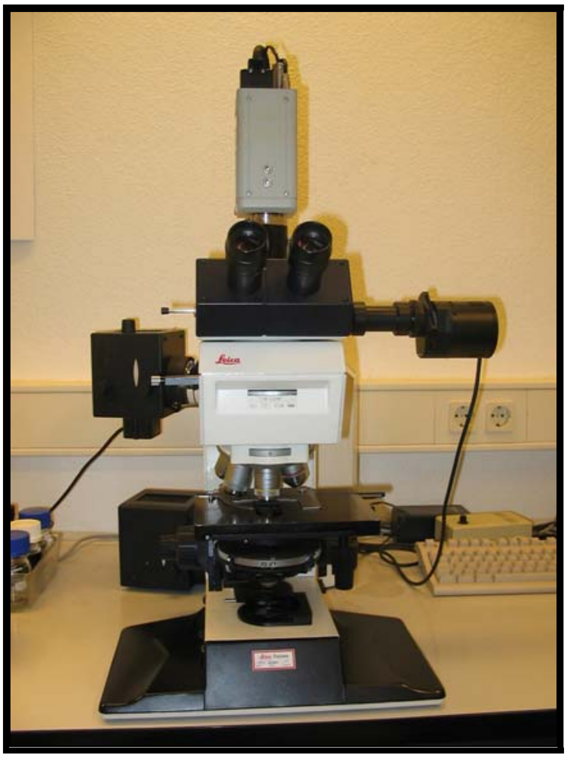


Figure 3.5: Scanning microscope with digital camera

The dust particles have been sampled with an Andersen Cascade-Impactor collector (Schaefer Company, Langen, Germany). This collector consists of a vacuum pump and eight glass impactor plates, as shown in figure 3.8 to divide the dust into different particle size fractions within eight stages according to their aerodynamic diameter, table 3.1.

The vacuum pump has been adjusted to 28.3 l/min to set the air velocity on the Andersen collector higher than 0.2 m/s, as recommended by **(Nannen, 2005)**. The impactor collector is located at 1 m above the barn ground, and the running time for sampling was 20 minutes.

Table 3.1: Size ranges for different Andersen collector stages

Stage	Size range
1	> 11 µm
2	7 bis 11 µm
3	4.7 bis 7 µm
4	3.3 bis 4.7 µm
5	2.1 bis 3.3 µm
6	1.1 bis 2.1 µm
7	0.65 bis 1.1 µm
8	0.43 bis 0.65 µm

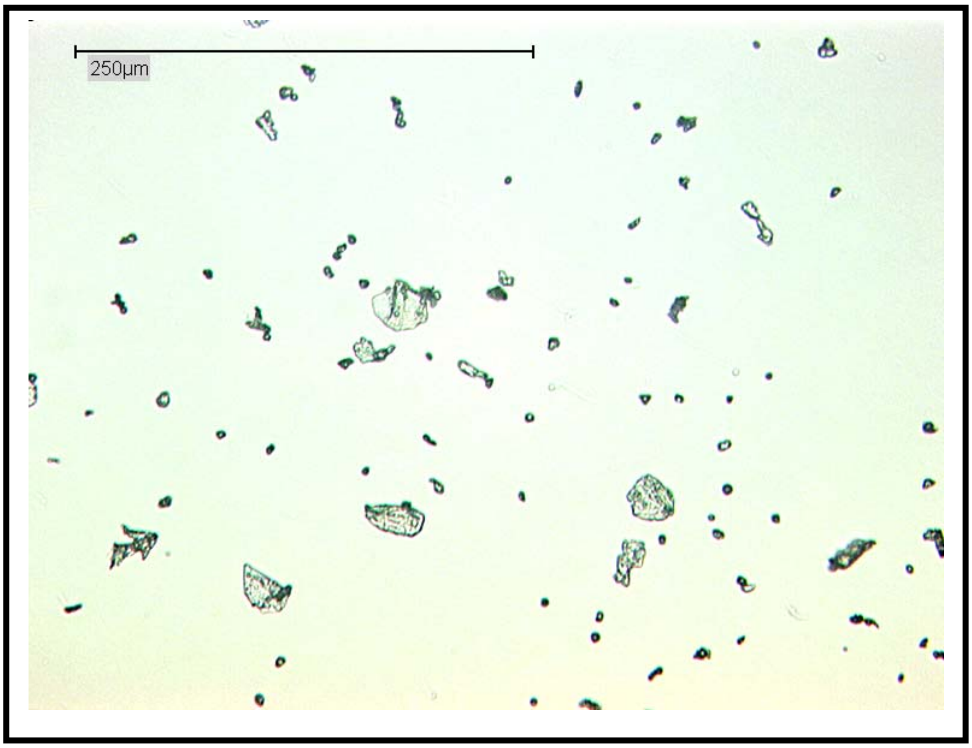


Figure 3.6: Microscopic image of the different particle fractions for cage system

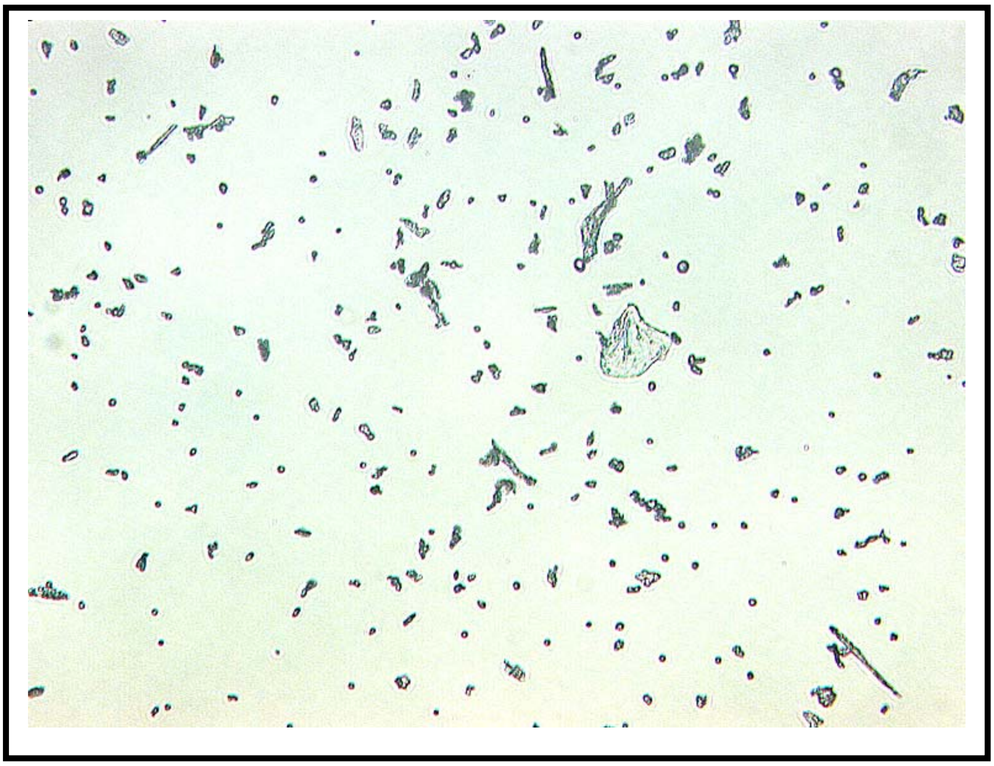


Figure 3.7: Microscopic image of the different particle fractions for aviary system

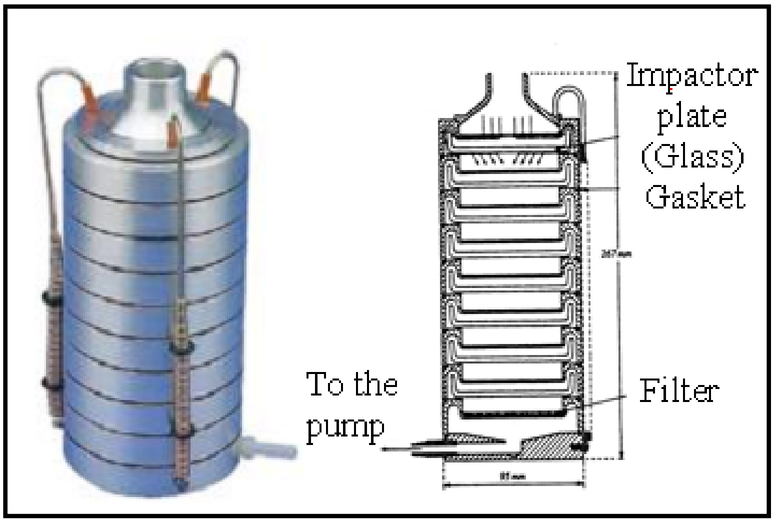


Figure 3.8: Construction of the Andersen Cascade-Impactor sampler

The length and area of the particle matter has been determined by using the digitalized microscopic picture, using Scion image software, figure 3.9. The shape factor has been calculated using the length and area of the particle matter for different fraction sizes, according the equation 3.1.

$$\text{Shape factor (k)} = \text{Length} \Big/ 2\sqrt{\pi * \text{Area}} \qquad \textbf{3.1}$$

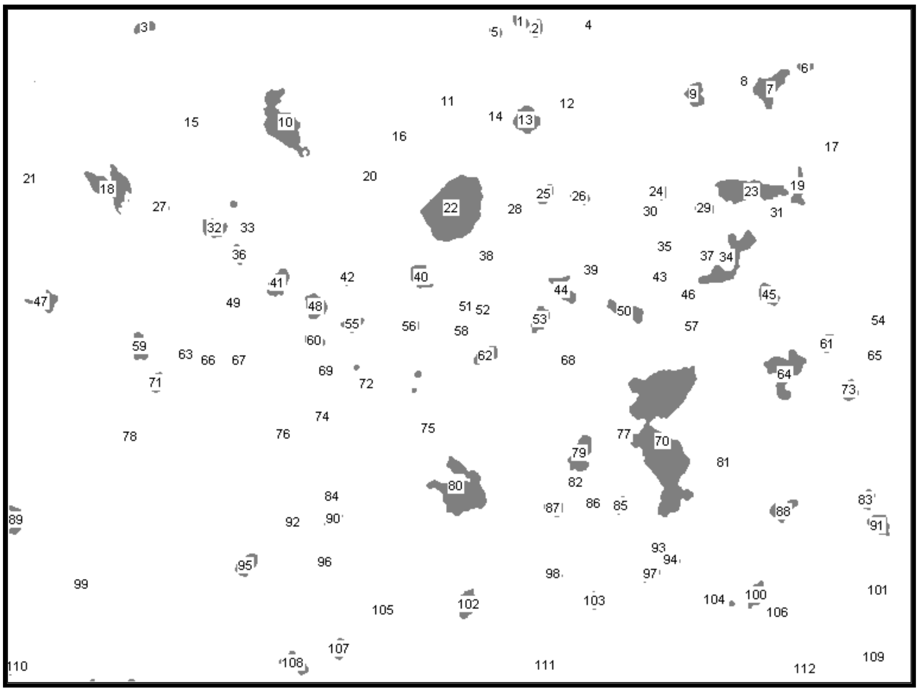


Figure 3.9: Microscopic image for particle matters after analyzing; the figures next to the particles specify their respective size

3.2.2 Sedimentation

The basic idea behind the measuring apparatus as mentioned by **(Schmitt-Pauksztat, 2006)** is to allow a free fall of the particle matter as it actually takes place in the air. When a sample of the particle matter with different size ranges is released the particles fall to the ground with different speeds due to gravity sedimentation. There, the faster particles initially subside and are then followed by the slower particles. All particle sizes with identical shape and density reach the ground. The larger particles arrive first and are then followed by smaller particles. Diffusion effects lead to a time-Gaussian distributed arrival of the particles on the ground.

The sedimentation chamber is a standing vertical cylinder. Its radial symmetry allows peripheral effects of undisturbed particle sedimentation. The height of the sedimentation cylinder affects the sedimentation time to reach the ground for different particle sizes. The width of the cylinder has been calculated to make the particle deposition on the cylinder walls negligible.

In the top part of the cylinder there is a dispersion device (Venturimeter) which works with air pressure to release the pulse of the dust samplers quickly. In the bottom of the cylinder, there is an optical particle counter, which measures the particle concentration in number as a function of time and particle size. The average sedimentation time for the various fractions of particles can be determined. Figure 3.10 shows the sedimentation cylinder with its sub-components outlined.

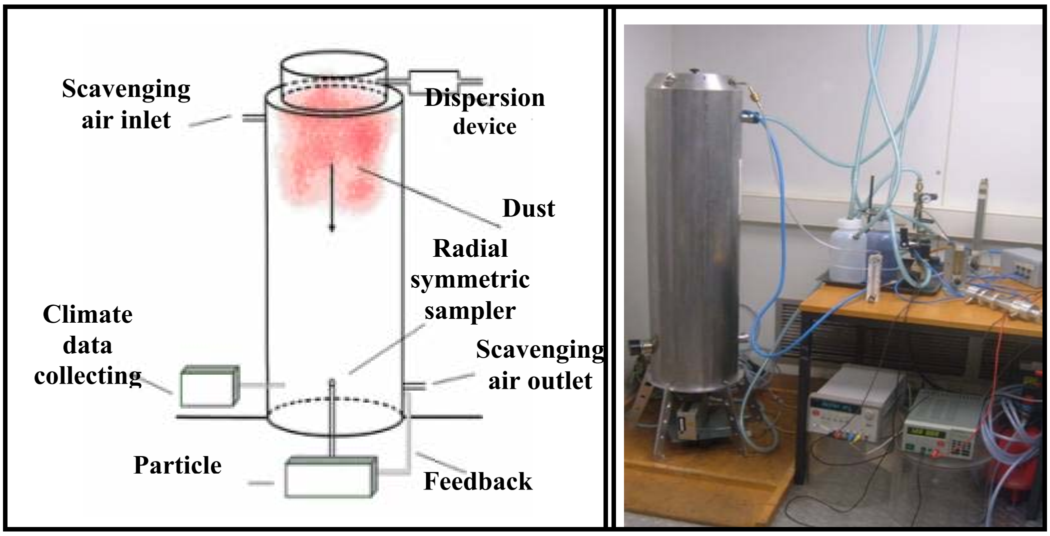


Figure 3.10: Measuring apparatus principle sketch (left) and Sedimentation cylinder (right) (Schmitt-Pauksztat, 2006)

The particle density is calculated using equation 3.2, which has been created by **(Rosenthal, 2006)**. Sedimentation velocity (V_s) for each particle fraction has been determined using equation 3.3. The sedimentation stroke can be determined as the length of the sedimentation cylinder (1.1±0.05 m). The particle shape factor has been determined according to microscopic analysis.

$$V_s = \frac{1 + \dfrac{\lambda_0 \left(\dfrac{T}{T_0}\right)\left(\dfrac{P_0}{P}\right)\xi}{d} \left[2.34 + 1.058 e^{-0.39 \frac{d}{\lambda_0 \left(\frac{T}{T_0}\right)\left(\frac{P_0}{P}\right)\xi}} \right] \rho d^2 g}{18 \left(A + B\vartheta + C\vartheta^2 + D\vartheta^3 + E\vartheta^4 + F\vartheta^5 + \dfrac{X_{H_2O}}{1 + X_{H_2O}} \left(G + H\vartheta + I\vartheta^2 + K\vartheta^3 + M\vartheta^4 \right) 10^{-6} \right) k} \qquad \textbf{3.2}$$

$$\xi = \frac{1 + \dfrac{110.4}{T_0}}{1 + \dfrac{110.4}{T}}$$

where:

V_s	=	Sedimentation velocity.	m/sec
λ_0	=	Free mean path.	67.3 nm
T	=	Temperature.	K
T_0	=	296.15 K	
ϑ	=	Temperature.	ºC
P_0	=	$1.01*10^5$ Pa	
P	=	Air pressure.	Pa
d	=	Particle diameter.	m
ρ	=	Particle density.	Kg/m^3
g	=	Acceleration of gravity.	$9.81\ m^2/sec$
X_{H_2O}	=	Mixture ratio: **(Water vapor / dry air).**	Kg/Kg
k	=	Particle shape factor	
A,B,C,D,E,F,G,H,I,K and M	=	Constants, from table 3.2	

Table 3.2: Coefficients of dynamic viscosity calculation under consideration of mixture ratio (Rosenthal, 2006)

Constant	Value	Constant	Value
A	17.14237	**G**	-9.108949
B	0.0463604 $^{\circ}C^{-1}$	**H**	0.02654355 $^{\circ}C^{-1}$
C	$-2.7458*10^{-05}$ $^{\circ}C^{-2}$	**I**	$-6.4324*10^{-05}$ $^{\circ}C^{-2}$
D	$1.8112*10^{-08}$ $^{\circ}C^{-3}$	**K**	$1.3079*10^{-07}$ $^{\circ}C^{-3}$
E	$-6.7450*10^{-12}$ $^{\circ}C^{-4}$	**M**	$-8.1903*10^{-11}$ $^{\circ}C^{-4}$
F	$1.0277*10^{-15}$ $^{\circ}C^{-5}$		

$$V_s = \frac{\text{Sedimentation stroke}}{\text{Sedimentation time}} \quad \textbf{3.3}$$

The mass factor of layers of particle matters for different fractions, table 3.3, has been determined using the method provided by **(Nannen, 2007)**.

Table 3.3: Mass factors of layers dust for both breeding system

Particles fractions rang [µm]	Mass factor [µg]	
	Cage system	Aviary system
0.30 - 0.40	5.61E-08	5.39E-08
0.40 - 0.50	1.19E-07	1.15E-07
0.50 - 0.65	2.49E-07	2.39E-07
0.65 - 0.80	4.99E-07	4.79E-07
0.80 - 1.00	9.54E-07	9.16E-07
1.00 - 1.60	2.88E-06	2.76E-06
1.60 - 2.00	7.63E-06	7.33E-06
2.00 - 3.00	2.05E-05	1.96E-05
3.00 - 4.00	5.61E-05	5.39E-05
4.00 - 5.00	1.18E-04	1.13E-04
5.00 - 7.50	2.57E-04	2.19E-04
7.50 - 10.0	6.74E-04	5.77E-04
10.0 - 15.0	1.58E-03	1.46E-03
15.0 - 20.0	3.31E-03	3.37E-03
> 20.0	9.77E-03	9.14E-03

3.3 Dust concentration quantification

The dust concentration has been measured continuously using an Aerosol spectrometer (model 1.108 GRIMM Aerosol techniques, Ainring, Germany) as shown in figure 3.11.

3.3.1 Measuring principle

The occupation of the dust monitor delivers the signal particle counts and classifies these particles according to their size in real time. A random sampling head collects the dust via a volume controlled pump and leads these particles directly into the optical chamber, which has a beam of light produced by a focused laser diode. There, each scattered signal generated by dust particles that cross this beam is detected with a high speed photo diode. The particle colour changes at 90° can be neglected. This pulse is analyzed by an integrated pulse height analyser. The particles are counted and classified by size into 15 different size ranges. These counts are stored on the data storage card and are displayed in intervals every minute.

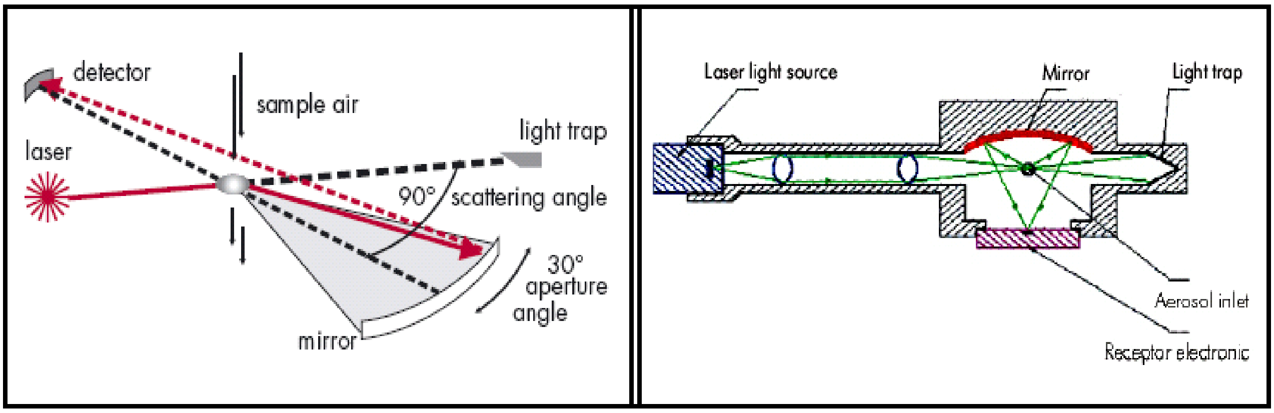


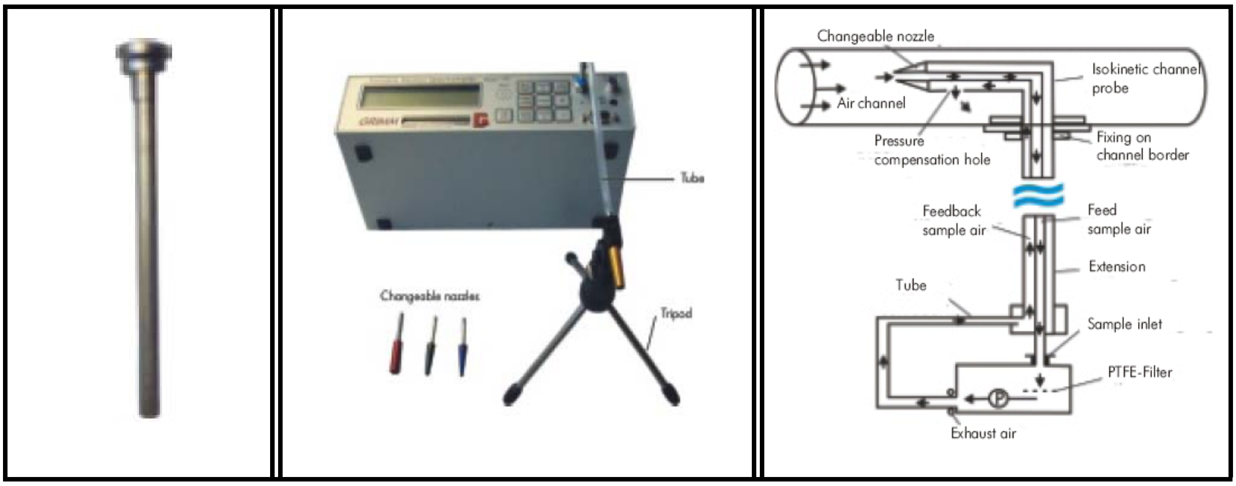
Figure 3.11: Measuring principle of aerosol spectrometer instrument (left: Principle function, right: Laser measuring chamber) (Grimm, 2004)

3.3.2 Instrument components

The aerosol spectrometer can be operated by battery and/or AC. The results were stored in a removable data logger card. The aerosol spectrometer has a removable filter. This filter is 47 mm in diameter and is used to collect the sampled aerosol. This filter has been fabricated from polytetrafluoroethylene (PTFE) which works in ranged temperatures of (-60 to 190 ˚C). The GRIMM dust monitor is provided with a volume controlled pump for a constant flow rate of 1.2 l/min. Therefore, a size-representative sampling depending on the sampling location is important. In order to ensure such a sampling which is required for particle measurements (especially for particles larger than 1 µm), the flow into the probe must be isokinetic. The speed and direction of the air flow entering the probe must be equal to those of the primary stream. Depending on the sampling conditions GRIMM has different sampling systems, as shown in figure 3.12.

1. **Radial symmetric sampling head**

The radial symmetric sampling head is used for indoor and outdoor measurements (air velocity from 0 to 2.5 m/s and different wind directions). For indoor measurements at work places and outdoor measurements the sample head is attached to the air inlet. The dust monitor is able to suck the sample air via the sample head through the measuring chamber, Figure 3.12 a.



a) Radial symmetric sampling head. b) Isokinetic sampling probe for unidirectional air-flows. c) Isokinetic stainless steel sampling probe.

Figure 3.12: Sampling systems for the aerosol spectrometer (Grimm, 2004)

2. **Isokinetic sampling probe for unidirectional air-flows (optional)**

This isokinetic sampling 3.12 b is used for the measurements in the air flow after filter systems where the air exits almost constantly with a velocity up to 4 m/s. This sampling probe consists of a tripod, a short tube and four interchangeable nozzles depending on the air velocity as following:

Nozzle colour	Air velocity range
Red	up to 0.5 m/s
Gold	up to 1.0 m/s
Green	up to 2.0 m/s
Blue	up to 4.0 m/s

The tube length between the nozzle and sample inlet at the dust monitor should be as short as possible to minimize the sedimentation of larger particles. When the air flows down from the top, it is possible to place the nozzle directly into the air inlet.

3. Isokinetic stainless steel sampling probe (optional)

Isokinetic stainless steel sampling from air ducts or stacks where air is led through a filter is suitable for air velocities up to 25 m/s, figure 3.12 c. The isokinetic sampling set includes four interchangeable inlet nozzles with different inlet diameter which can be screwed in depending on the air velocity as following:

Inlet diameter	Air velocity range
3.0 mm	2 up to 4 m/s
2.0 mm	4 up to 8 m/s
1.5 mm	8 up to 16 m/s
1.0 mm	16 up to 25 m/s

3.3.3 Instrument specifications

The main specifications of the aerosol spectrometer are as following:

Measuring principle:	Scattering laser light and filter collection (dual technology)
Measuring range:	0.3 to >20 µm
Size channels:	15 channel sizes
Sample flow rate:	1.2 litre/minute, volume controlled
Sensitivity:	1 particle/litre
Reproducibility:	± 2% in maximum range

PTFE filter Size:	47mm
Operating Temperature Range:	$4^{o}C$ to $45^{o}C$
Dimensions:	24 x 12 x 6cm
Weight:	2.4 kg
Power Requirements:	Battery or 110/220 VAC with external power supply

3.3.4 Working sequence

Quantification of the dust concentration has been done within two different breeding systems for laying hens to find out the effect of breeding systems on the dust concentration. These experiments were carried out in two different houses in the Dülmen farm. The first barn was for a cage system with 46.000 laying hens and the second barn was for an aviary system with 14.600 laying hens. These measurements have also been done continuously for 24 hours during different days through out two different seasons (summer and winter) to estimate the effect of day/night time and season on dust concentration and its emission rate.

The measurements have been done above the ceiling of the laying hen barn using an aerosol spectrometer. A heating system has been used during the outside measurements whilst cold weather. This system does not heat the sample pipe because heating the sample pipe would simply drive out all the semi volatiles from the air and give wrong results. The instrument is also kept inside a metal box to protect it from the rain during the measurement periods as shown in figure 3.13.

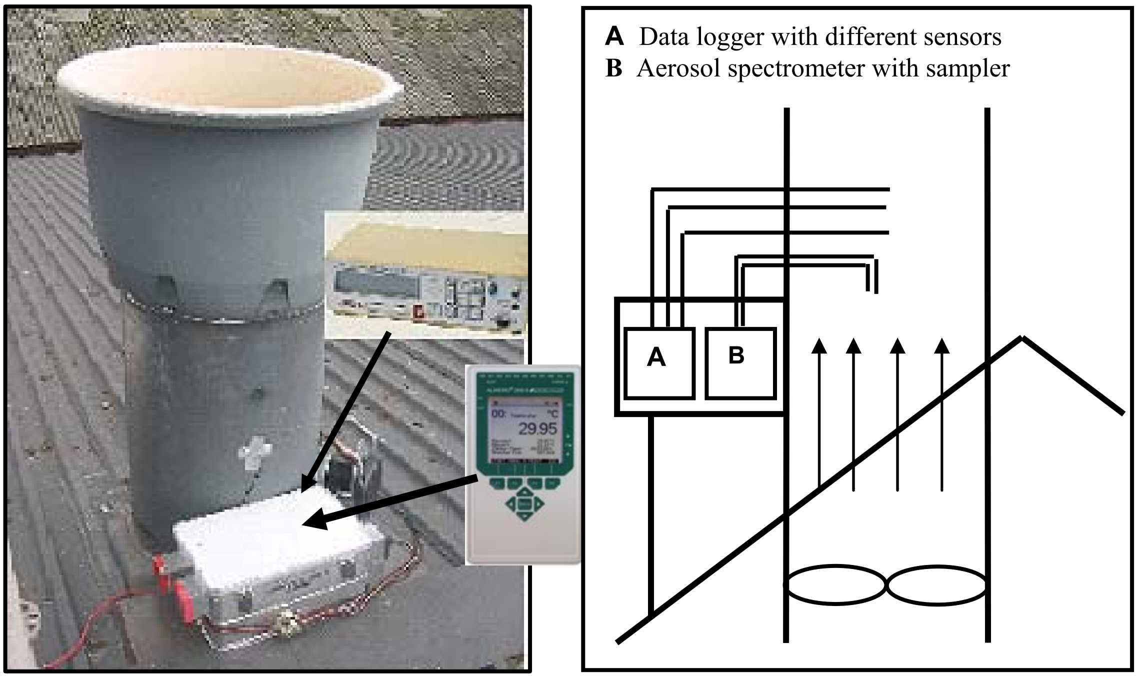


Figure 3.13: Quantification of the dust concentration (left: real image for instruments setup, right: Schematic for instruments setup)

The air velocity inside the chimney, air temperature of the barn and its relative humidity have been measured via data logger and specific sensors.

3.4 Estimation of dust emission

The dust emission rate has been calculated using equation 3.4:

$$\underset{[\mu g/h]}{\textit{Dust emission rate}} = \underset{[Particle/m^3]}{\textit{Particle Nr.}} * \underset{[\mu g/particle]}{\textit{Mass factor}} * \underset{[m^3/h]}{\textit{Air volume flow}} \qquad 3.4$$

1. The particle number has been quantified into different fraction sizes using the aerosol spectrometer.
2. The mass of the particle factor has been estimated using:
    a. Shape factor which has been determined by microscopic analysis.
    b. Dust density which has been determined using a sedimentation cylinder.
3. The air volume flow for the whole day has been determined by means of climate computer and calibrated measuring fans as shown in figures 3.14, 3.15, and 3.16.

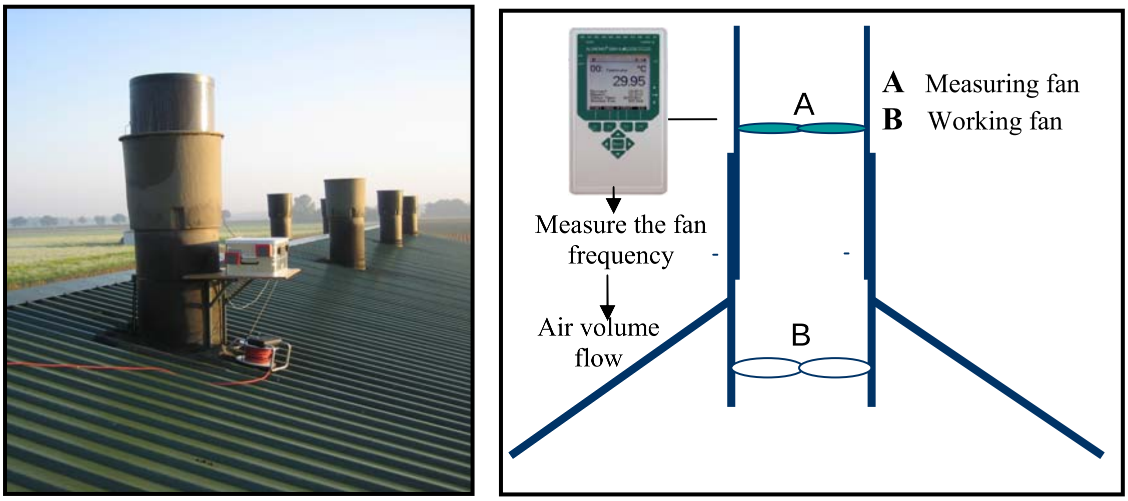


Figure 3.14: Air volume flow (Ventilation rate) measurement (left: real image for instruments setup, right: Schematic for instruments setup)

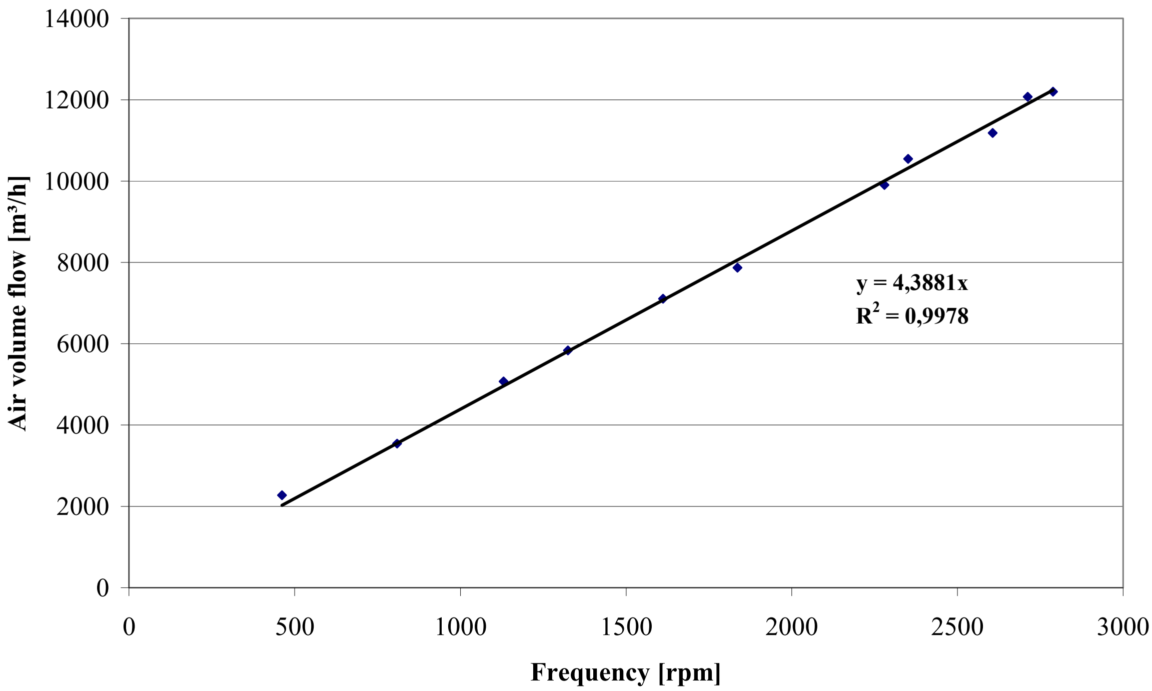


Figure 3.15: The calibration curve of the used measuring fan with 630 mm diameter

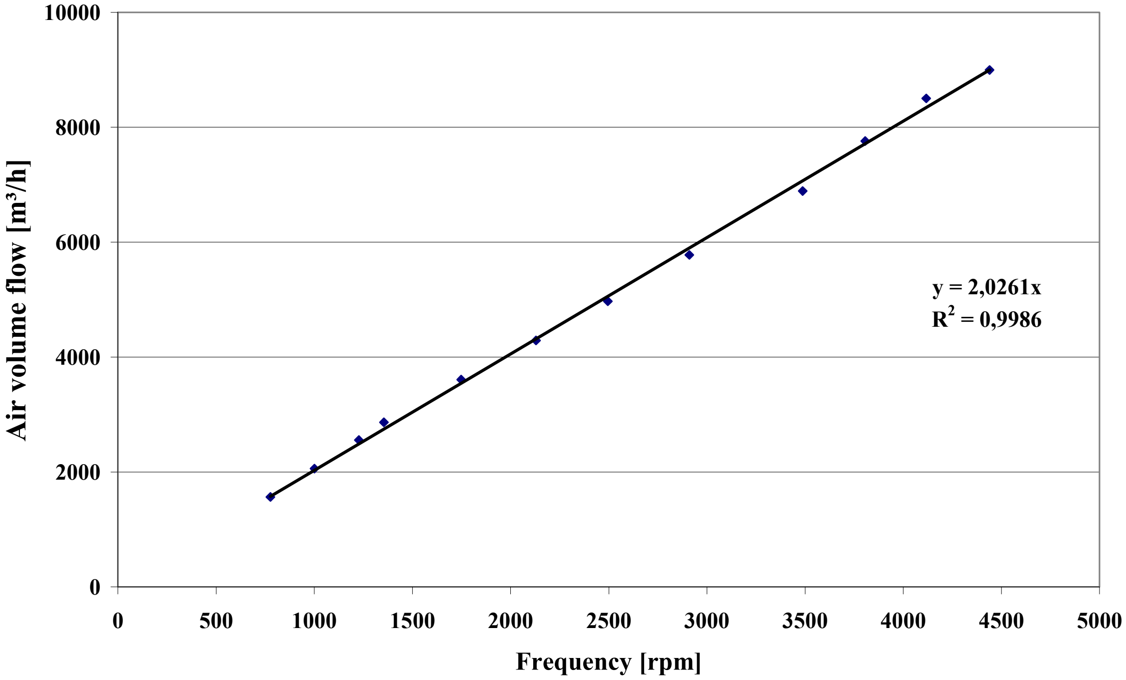


Figure 3.16: The calibration curve of the used measuring fan with 520 mm diameter

3.5 Theoretical animal activity

Animal activity has a large influence on the generation of dust inside the barn and increases the emission into the surrounding environment. The theoretical animal activity has been estimated according to the experimental equation (3.5) provided by **(Pedersen and Sällvik, 2002).**

$$A = 1 - a * \sin\left[\left(2 * \frac{\pi}{24}\right) * \left(h + 6 - h_{\min}\right)\right] \qquad \textbf{3.5}$$

Where:

A = Relative animal activity.

a = Constant (expressing the amplitude with respect to the constant 1).

= 0.61 for laying hens from table, table 3.4.

h_{min} = Time of the day with minimum activity (hours after midnight).

= - 0.1 for laying hens from table, table 3.4.

Table 3.4: The parameters of theoretical animal activity equation (Pedersen & Sällvik, 2002)

Type of Animals	a	Time of the day with minimum activity
Dariy cows, tie stall	0.23	2.2 (02:10)
Dariy cows, cubicles	0.22	2.9 (02:55)
Heifers	0.38	3.1 (03:05)
Calves	0.29	2.0 (02:00)
Lactating sows	0.35	1.8 (01:50)
Wearers	0.63	2.9 (02:55)
Fattening pigs, partly slatted floor	0.43	1.3 (01:20)
Fattening pigs, deep litter	0.53	1.7 (01:40)
Layers	0.61	-0.1 (23:55)
Broiler (permanent light and ad lib.feeding)	0.08	Not defined

3.6 Dust reduction systems

The main goal of the project was to reduce the indoor dust concentration and keep a clean area for the laying hens and workers by recycling the air inside the barn as shown in figure 3.17. This goal has been achieved by using two different systems inside the laying hen house under an aviary breeding system to find out the highest reduction efficiency. These two filter systems are a dry filter system and a wet filter system.

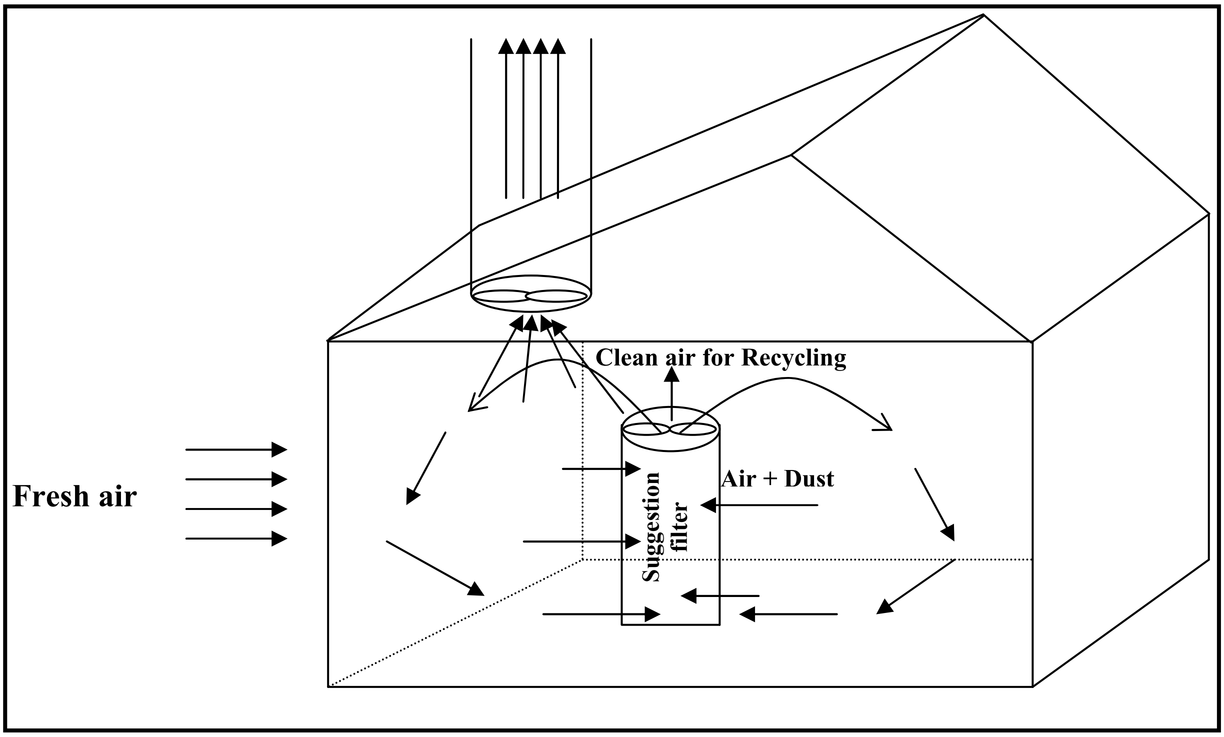


Figure 3.17: Working way of suggestion filters

3.6.1 Dry filter systems.

3.6.1.1 Designed dry filter.

Selecting the filter material and the right ventilator was an important aspect whilst designing the filter. Three different materials have been tested in the institute of agricultural engineering, Bonn University, under laboratory scale using a wind channel as shown in figure 3.18. The wind channel is a tube of 15 m length and 0.92 m in diameter. This wind channel consists of a working ventilator, measuring ventilator, wood box and a dust release unit. The air velocity inside the wind channel has been adjusted by controlling the rotation of the working ventilator. The air velocity has been selected to be 0.75, 1.00 and 1.25 m/s. The filter materials have been located inside the wood box to test them.

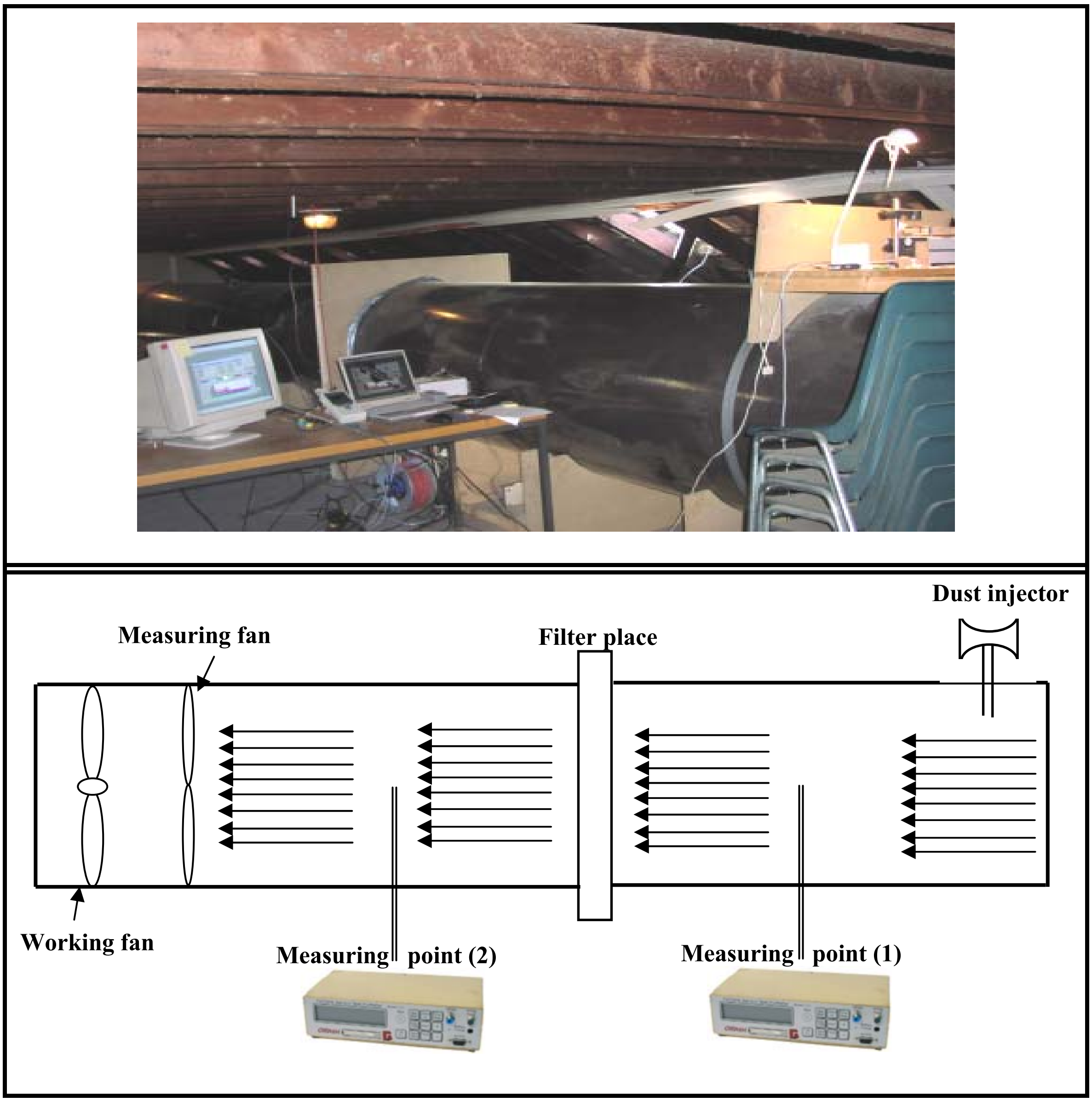


Figure 3.18: Wind channel for laboratory measurements

These filter materials have been provided by the big Dutchman company for poultry houses which work with the principle of centrifugal force. These three filter materials are:

1. StuffNix material

This filter material is a multilayer filter wall. Dust particles collect outside the air flow in the V-shape chamber as shown in figure 3.19.

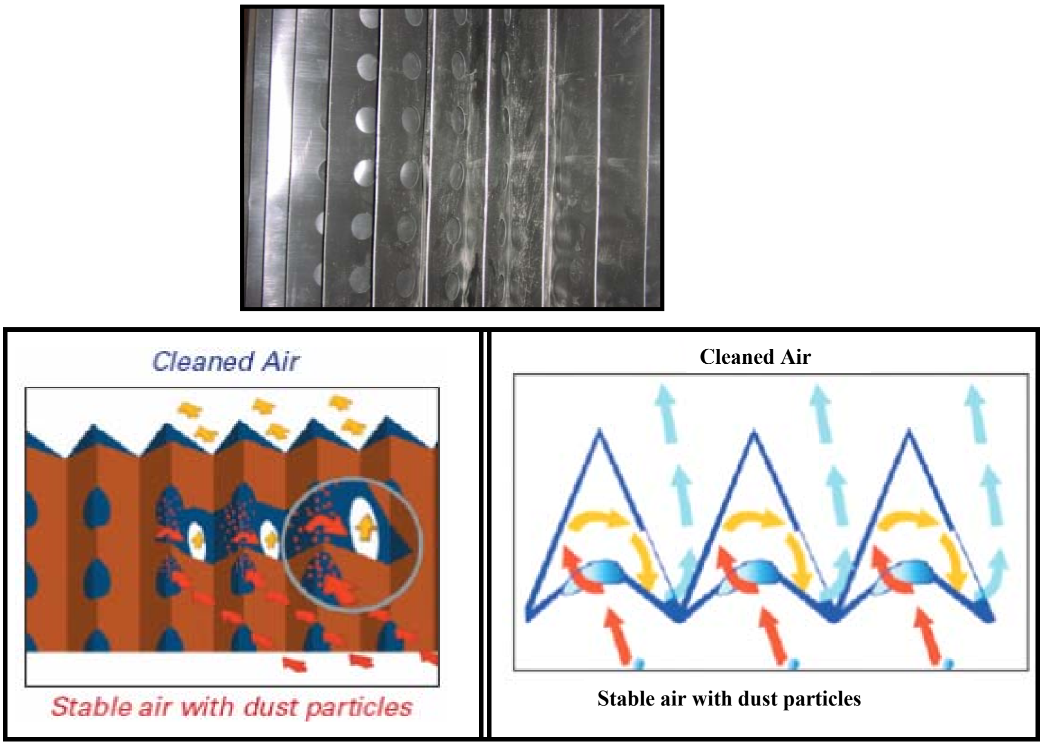


Figure 3.19: StuffNix filter material

As shown in figure 3.20, this material consists of a half tube with a 50 mm diameter. These tubes combine in a parallel structure. The distance between the two tubes in the same line is 10 mm.

2. Half tube material

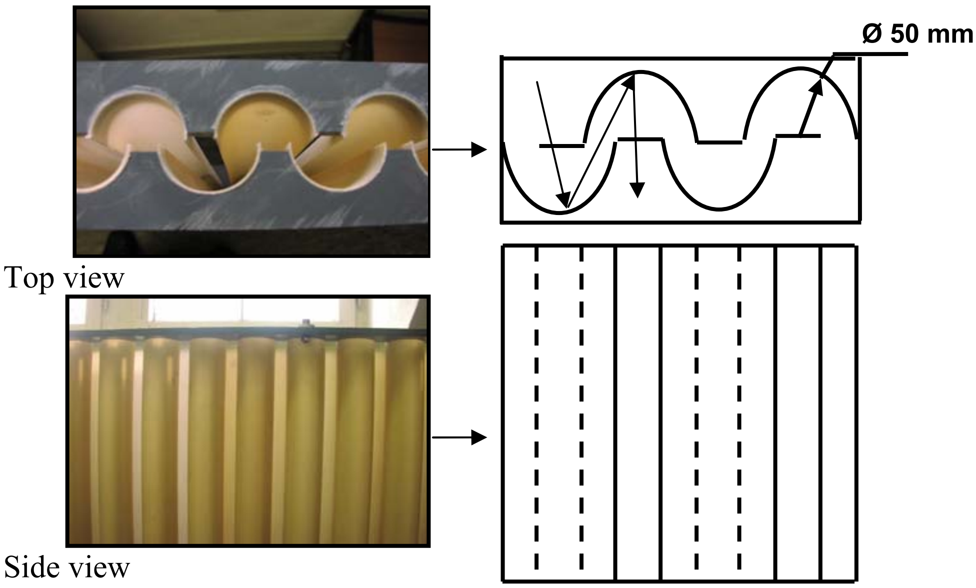


Figure 3.20: Half tube filter material

3. Double tube material

As shown in figure 3.21, this material is half rectangular with a 50 mm width. These rectangles combine in a parallel structure. The distance between two rectangles in the same line is 10 mm. Each rectangel has two small tubes with 25 mm diameter.

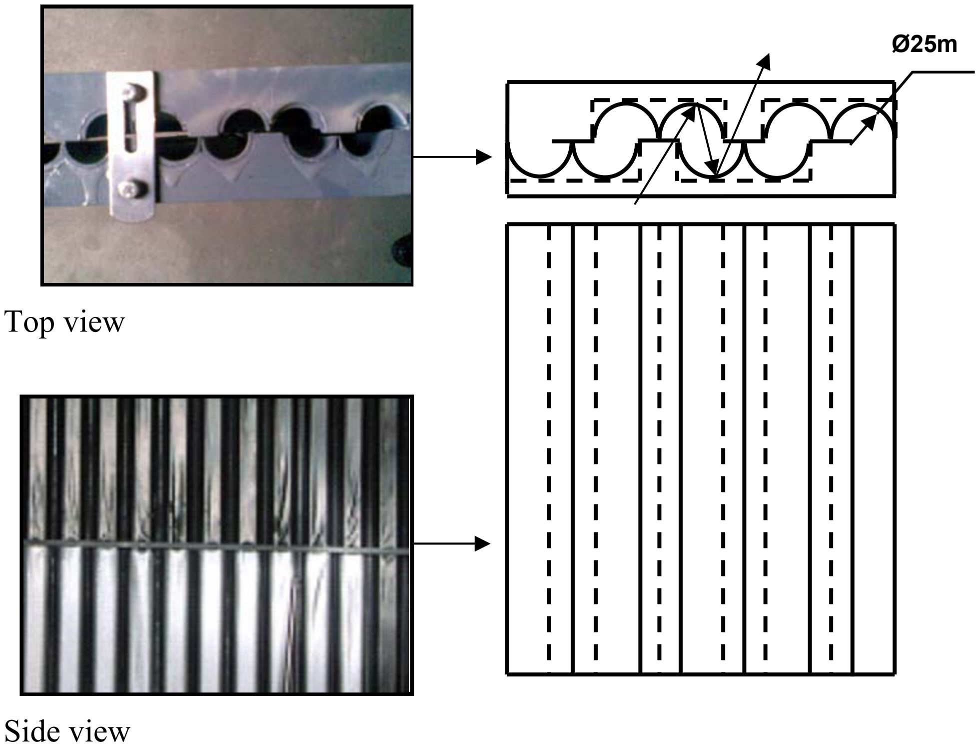


Figure 3.21: Double tube filter material

The intake of dust inside the wind channel has been done using a release unit as shown in figure 3.22.

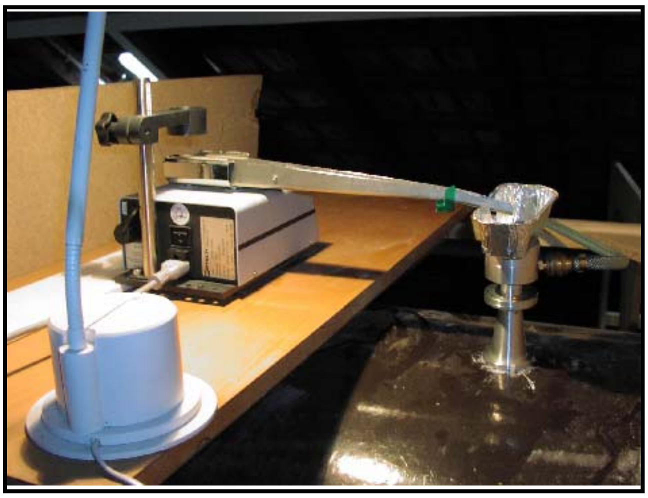


Figure 3.22: The components of the dust release unit

This release unit consists of two main parts: a vibratory channel and a dust injector. The vibratory channel (Retsch company, model DR 100) transfers the dust to the injector with a fixed rate for all the experiments, figure 3.23. The dust injection has been done using a Venturimeter which works with air pressure. The air pressure has been adjusted to 2 bar for all of the experiments. The measurements have been done using layers and dolomite dust. The used dust in the laboratory experiments has been collected from the laying hen in Dülmen farm.

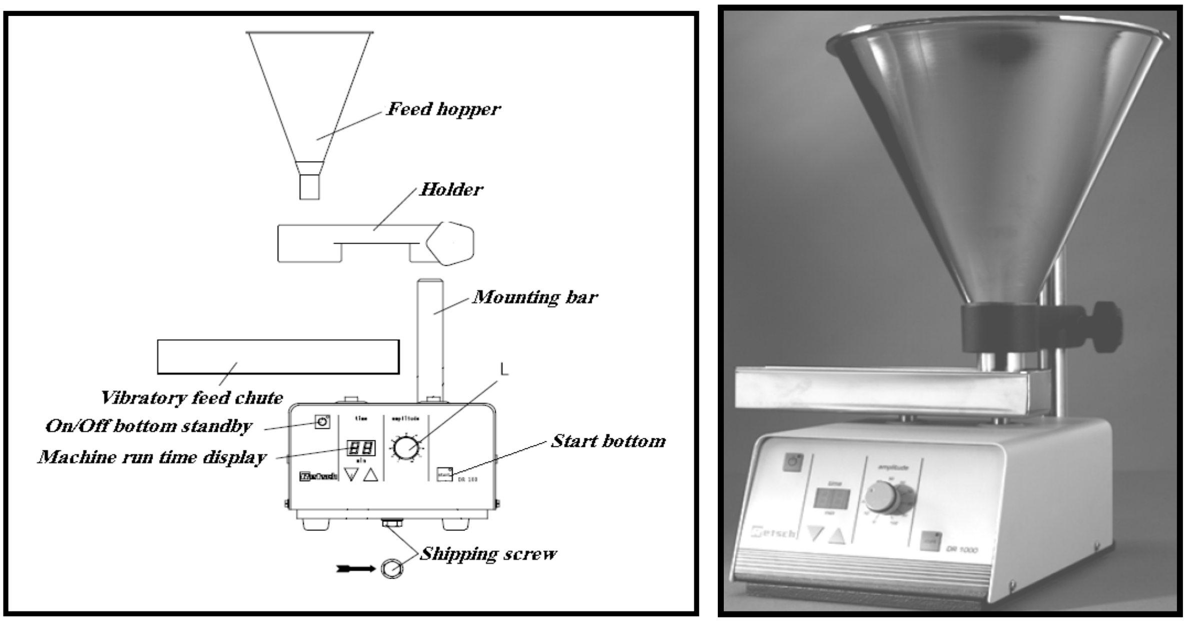


Figure 3.23: Vibratory releasing unit

The previous measurements showed the highest efficiency of StuffNix filter material with 1 m/s air velocity. According to these results, the StuffNix filter system has been designed and fabricated in the workshop of the Agricultural Engineering Institute, Bonn University. As shown in figure 3.24, this filter system consists of a ventilator, StuffNix material and a wood box. The air volume flow of the used ventilator under this air velocity is 800 m^3/h. and other technical data are shown in Appendix (1).

The designed filter has been tested on a small scale farm (Frankenforst) to find out its efficiency regarding the reduction of the indoor dust concentration and emission. A smoke generator was used for estimating the position of the filter inside the barn.

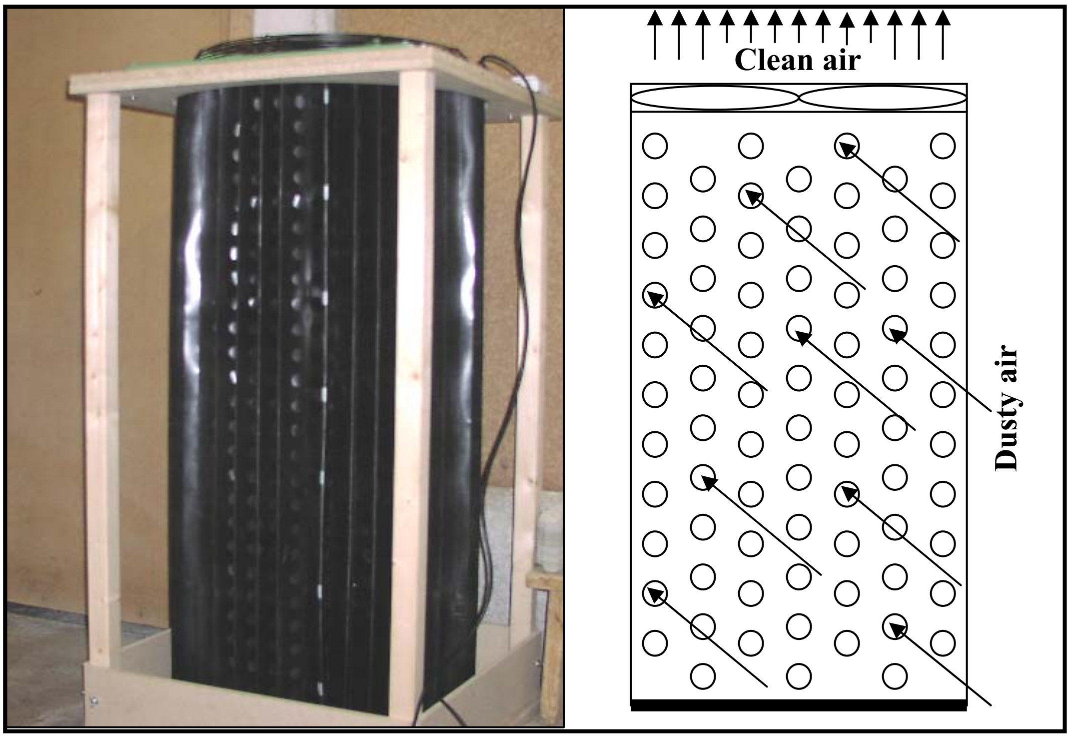


Figure 3.24: Designed StuffNix filter

3.6.1.2 Cyclone

A cyclone as shown in figure 3.25, removes particulates by causing the dusty air stream to flow in a spiral pattern inside a cylindrical chamber. Dusty air enters the chamber from a tangential direction at the outer wall of the device forming a vortex as it swirls within the chamber. The larger particulates move outward because of their greater inertia and are forced against the chamber wall. Slowed by friction with the wall surface the particles slide down the wall into a conical dust hopper at the bottom of the cyclone. The cleaned air swirls upward in a narrower spiral through an inner cylinder and emerges from an outlet at the top. Accumulated particulate dust is periodically removed from the hopper for disposal.

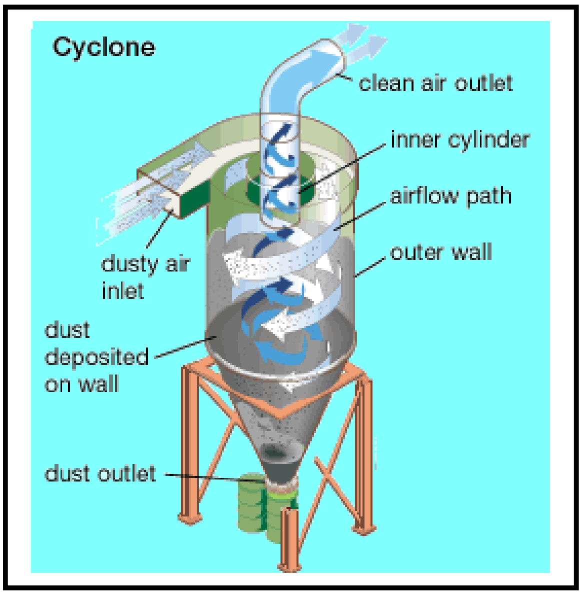


Figure 3.25: The principle work for cyclone separator

For a small scale experiment a vacuum cleaner working with the cyclone system has been used. This vacuum cleaner, shown in figure 3.26 is fabricated by the Dyson company (model DC 08) and called a cyclone vacuum. The vacuum cleaner sends the air stream through more cylinders along a high-speed spiral path. As the air stream shoots around in a spiral all of the dust particles experience a powerful centrifugal force. The particles are whipped outward away from the air stream. With this method the dust particles are extracted from the air without using any sort of filter. They simply collect at the bottom of the cylinder.

Figure 3.26: Vacuum cleaner working with root cyclone technology system (left: working theory, right the used cyclone)

3.6.2 Wet filter system (scrubber)

The used wet filter system has been designed by modifying the system, which is provided by (**Hölscher, 2006)**. As illustrated in figure 3.27, this recirculation system consists of a ventilator, filter material, a tube with 630 mm diameter and water sprinklers. The technical data and performance curve for the selected ventilator is shown in appendix (2).

The used filter material is called mist eliminator component (TEP 130) and is produced by the 2H Kunststoff company with 630 mm in diameter, figure 3.28. Two pieces from this material were used to obtain high air quality. This material has the ability to absorb the chemical and physical components.

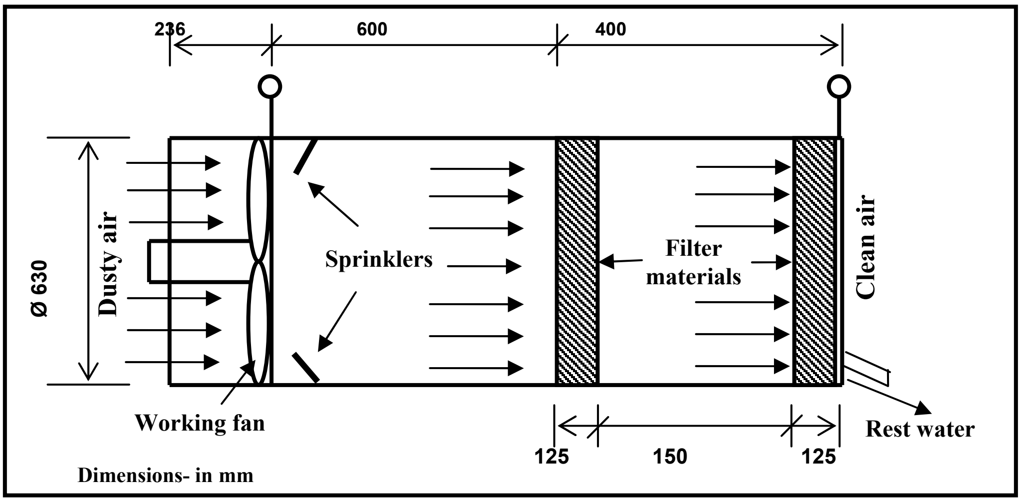


Figure 3.27: Designed wet filter (scrubber)

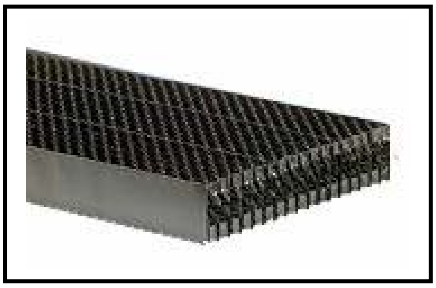


Figure 3.28: TEP 130 - eliminator component

Two flat brass sprinklers were used (800050, Spraying 7Systems Deutschland GmbH). As shown in figure 3.29, each sprinkler consists of a sprinkler body, filter and nozzle. The technical data such as water pressure and discharge of theses filters are shown in appendix (3).

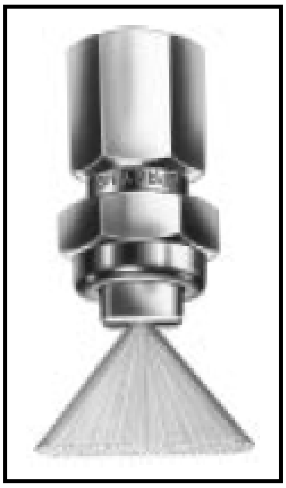


Figure 3.29: UniJet flat sprinkler

The primary experiments were done on the Dikopshof farm to find out the optimum working condition for water pressure and air velocity, figure 3.30. The dust injection was done with the previous which has been used for laboratory measurements of dry filter materials. The various parameters of water pressure were 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 bar. The various parameter of air velocity were 3, 4, 5 and 6 m/s.

From these primary experiments air velocity was set at 4 m/s and water pressure was selected at 1 bar respectively. The wet filter system was also tested on the small scale farm in Frankenforst. With 4 m/s air velocity the air volume flow for the system was 4500 m^3/h. The position of this filter in the farm was estimated with a smoking machine.

After testing dry and wet filter systems on the small scale Frankenforst farm the designed dry filter system with StuffNix filter gave the highest efficiency. Accordingly, on the commercial farm in Düren, StuffNix filter has been tested to discover its efficiency in the large scale farm and the possibility of using it in commercial scale with high efficiency.

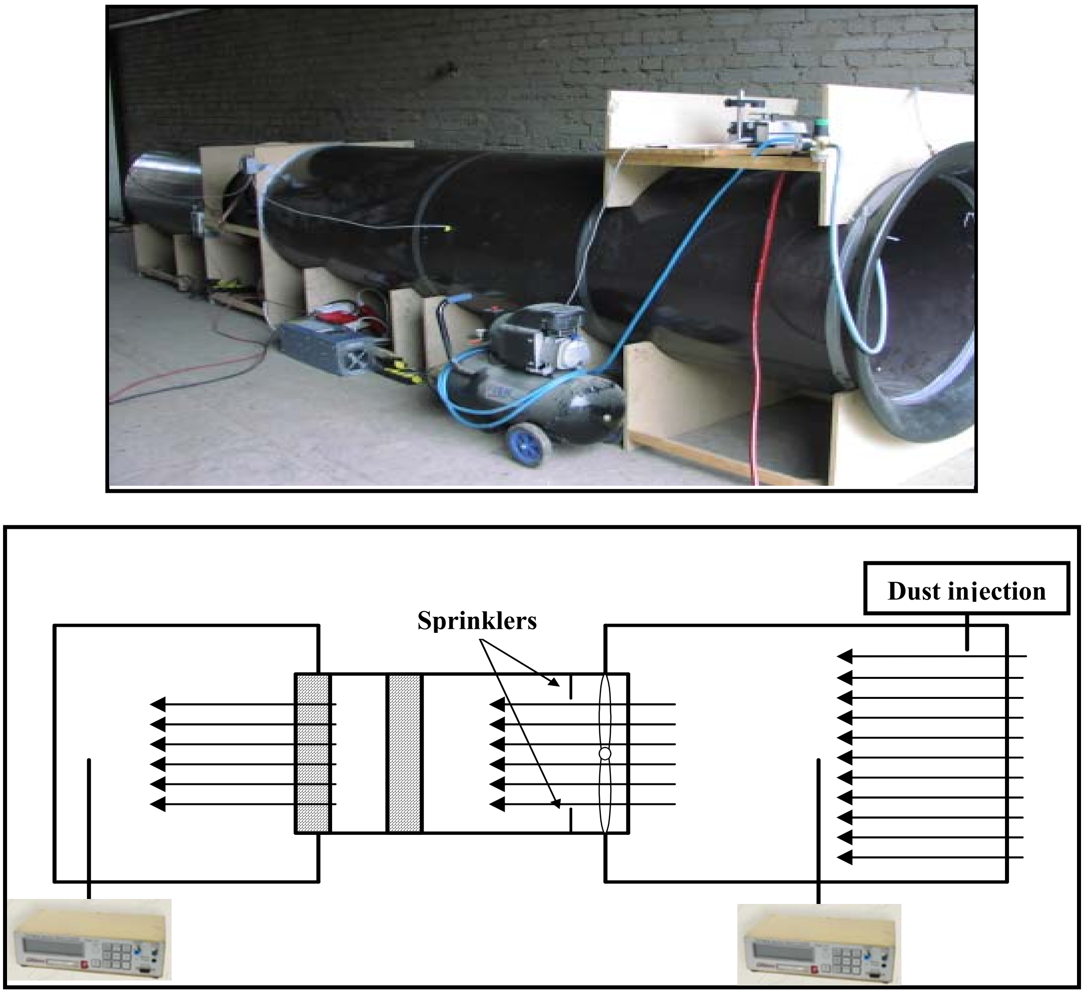


Figure 3.30: Laboratory testing device for measurements of wet filter system

4 Results

4.1 Dust characterization

The calculated dust emission rate is needed in order to characterize the dust and recognize its physical properties such as the particle shape and density. The Particle shapes have been determined by microscopic analysis however the particle density has been determined by sedimentation measurements. Particle shape and density have been used to calculate the mass factor, which has been used to calculate the dust emission rate as explained previously in chapter 3.

4.1.1 Dust density

Figure 4.1 illustrates the relation between particle matter size ranges and sedimentation velocity. Sedimentation velocity was slower for the small particles than for the large particles. The gravity of particle matter has a strong influence on the time of its sedimentation to the ground. The large particles fall down to the ground quicker than the small particles. The sedimentation velocity also depends on the particle weight, size ranges, air temperature, and relative humidity.

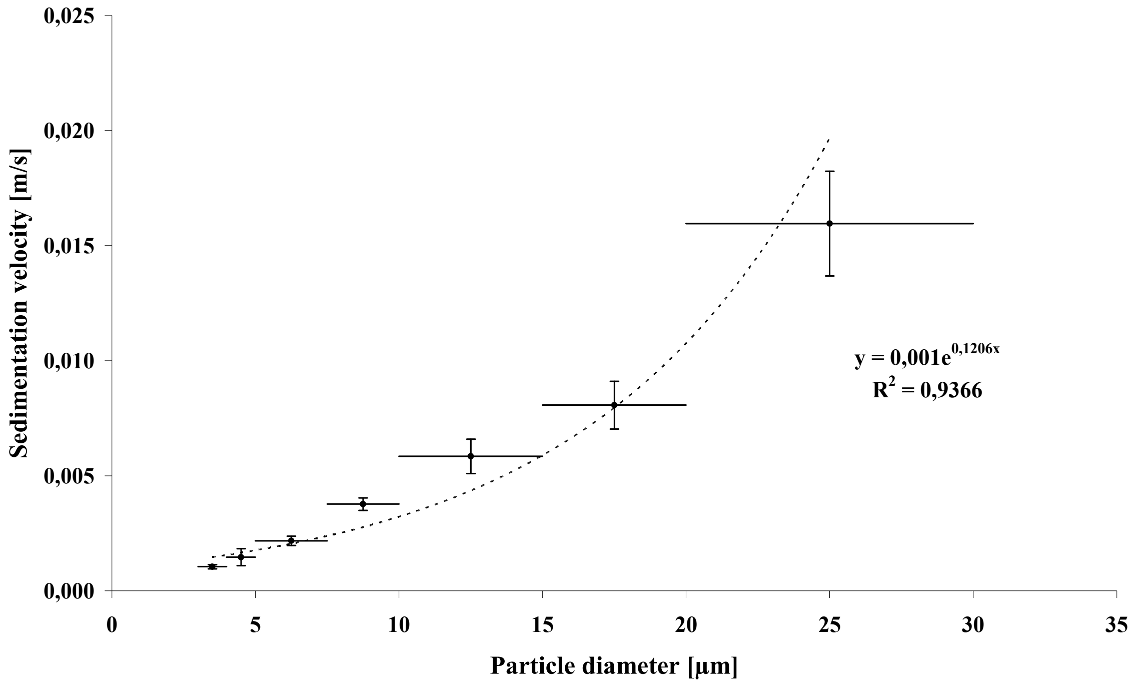


Figure 4.1: Sedimentation velocities of different particle size ranges

Relationship between particle shape factor and density on different particle size ranges has been calculated. The computation ratio of the particle density and shape factor depends upon the particle diameter as observed in figure 4.2. This ratio was higher with smaller particles than large particles.

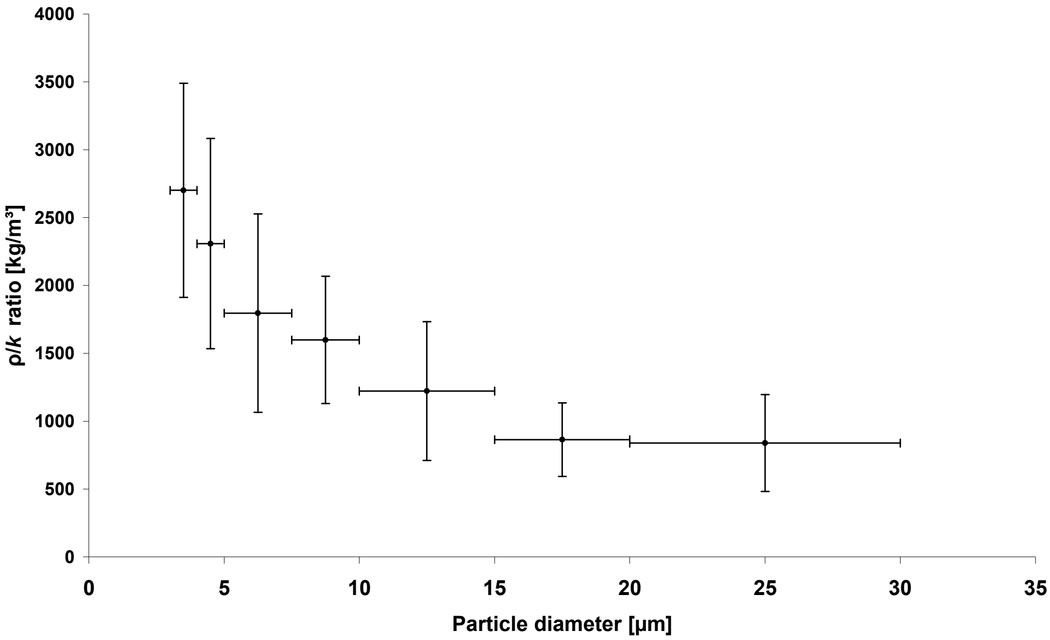


Figure 4.2: Relationship between particle density and its shape factor for different particle size ranges

4.1.2 Particle shape

Estimation of the particle shape factor and density were required in order to calculate the mass factor and dust emission rate. The shape factor has been determined by using microscopic analysis and has been examined with a special computer program in order to obtain images. The computer program estimated the length, area and the diameter of each single particle. The obtained values have been used to estimate the shape factor. Figure 4.3 illustrates the shape factor for different particle fraction ranges in both breeding systems (aviary and cage housing system). According to the particle diameter the shape factor ranged from 1.00 to 1.57 and from 1.20 to 1.77 for cage and aviary systems respectively. As shown in figure 4.3, the shape factor for the large particles was higher than for the small particles. Significant mean difference has been observed from statistic analysis using SPSS program. In consequence each fraction has to be calculated individually in the filter density investigation. An estimation of the exact shape factor for the particle matter with a diameter lower than 4 µm was very difficult due to inability of the used microscope to recognize these fraction sizes. Determined data from mean particle shapes and densities in dependence of the particle size has been used to calculate the mass factor and dust emission rate.

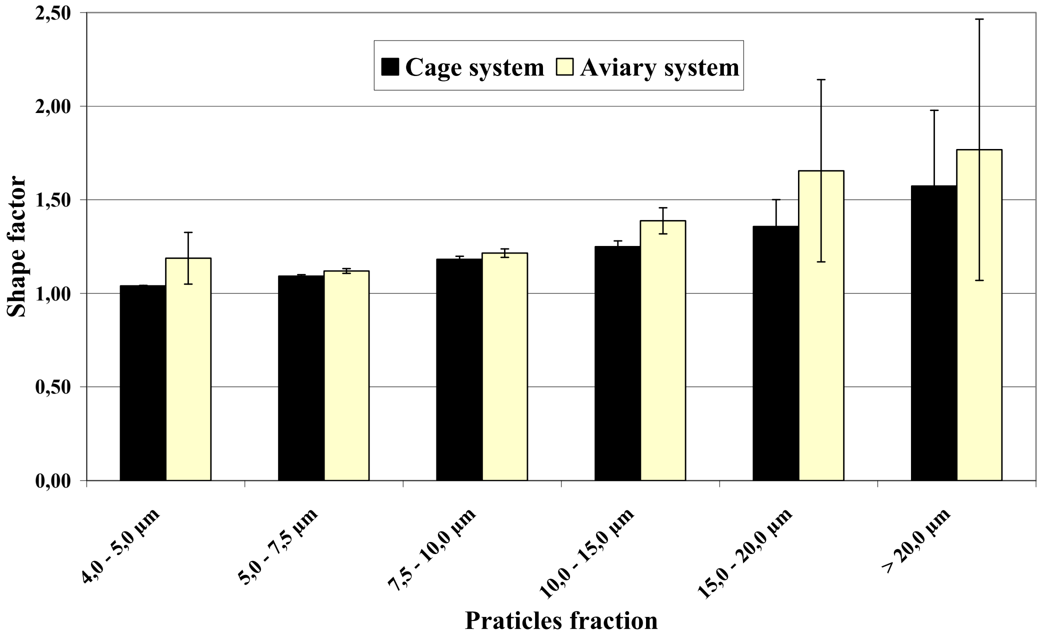


Figure 4.3: Shape factors for different particle fractions with two breeding systems (Differences are significant, P < 0.05)

4.2 Influences on indoor dust concentration and emission rate

4.2.1 Effect of breeding system

Breeding system has a big influence on the indoor dust concentration and the dust emission rate. Figure 4.4 illustrates the effect of different breeding systems on the indoor dust concentration with different particle ranges. As one can see both breeding systems show a high mass concentration with the large particle ranges compared to the small particles ranges. Breeding with the aviary system showed a higher mass concentration than the cage breeding system. The variety of indoor mass concentration is different according to the particle size ranges. This difference of indoor mass concentration was six time higher in an aviary system than in a cage system for the particle diameter ranges from 10 – 15 µm. In Figure 4.5 the housing factor effects an increase in the aviary system in comparison to the cage system with all particle ranges during the winter season. The housing factor has been calculated with different particle ranges (Cage/Aviary *100) by means of dividing the indoor dust concentration from the cage system through the indoor dust concentration from the aviary system. The figure also illustrates the total indoor dust concentration in an aviary system to exceed the cage system by 18.76 %. This increase appeared clearly within the smallest particle ranges as well as the larger particle ranges. The same results were observed during the winter season measurements.

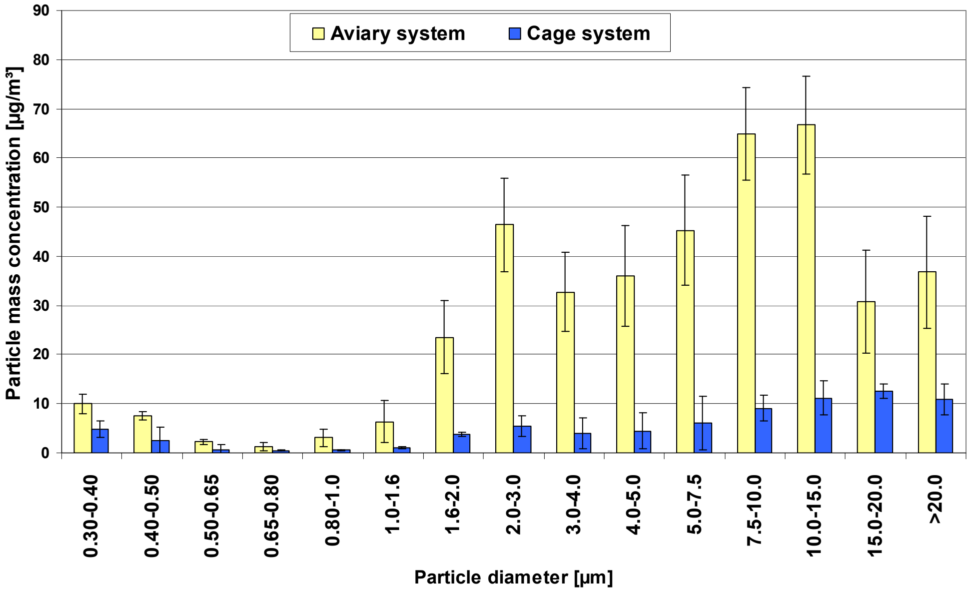


Figure 4.4: Particle mass concentration with two different breeding systems

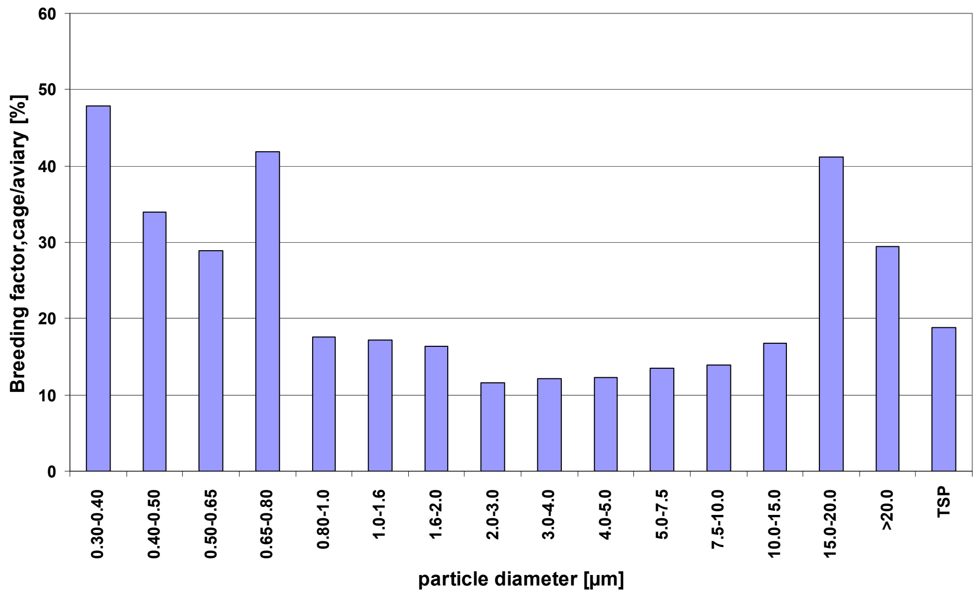


Figure 4.5: Housing factor (aviary system / cage system) with different particle fractions

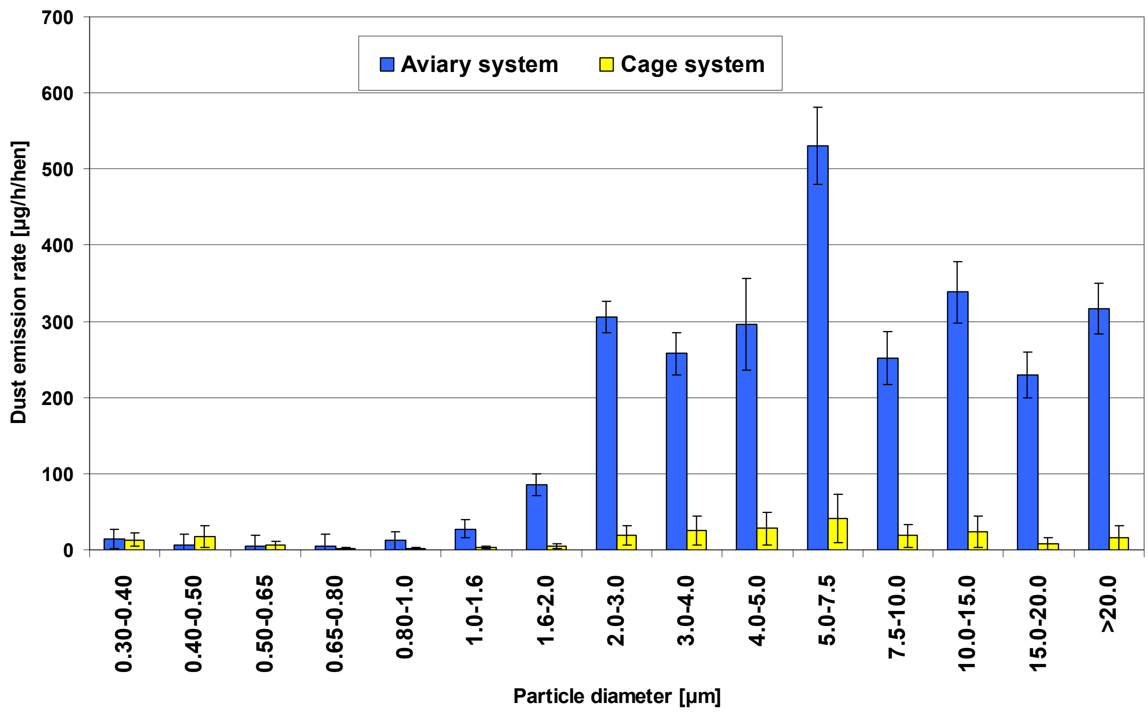


Figure 4.6: Dust emission rate with two different breeding systems

Figure 4.6 describes the dust emission rate of different particle ranges for both breeding systems (aviary and cage housing systems). The aviary system showed a greater dust emission rate than the cage system. The highest emission rate for the aviary housing system clearly results from large particles ranges. This housing system reached its maximum emission rate with 530 µgh^{-1}hen^{-1} at 5.0 – 7.5 µm particle ranges. Its minimum emission rate was 14 µg h^{-1}hen^{-1} in the 0.5 – 0.6 µm particle range. The dust emission rate in the cage system is very low in all particle ranges. The average dust emission rate in the cage system ranges from 1.5 µg h^{-1}hen^{-1} in the 1.8 – 1.0 µm particle fraction classes to 40.5 µg h^{-1}hen^{-1} in the 5.0 – 7.5 µm particles fraction classes. Figure 4.6 describes the data from the summer season measurements. Similar results have been observed during the winter season measurements.

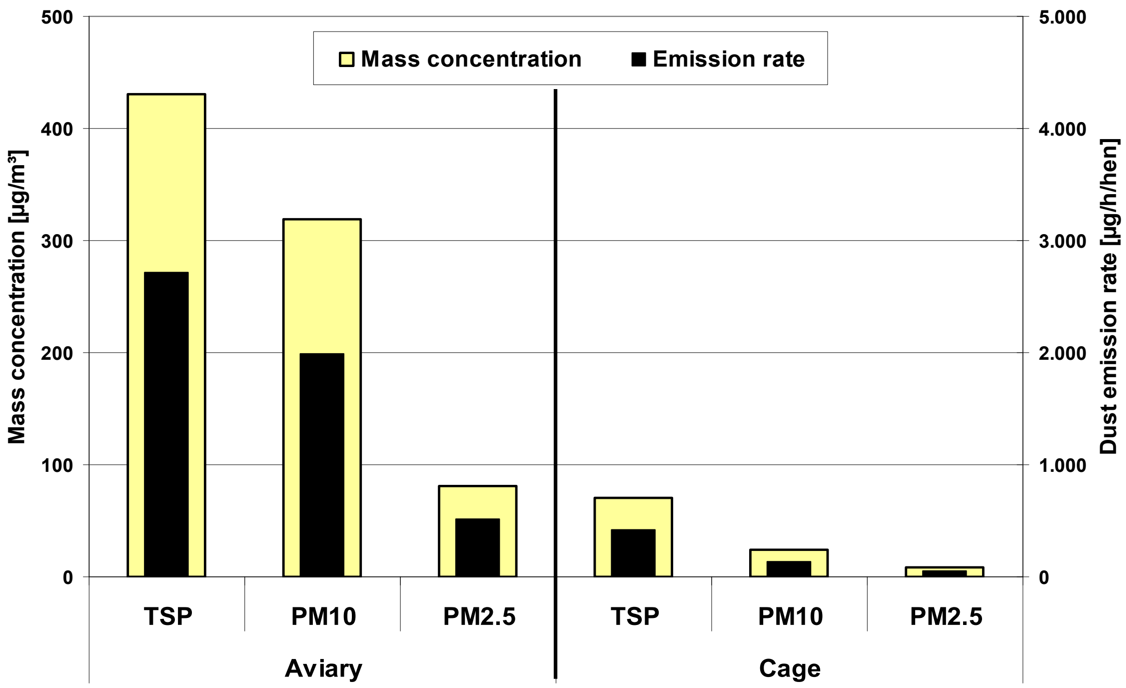


Figure 4.7: Indoor dust concentration and dust emission rate for different particle diameter categories (Differences are significant, P<0.05)

Figure 4.7 shows the total indoor mass concentration and dust emission rate for both breeding systems with different particle fraction categories during the summer season measurements. The total indoor dust concentration was 430.75 and 70.36 µg m^{-3} for aviary as well as cage housing systems. PM_{10} and $PM_{2.5}$ concentrations were 319 and 81µgm^{-3} for the aviary housing system and the cage housing system's concentrations were 23.7 and 1.5 µg m^{-3}. The total dust emission rates were 2917 and 421 µg $h^{-1}hen^{-1}$ for aviary and cage housing systems respectively. PM_{10} and $PM_{2.5}$ emission rates were 1994 and 513 µg $h^{-1}hen^{-1}$ respectively for the aviary housing system and were 138 and 48 µg $h^{-1}hen^{-1}$ for the cage housing system. The mean differences for indoor mass concentration and dust emission rate are significant at the $P < 0.05$ level.

4.2.2 Seasonal effects

Figure 4.8 illustrates the influence of the seasonal effects on indoor mass concentration and its correlation with air temperature and relative air humidity. The difference of dust mass concentration in summer and winter time for both breeding systems was minimal. The total indoor mass concentration in an aviary housing system was 431, 470 and 413 µg m^{-3} for

June, August and January respectively. The same could be observed for PM_{10} and $PM_{2.5}$ in both breeding systems. There was a significant difference between winter and summer season in the indoor particle concentration ($P < 0.05$) as shown in figure 4.9. As expected, the winter time showed a higher indoor particle concentration than the summer time with all particle categories.

The total indoor particle concentration during winter was 255 and 108 million particles m^{-3} for the aviary and the cage housing system, respectively. On the other hand the indoor particle concentration during summer (June) was 65 and 38 million particles m^{-3} for the aviary and the cage housing system respectively.

The seasons also showed a significant difference in the dust emission rate in both breeding systems. The dust emission rate is almost the same in summer as shown in the two months' measurements (June and August). The difference appeared in the winter time in comparison to the summer time. As shown in figure 4.10 the total dust emission rates in the aviary house during the summer season were 2.917, 2.682 µg h^{-1} hen^{-1} for June and August respectively and in the cage system were 421, 227 µg h^{-1} hen^{-1} for June and August respectively. In the winter time the total dust emission rates were 734 and 126 µg h^{-1} hen^{-1} for aviary and cage systems respectively. The same results have been observed with other particle fraction categories, PM_{10} and $PM_{2.5}$.

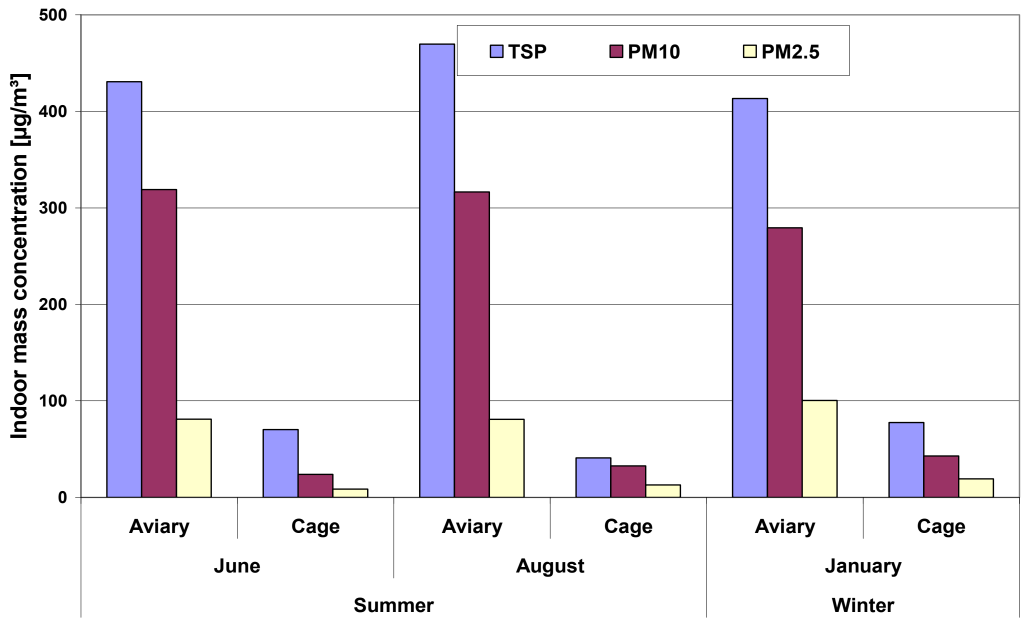


Figure 4.8: Indoor mass concentration during two different seasons (Differences are significant, $P < 0.05$)

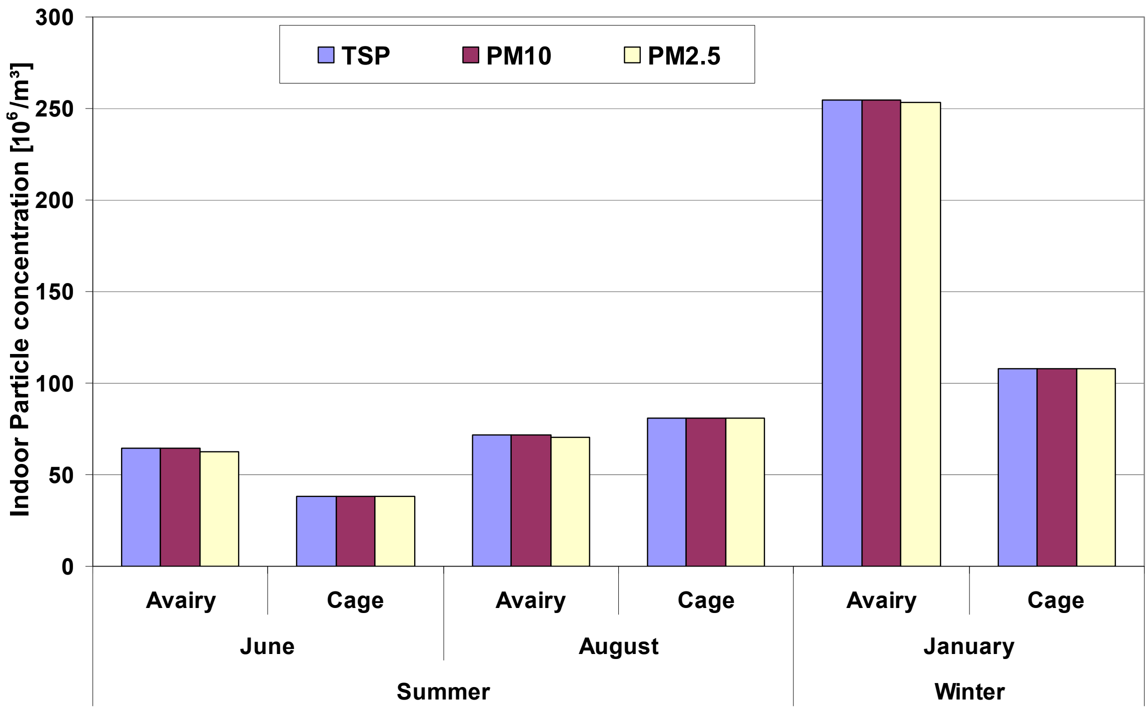


Figure 4.9: Indoor particle concentration during two different seasons (Differences are significant, $P < 0.05$)

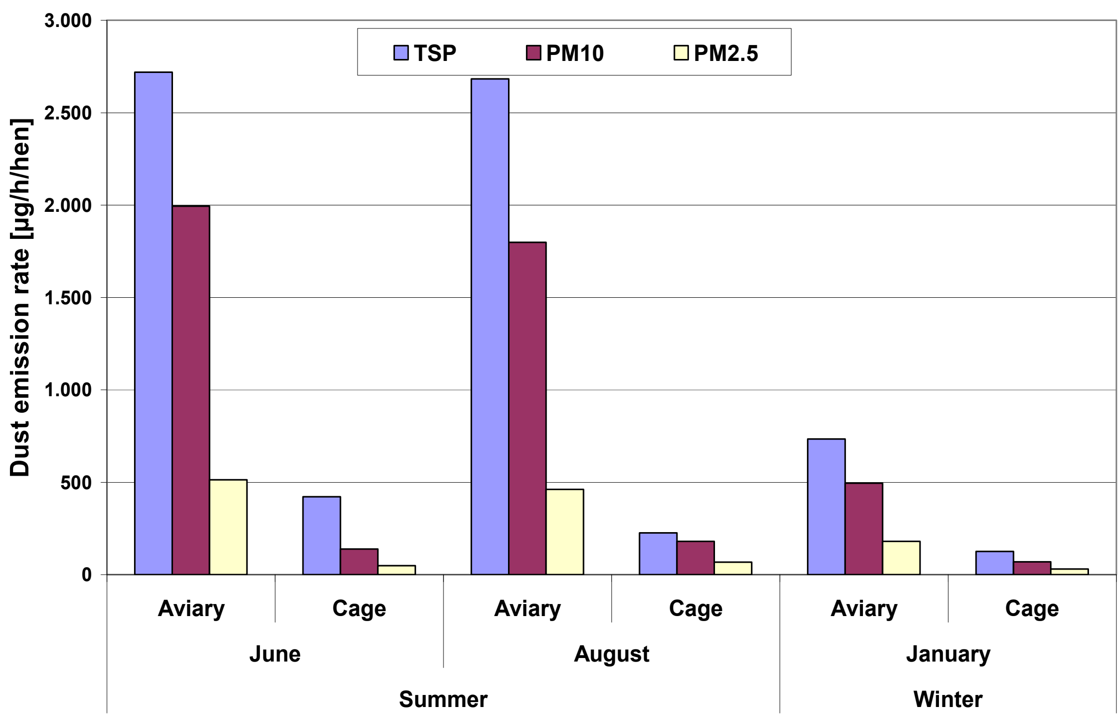


Figure 4.10: Dust emission rate during two different seasons (Differences are significant, $P < 0.05$)

4.2.3 Diurnal change

Figure 4.11 illustrates the distribution of the indoor mass concentration for the whole day during the winter season. The indoor dust concentration increases gradually in both breeding systems. This increase starts at 3:00 O'clock in the morning until midday and then decreases gradually until 20:00 O'clock. The dust concentration is almost stable after 20:00 O'clock until the next morning. The results for both breeding systems are nearly the same with the summer time measurements.

4.2.4 Animal activity

Theoretical animal activity has been calculated in order to find out its relation to the dust emission rate in a layers barn. Figure 4.12 describes this relation for the aviary housing system in August (summer time) throughout the whole day. The theoretical animal activity appears as a sine curve. The total dust showed a high emission rate with increasing animal activity in the chicken coop. This increase of the dust emission rate started in the early hours of the day till it reached its maximum in the middle of the day and then it decreased with low animal activity to a minimum emission at midnight. The same results have been observed during June and January for both housing systems. The theoretical dust emission has also been predicted using an equation (3.5) for theoretical animal activity. Figure 4.13 describes the relation between theoretical animal activity and theoretical dust emission. The theoretical dust emission shows the same sine curve as the theoretical animal activity.

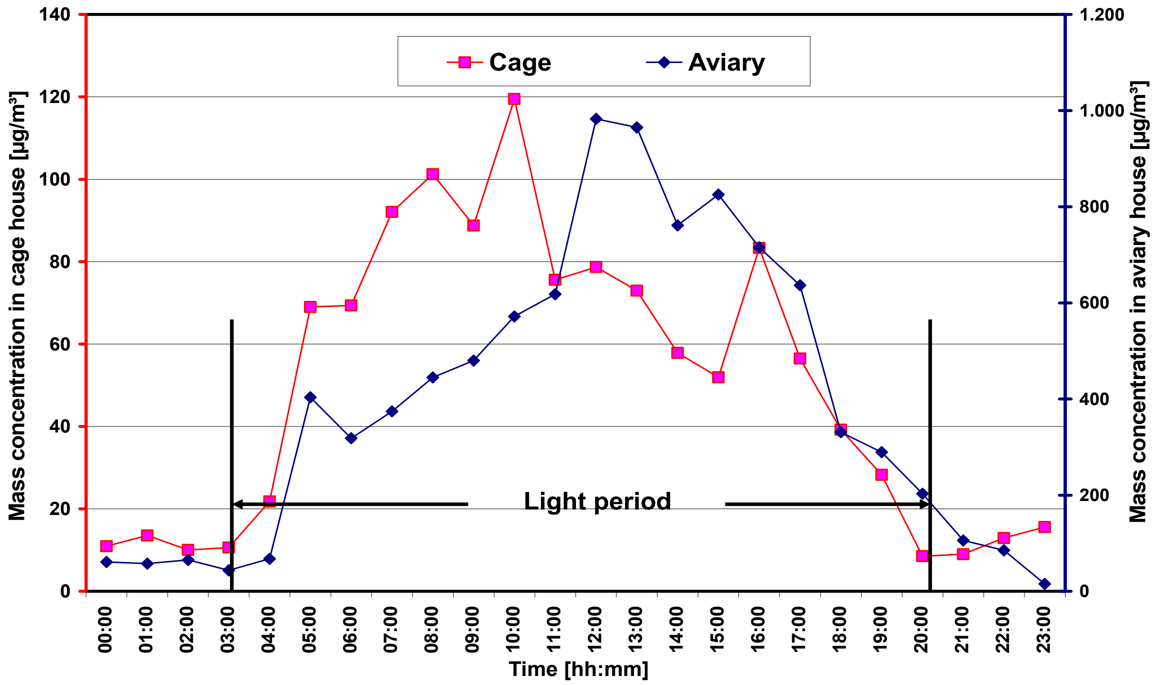


Figure 4.11: Relationship between diurnal change and particle mass concentration during winter season for both breeding systems

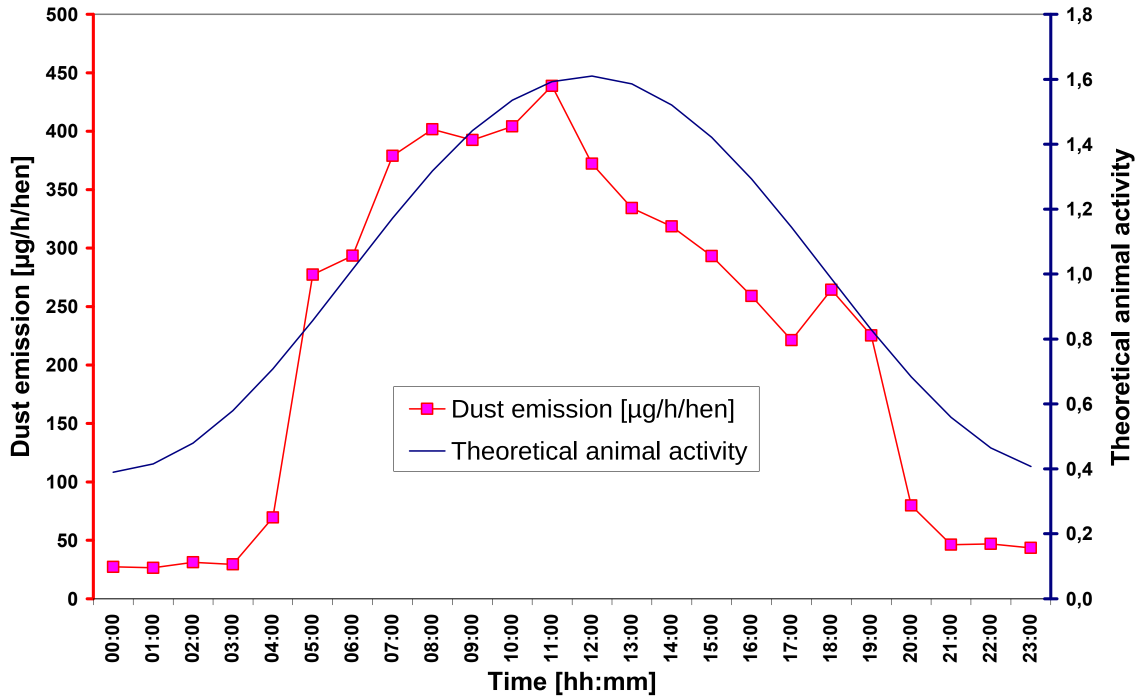


Figure 4.12: Total dust emission and theoretical animal activity for the whole day during January

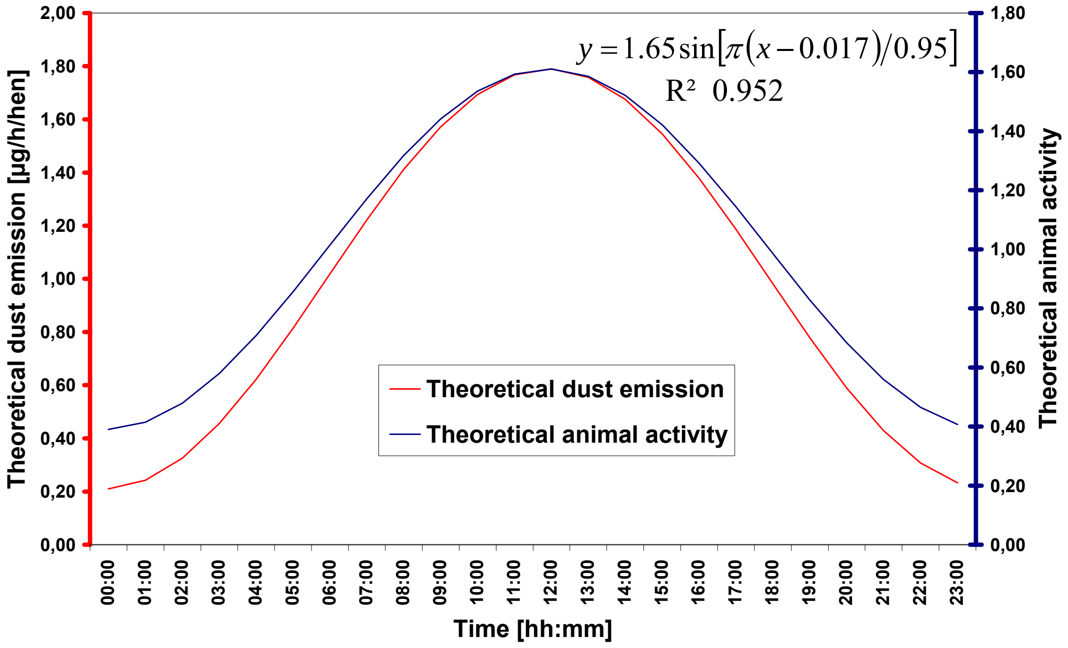


Figure 4.13: Relationship between theoretical animal activity and theoretical dust emission

4.3 Dust reduction systems

Two different dust reduction techniques have been used to select the highest system efficiency for reducing the indoor dust concentration. Laboratory experiments have been done in order to evaluate the materials of the designed filter systems and study the best working conditions. Small scale farm experiments have been done to compare between two different reduction techniques and then recommend one of these techniques to test it on a large scale.

4.3.1 Laboratory measurements

These experiments have been done with dry filter systems in order to select the fitting materials and with wet filter systems in order to select the working conditions.

4.3.1.1 Dry filter systems

Two different types of dust (dolomite and layer dust) have been tested with three different filter materials. These measurements have been done in a wind channel with three different air velocities (0.75, 1.00 and 1.25 m/s). Figure 4.14 shows the efficiency of different filter materials with different particle categories and air velocities.

The StuffNix material showed the highest efficiency with dolomite dust in comparison to the other filter materials. The highest dust reduction efficiency of StuffNix material resulted at 1 m/s air velocity. This efficiency with total dust was 87 % but on the other hand it was 68 % and 86 % at 0.75 and 1.25 m/s respectively. Almost the same results have been observed with other particle categories (PM_{10} and $PM_{2.5}$). In comparison to the StuffNix material the other filter materials showed a low efficiency with all air velocities. The efficiencies of total dust reduction for half tube and double tube filter materials were 62 % and 50 % respectively at 1 m/s. With other particle categories, 1.25 m/s was the highest efficiency for double tube and half tube materials. These efficiencies were 42 % and 57 % for $PM_{2.5}$ and PM_{10} respectively with half tube materials. With double tube material they were 51 % and 58 % for $PM_{2.5}$ and PM_{10} respectively.

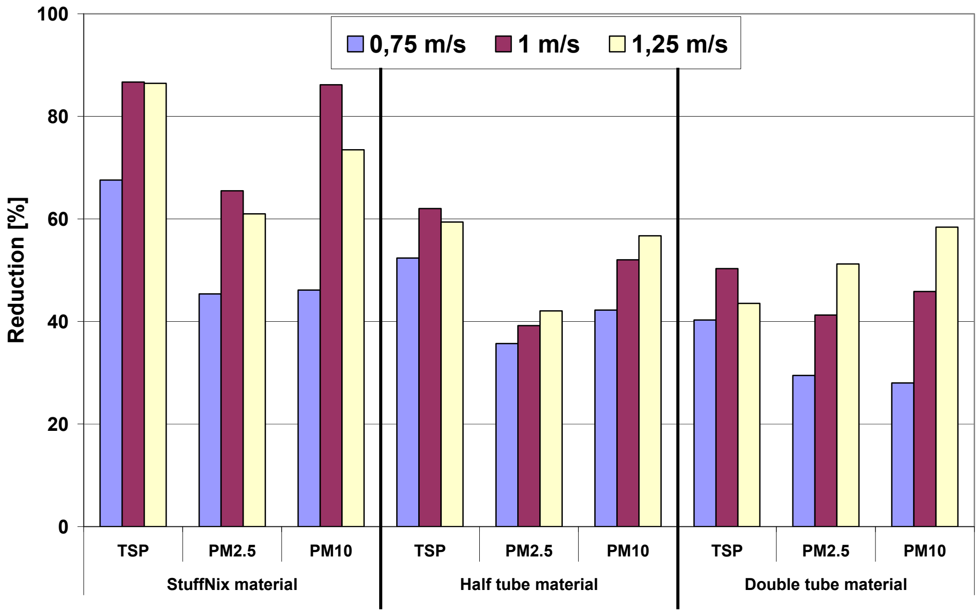


Figure 4.14: Efficiency of different material filters with dolomite dust by different air velocities

As shown in figure 4.15, the experiments with layer dust show the highest efficiency for all filter materials at 1 m/s. The efficiency of the total dust reduction was 65 % for StuffNix, 58 % for half tube and 41 % for double tube filter materials. With the other particle categories, 1 m/s air velocity also showed the highest efficiency for StuffNix and half tube filter material in comparison to the other air velocities. The difference appeared with double tube material only when the efficiency of PM_{10} reduction at 1.25 m/s air velocity was higher than 1 m/s. The reduction efficiencies of PM_{10} for double tube material were 31, 26 and 26 % at 1.25, 1.00 and 0.75 m/s respectively.

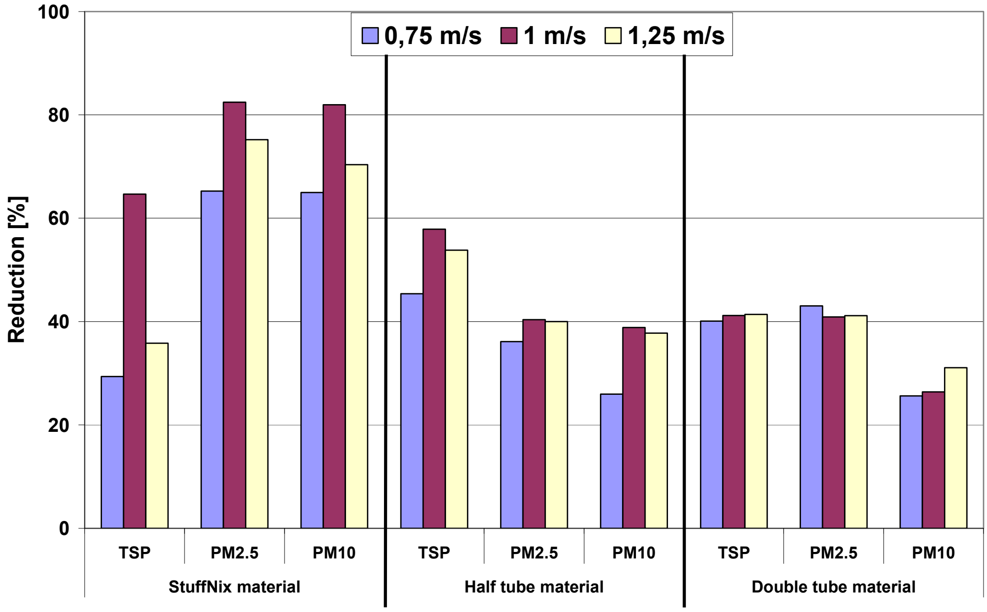


Figure 4.15: Efficiency of different filter materials with layer dust by different air velocities

The conclusion of the filter material selection appears in figure 4.16. This figure shows the highest efficiency of StuffNix filter material at 1 m/s air velocity for almost all particle categories and all dust types.

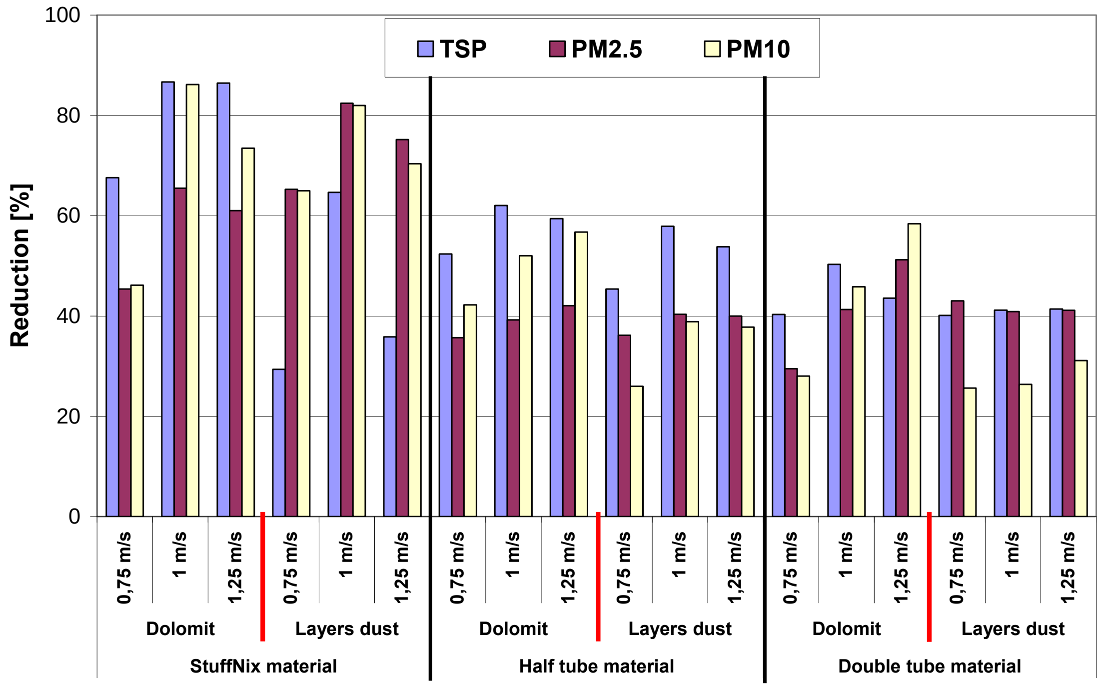


Figure 4.16: Filter Efficiency with different air velocities for both layer and dolomite dust

Figure 4.17 shows the efficiency of StuffNix filter material with different particle ranges of dolomite and layer dust. The efficiency for dolomite dust increased with particle ranges. On the other hand layers dust stayed stable in its reduction efficiency with small fractions and then the efficiency decreased with large particles. The concentration of the particles larger than 20 µm after filtering is higher than before because of the agglomeration of the particles in the V-shape chamber of the filter. For this reason the figure shows the efficiency of the filter with particle fractions larger than 20 µm at -20%.

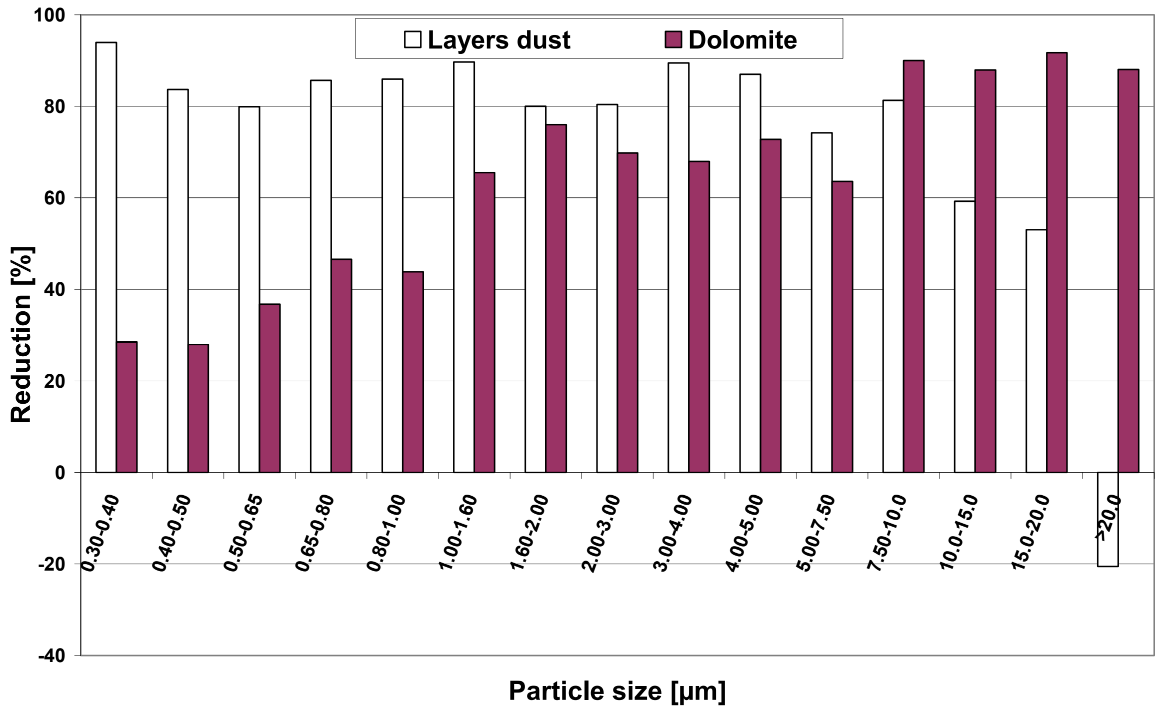


Figure 4.17: Efficiency of StuffNix filter material at 1 m/s air velocity with different particle sizes

Figure 4.18 shows the particle mass distribution of layer dust at 1 m/s air velocity with different fraction ranges before and after the StuffNix filter. With small particle ranges the dust concentration in the air before the filter was higher than after filtration. At particles range 10 – 15 µm the dust concentration in the air after the filter started to increase in comparison to the dust concentration before the filter.

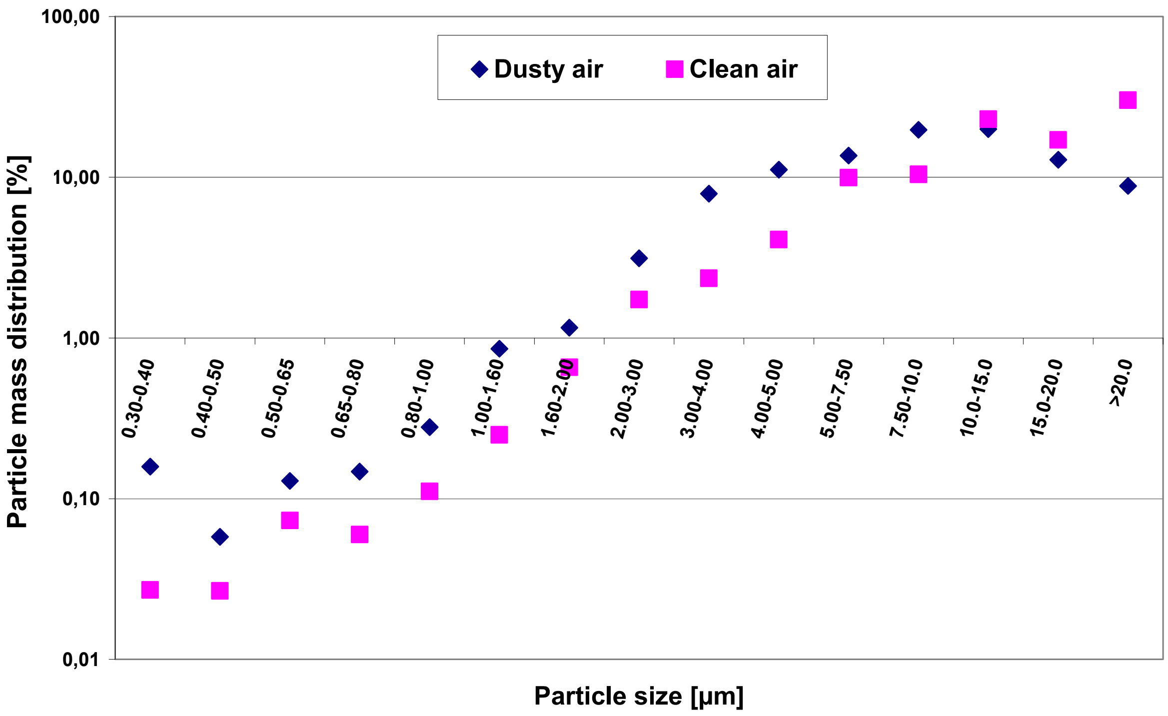


Figure 4.18: Particle mass distribution of different fractions for StuffNix filter material at 1 m/s air velocity

4.3.1.2 Wet filter system

The wet filter system has been tested to evaluate the best working conditions to attain the highest dust reduction efficiency. As shown in figure 4.19, the highest dust reduction efficiency appeared at 6 m/s air velocity and 2.5 bar water pressure. The efficiency under these conditions was 90 %. The difference in dust reduction efficiency under these working conditions and other working conditions was minimal. The dust reduction efficiency at 4 m/s air velocity and 1 bar water pressure was 87 %. This means, that there is only a 3 % difference in the efficiency of these working conditions in comparison to the highest efficiency which has been obtained by this system. Working conditions of 4 m/s air velocity and 1 bar water pressure have been selected due to the economical considerations. Working under these conditions saves water and electricity.

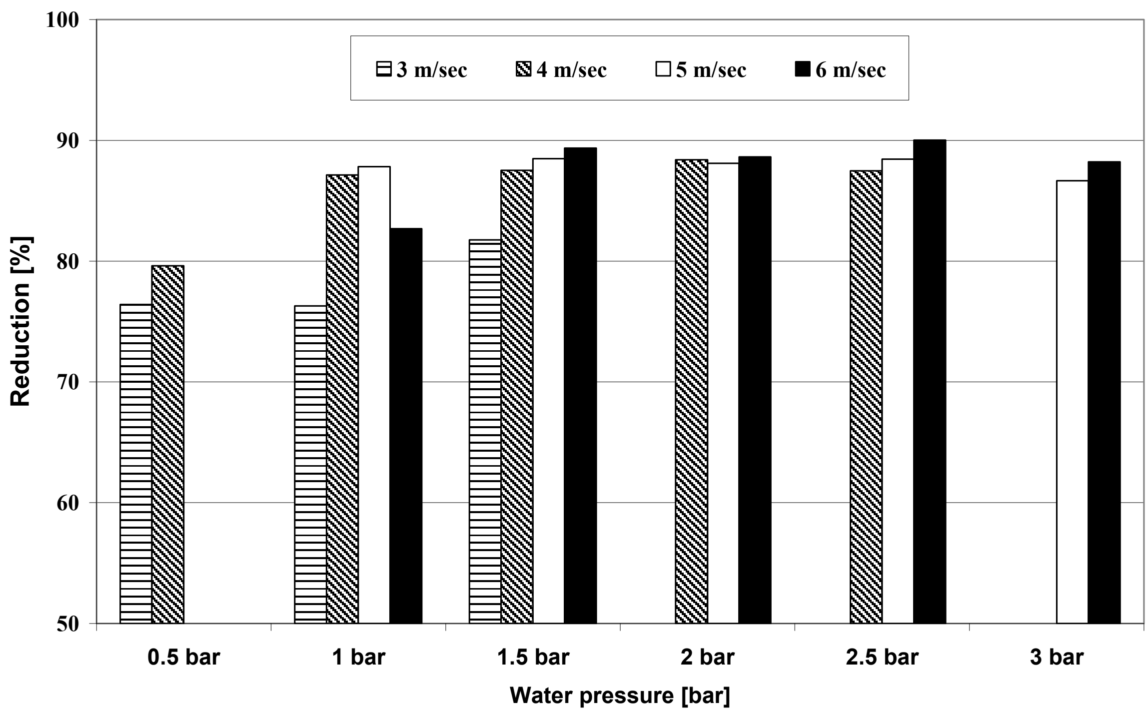


Figure 4.19: Wet filter efficiency with different air velocities and different water pressures

4.3.2 Small scale farm measurements

The small scale farm experiments have been done to compare between two different filter systems.

4.3.2.1 Dry filter systems

Two different techniques have been used as dry filter system to reduce the indoor dust concentration. First technique is a StuffNix filter system which was designed according to laboratory measurements. The second system is a vacuum cleaner working with a cyclone system.

4.3.2.1.1 StuffNix filter system

The designed StuffNix filter has been tested with 1 m/s air velocity as recommended by laboratory measurements for a small scale chicken coop. Figure 4.20 illustrates the dust reduction efficiency of StuffNix filters and its ability to reduce the indoor dust concentration and dust emission rate. The efficiency of this filter was 83 % with total dust but this efficiency arrived to 90 % with $PM_{2.5}$. The StuffNix filter system also showed high efficiency with a dust emission rate for all particle categories. The efficiencies of the filter were 75, 84 % and 85 % for total dust, PM_{10} and $PM_{2.5}$ respectively. Efficiencies of the StuffNix filter with indoor mass concentration were 35, 39, and 45 % for total dust, PM_{10} and $PM_{2.5}$ respectively.

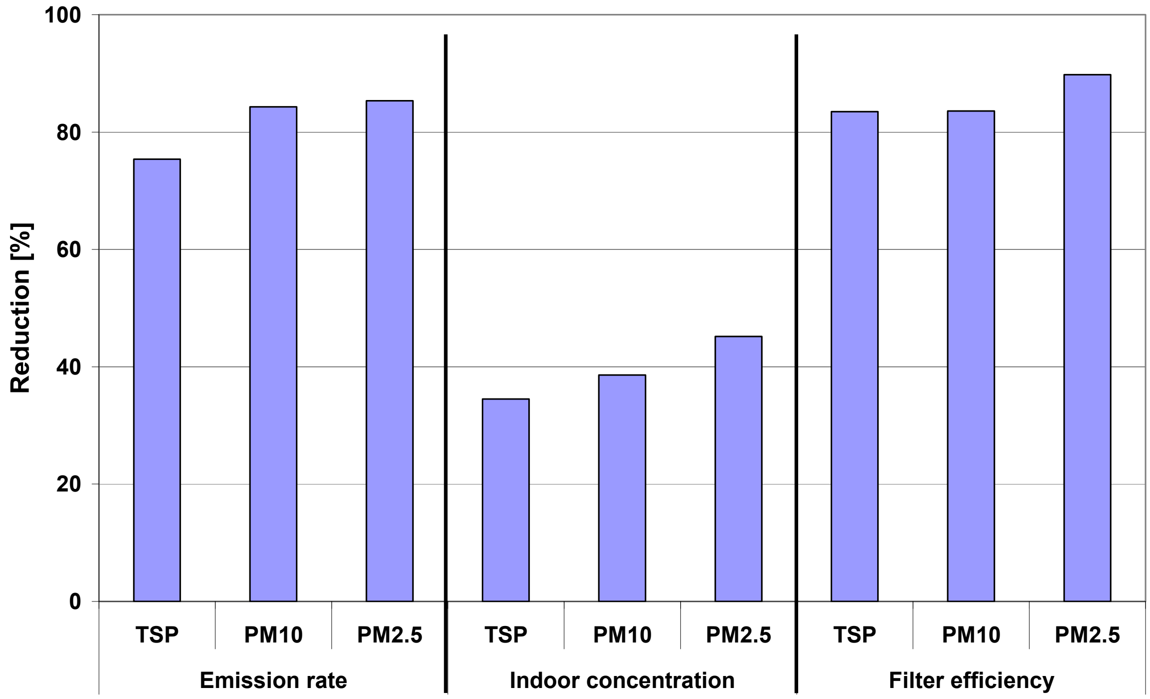


Figure 4.20: Efficiency of the designed StuffNix filter system tested under small scale experimental station conditions

4.3.2.1.2 Cyclone

The dust reduction efficiency of the cyclone has been tested in a small scale chicken coop. The cyclone showed high efficiency with small particle ranges as shown in figures 4.21 and 4.22. The cyclone efficiencies for different particle categories (total dust, PM_{10} and $PM_{2.5}$) were 46, 52, and 70 % respectively. The cyclone also showed high efficiencies with small particles in comparison to large particle matter both in indoor mass concentration and dust emission rate, figure 4.21. The efficiencies of the cyclone with indoor dust concentration were 14, 15, and 20 % for total dust, PM_{10} and $PM_{2.5}$ respectively. The efficiencies of the cyclone with dust emission rate were 13, 15 and 20 % for total dust, PM_{10} and $PM_{2.5}$ respectively.

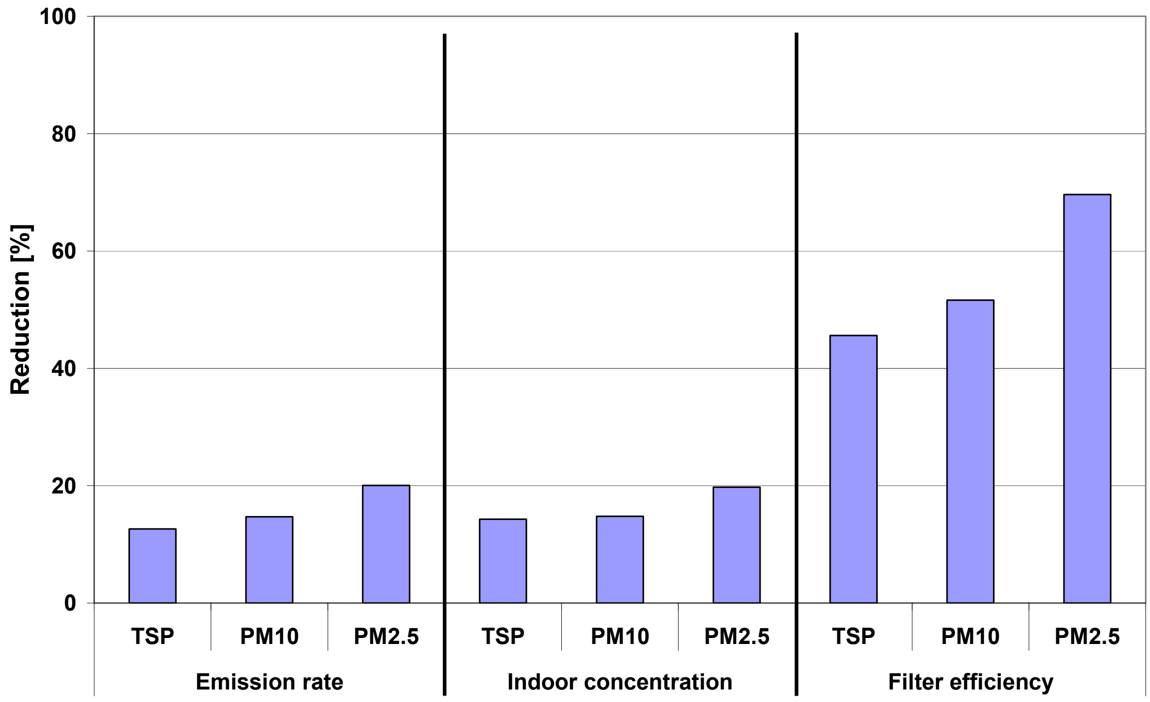


Figure 4.21: Efficiency of cyclone filter system

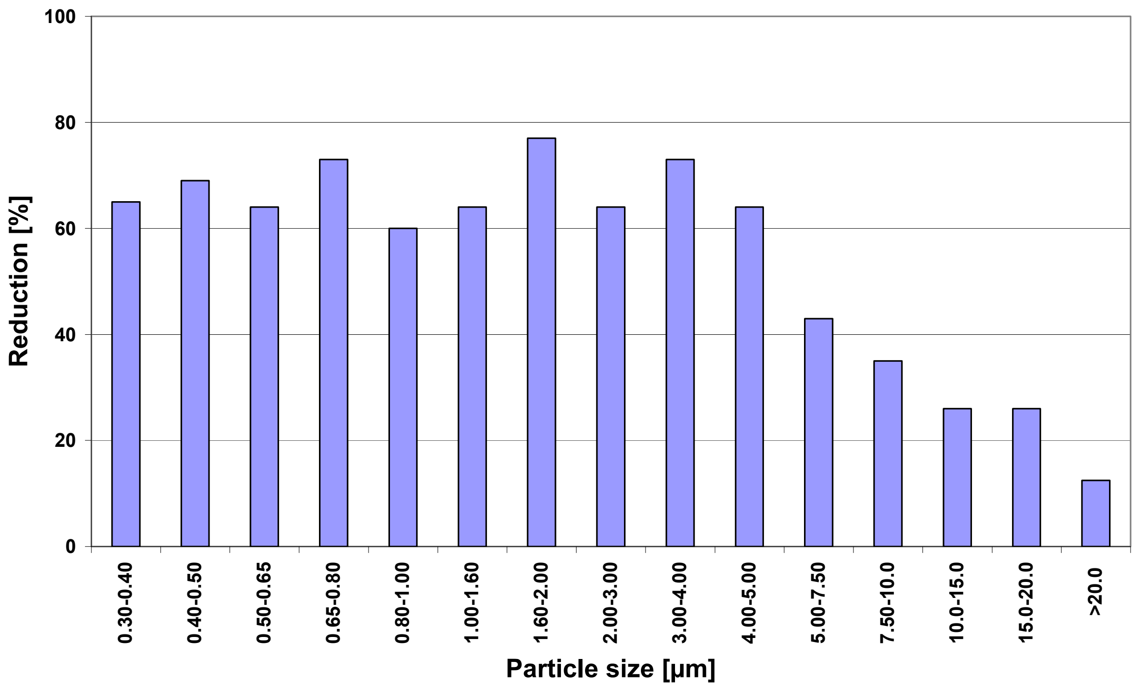


Figure 4.22: Cyclone efficiency with different particle fractions

4.3.2.2 Wet filter system

The wet filter system has been tested in a small scale chicken coop. The working conditions recommended by laboratory measurements regarding water pressure and air velocity have been used. The dust reduction efficiencies of wet filter systems as shown in figure 4.23, were high for all particle categories. These efficiencies were 81, 92, and 95 % for total dust, PM_{10} and $PM_{2.5}$ respectively. The efficiencies of the filter with indoor mass concentration were 24, 30, and 29 % for total dust, PM_{10} and $PM_{2.5}$ respectively. The efficiencies of the filter with dust emission rate were 33, 51, and 52 % for total dust, PM_{10} and $PM_{2.5}$ respectively.

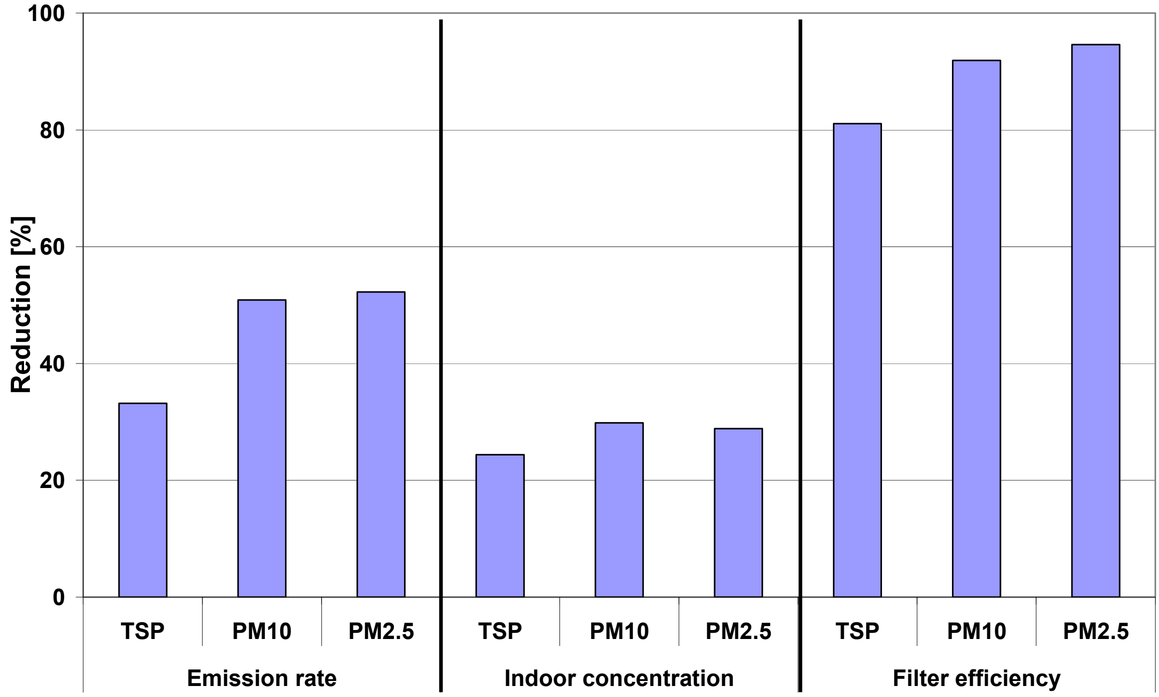


Figure 4.23: Efficiency of wet filter system

Figure 4.24 compares between two different filter systems under different air recirculation volume rates to select the highest filter efficiency in order to use it in a large scale farm. Cyclone filter systems show the lowest filter efficiency in comparison to the other filter systems. Wet and StuffNix filter systems showed almost similar filter efficiencies. The StuffNix filter system had the highest efficiency with indoor mass concentration and dust emission rate for all particle categories. Due to the results of the small scale chicken coop measurements StuffNix filter system has been recommended for evaluation for the commercial scale farm.

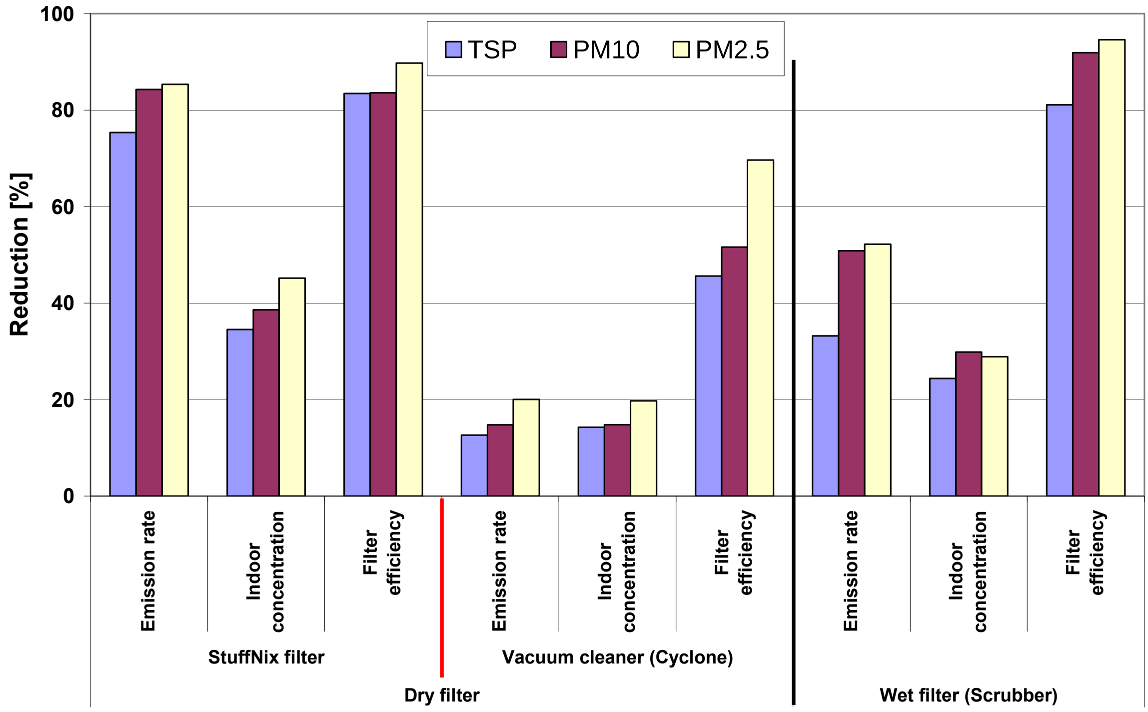


Figure 4.24: Efficiencies of the filter systems (different air recirculation volume rates)

4.3.3 Commercial scale farm measurements

After four days of testing in a commercial scale barn (two days without the filter and two days with the filter) the designed StuffNix filter showed high dust reduction efficiency with both indoor dust concentration and dust emission rates as shown in figure 4.25. The high efficiency was even better with the small particle matter category ($PM_{2.5}$) rather than large particle category (PM_{10}) and total suspended particles (TSP). The filter efficiencies with indoor dust concentration were 55, 57, and 63 % for TSP, PM_{10} and $PM_{2.5}$ respectively. The filter efficiencies with the dust emission rate were 72, 78, and 78 % for TSP, PM_{10} and $PM_{2.5}$ respectively.

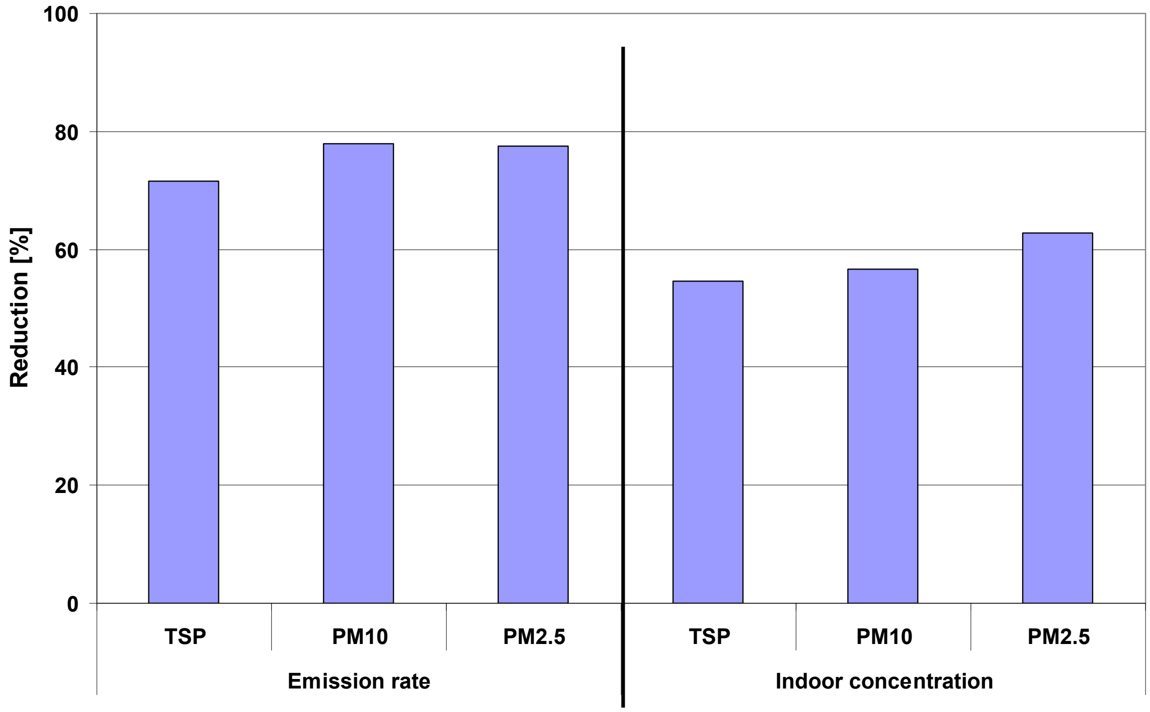


Figure 4.25: Efficiency of designed StuffNix filter system in the commercial scale barn (two days turn comparison)

5 Discussion

The target of this investigation was to increase indoor air quality in laying hen houses and reduce emission rates. To achieve this aim it was important to describe the parameters influencing indoor dust concentration, dust characteristics and the emission rate from the coop to the surrounding environment.

5.1 Applied measurement methodology

5.1.1 Particle matter measuring technique

In order to measure the particle concentration it was necessary to install a flexible instrument which could easily be maintained. The mobile type of aerosol spectrometer showed a high degree of flexibility especially during comparative measurements. The output of this instrument affected particle number concentration with different size fractions. The direct determination of the particle mass concentration was not possible. The translation of particle number concentration into particle mass concentration is required to determine the conversion factors (gravimetric factors). There were no problems during measurements in a time plan up to four days without interruption. The isokinetic sampling and radial symmetric sampling functioned successfully. During each measurement period the air velocities in the exhaust air showed no major fluctuations, thus changing of the isokinetic sampler nozzles during the operating period was not necessary.

5.1.2 Measurement of the air volume flow

The determination of the air volume flow in a force-ventilated barn with a measuring fan proved an easy installation and dismantling system. In addition to storing the data of the measuring fan there were sensors used for relative humidity and temperature in order to determine the climatic conditions of the exhaust air and the outside air.

5.1.3 Physical properties measurements

Samples of dust have been characterized to describe some physical properties which are useful for estimating the mass factor. Based on the mass factor the dust emission rate has been calculated. The physical properties, which have been described in chapter three are particle shape factor and density. The physical properties of the dust samples have been confirmed by **Reist (1984), Nannen (2005), Schmitt-Pauksztat (2006) and Rosenthal (2006).**

5.2 Influence of different parameters on indoor dust concentration and its emission rate

As expected the results showed that different parameters have an effect on indoor dust concentration and its emission rate.

5.2.1 Effect of housing system

The results of this study show the effects of different housing systems on indoor dust concentration and the total dust emission rate. Thereby the indoor dust concentration and the dust emission rate in an aviary system are higher than in a cage system as described in figures 4.4 and 4.6. Reasons refer to the large exposed surfaces of manure and litter accumulating in aviary systems due to which dust will rise during activity of the layers as explained by **Aarnink and Ellen (2007)**. Cage systems restrict the activity of the layers inside the battery due to the small amount of area per hen. This result agreed with **Nimmermark and Gustafsson (2005), Martensson and Pehrson (1997) and van der Hoek (2007).**

The housing factor has been calculated to show the influence of housing systems on indoor dust concentration and the dust emission rate with different particle fractions. The high percentage of the housing factor for the small fraction in aviary systems derives from the light weight of these particles and their ability to be carried in the air by the movement of the layers inside the barn. The housing factor for the large particle fractions increases in aviary systems due to dust mixing with other materials. This increases its weight with low particle numbers.

Similar to the results which are reported by **Ellen et al. (2000)** the dust emission rates of aviary housing systems are higher than cage systems as shown in figure 4.6. As observed in table 5.1, there is a higher air volume flow in cage systems than in aviary systems. This high air volume flow did not increase the dust emission rate in cage systems more than aviary systems. The low dust emission rate in cage system with the high air volume flow returns to the low quantity of indoor mass concentration. On the other side the high emission rate in the aviary system with low air volume flow returns to the high quantity of indoor mass concentration.

5.2.2 Seasonal effects

A slight difference for indoor mass concentration has been observed during different seasons in contrast to the indoor particle concentration. The reason results from the large number of small particle fractions as shown in figure 5.1, which have a very low mass.

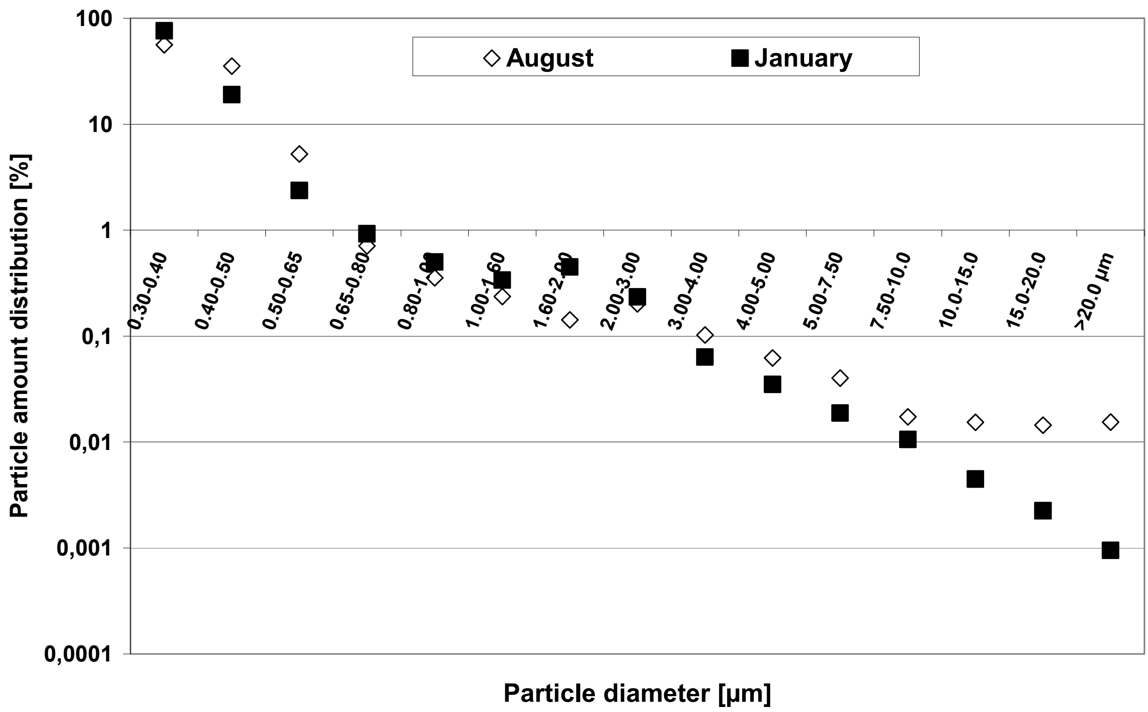


Figure 5.1: Indoor particle amount distribution for aviary housing systems

The increase of the indoor particle concentration during winter time in comparison to summer time is agreed with **Hinz et al. (1999), Zhu et al. (2005), David et al. (2002) and Golbabaei and Islami (2000).** This increase refers to the low air humidity inside the barn during the winter time as shown in table 5.1. **Vučemilo et al. (2008)** described the relation between microclimate parameters (air temperature and relative humidity) and indoor dust concentration. Another reason for the decrease of indoor particle concentration in the summer time is the high air temperature during this period as shown in table 5.1. This high air temperature causes stupor, stagger and lethargy of the layers inside the barn moreover decreases its ability for movement. This low movement of the layers causes low dust production. In the opposite, through the winter season the cold weather allows more activity of the layers and increases the indoor particle concentration. High ventilation rates during the summer season decrease the indoor dust concentration by dilution.

Table 5.1: Mean levels of microclimatic parameters and air volume flow in chicken coops during different seasons

		Cage system			Aviary system		
		Temperature [˚C]	**Air humidity [%]**	**Air volume flow [m³/h]**	**Temperature [ºC]**	**Air humidity [%]**	**Air volume flow [m³/h]**
Summer season	**June**	26.5	64.5	249.252	27	63.5	67.448
	August	23	62	237.634	23	62.5	64.719
Winter season	**January**	20	59	69.616	20	58	27.472

The dust emission rate clearly showed a great difference during the seasons. The dust emission rate was higher in the summer season than in the winter season. This result was also reported by **Takai et al. (1998) and Redwine et al. (2002)**. The reason for the high dust emission during the summer season results from the high air temperature inside the barn. This high air temperature makes it necessary to switch on more exhaust air ventilators to reduce the air temperature inside the barn. According to these ventilators the air volume flow increases through the summer season in comparison to the winter season, as shown in table 5.1. Increasing the air volume flow leads the dust to emit from the barn to the surrounding environment.

5.2.3 Effect of diurnal change and animal activity

Light is considered a key factor in the dust formation in poultry farming, **Seedorf and Hartung (2000)**. The light program arranged was 16 hours of continuous light per day and eight hours darkness in each season in both housing systems as recommended by **Haseman and Scott Beyer (1998)**. During the light period in the winter season high indoor mass concentration throughout the day time could be observed in both housing systems aviary and cage system as reported by **Hessel and Van den Weghe (2007), Takai et al. (1998), Ellen et al. (2000) and Lim et al. (2003)**. This high concentration of dust during the light period can be related to the high animal activity during the day time which increases the indoor mass concentration as explained by **Gustafsson (1997), Nannen**

(2007) and Mitchell et al. (2004). The feeding and the operating activity inside the barn for daily services also contributed to the dust emittion during the day time in comparison to the night time.

5.3 Dust reduction techniques

5.3.1 Laboratory measurements

The aims of laboratory measurements were:

1. Selecting the suitable material for designing a dry filter system.
2. Selecting the best operating conditions which give the highest efficiency for indoor dust concentration reduction.

The first target has been achieved by selecting the StuffNix filter material. The StuffNix material had the highest dust reduction efficiency in comparison to the other two filter materials, figures 4.14 and 4.15. This result has been confirmed with two different dust types (dolomite and layer dust). The greatest efficiency of StuffNix filter material appeared under 1 m/s air velocity. The efficiency of StuffNix filter material was high and almost stable with all small particle fractions for layers dust but with large particle fractions the efficiency decreased. The source of this decrease may be the agglomeration of the small particles inside the V-shape chamber of the filter material. Due to the characteristics of layer dust there is a high ability to agglomerate because of its high content of protein. This agglomeration of the particles could be caused by electrical force as described by **Reis et al. (2006)**. As a result of the agglomeration process the number of large particles increases after the filter material in comparison to before. On the other hand, the efficiency of the StuffNix filter material for dolomite dust was lower for small particle fractions than the large particle fractions. These different efficiencies result from the character of dolomite dust. The ability of the dolomite dust to agglomerate is very low whereas in contrast the large particles get separated into small particles when they impact with the filter material. Due to this effect the number of small particle fractions after the filter material is greater than before the filter.

The second aim of laboratory measurements has been achieved by selecting the suitable air velocity at 1 m/s for operating the designed StuffNix filter. The operating conditions for the wet filter systems (scrubber) have been clarified in figure 4.19. The highest efficiency for the scrubber was with 2.5 bar water pressure and 6 m/s air velocity. Operating with these conditions required a large quantity of water and energy. The difference in efficiency with other working conditions was minimal. Other operating conditions have been selected according to economical considerations in order to save water and energy. These operating conditions are suitable especially for countries with water or energy problems, i.e. Egypt. Operating conditions of 1 bar water pressure and 4 m/s air velocity have been selected for supplementary measurements.

5.3.2 Small scale farm measurements

The aim of these measurements was to compare between two different filter systems. The filter systems which had the highest efficiency according to these measurements were used for commercial farm measurements.

5.3.2.1 Dry filter systems

5.3.2.1.1 StuffNix filter system

The designed StuffNix filter reduced particle matter emissions and indoor dust concentration by removing airborne particles while they fly in the air through the curtain. The efficiency of the StuffNix filter in the emission rate was 70 % as specified by the manufacturer. In this investigation the efficiency of the designed filter with dust emission rate was higher than the results obtained from **Lim et al. (2007), Aarnink and Ellen (2007), Hölscher (2006), Kosch et al. (2005)** and recommended by the company. The goal of the designed filter was to reduce the indoor dust concentration by recycling the air inside the barn. The efficiency of the designed StuffNix filter in reducing the indoor dust concentration is comparable with the efficiency of the other filter system techniques. The efficiency of StuffNix filter with small scale farm measurements was lower than the efficiency of the other techniques which were provided by **Ullman et al. (2004), Mitchell and Baumgartner (2007) and Atsuo (2002)**. The efficiency of StuffNix filter was higher than the techniques provided by **Gustafsson (1997) and Carey et al. (2004).** The designed StuffNix filter showed higher efficiency with the small particle categories than the large particle categories. This difference refers to the StuffNix material as explained previously in the chapter (5.3.1.). Reducing the small fraction particles for this kind of filter can be considered as an advantage because these small particles can penetrate deep into human and animal lungs as mentioned by **Seedorf and Hartung (2000)**.

5.3.2.1.2 Cyclone

The efficiency of the cyclone for reducing the indoor dust concentration and dust emission rate is very low as illustrated in figure 4.21. This efficiency is lower than the other filter efficiencies which are presented in the literature. The best efficiency of the cyclone appeared with small particle fractions in comparison to large particle fractions. The reason can be the high velocity of the air inside the cyclone. With this high velocity the cyclone removed small particle fractions but most of the large particle fractions remained inside the cyclone and exited again with the clean air.

5.3.2.2 Wet filter system (scrubber)

This wet filter system is similar to the system which was presented by **Hölscher (2006)** and was tested in pig farms. The efficiencies of the scrubber with the chicken coop were lower than the results which were obtained by **Hölscher (2006)** for the indoor dust concentration and dust emission rate. This difference could be due to the dust components and their sources inside the barn. The efficiency of the scrubber was lower than the efficiencies of the systems used by **Snell and Schwarz (2003), Wang et al. (1999a) and Mitchell et al. (2004),** but on the other hand was higher than the system used by **Gustafsson (1997).**

5.3.3 Commercial farm measurements

The results of different filter techniques showed the greatest efficiency for the designed StuffNix filter with indoor dust concentration and dust emission rate. Therefore, the designed StuffNix filter system has been tested on a commercial scale chicken coop.
The designed StuffNix filter achieved high dust reduction efficiency with the indoor dust concentration and dust emission rates in an actual commercial barn for laying hens with the aviary housing system, as shown in figure 4.25. In comparison to the other dust reduction techniques which are explained in chapter (2.7) the designed StuffNix filter showed a legally acceptable reduction efficiency for poultry breeding. In Germany the current limit values for respirable (< 5 µm particle diameter) dust concentration must not exceed 4 mg/m³ for the laying hens barn, according to MAC list (**M**aximum **A**cceptable **C**oncentration) **DFG (2006)**. **Saleh et al. (2004)** showed the mean value of inhalable dust concentration (< 10 µm particle diameter) for laying hens with aviary systems according to

the German situation must not exceed 3.8 mg/m³ and respirable 1.93 mg/m³. In this investigation, the indoor dust concentrations are shown in table 5.2.

Table 5.2: Mean total, inhalable and respirable dust concentrations in laying hen house with aviary system

	Total dust conc., **[mg/m³]**	**inhalable dust conc., [mg/m³]**	**respirable dust conc., [mg/m³]**
Without filter	17.7	15	10.2
With filter	8	6.5	3.4

The respirable dust concentration before using the filter was higher than the limit value which is provided by MAC. This concentration is decreased by using the filter and is within the acceptable value of the dust concentration inside the laying hen barn. This means using the filter increases the air quality inside the barn and creates the required working atmosphere for labour inside the barn. This advantage of the filter did not appear regarding the inhalable dust concentration. As showed in figure 4.16, 4.17, 4.20 and 4.25 the dust reduction efficiency of StuffNix filter decreased with the increase of the particle matter diameter. The reasons for this decrease have been explained in chapter (5.3.1).

6 Summery

The aim of this investigation was to increase the air quality by reducing the indoor dust concentration for laying hen coops. The aim has been achieved and compared with literature according to the following working sequence.

- **Quantification of the indoor dust concentration and emission rate**

This stage has been achieved by measuring the particle number concentration using portable and stationary aerosol particle counters and spectrometers. Measurements have been done with two different breeding systems (aviary and cage system) for laying hens. The measurements have been done within two different seasons (summer and winter) and during the whole day. From these measurements the highest indoor dust concentration was with aviary systems in the winter season during day time. The highest dust emission rate was in with aviary system in the summer season during day time. The indoor dust concentration increased with animal activity. The theoretical indoor dust concentration has been predicted using the equation of theoretical animal activity.

- **Characterization of particle matter**

The layer dust has been analysed microscopically in order to describe the particle shape factor and the particle density. It has also been determined by sedimentation experiments. With these physical properties the mass factor has been determined and the due emission rate has been calculated from the particle number.

- **Dust reduction techniques**

The dry filter technique has been designed and tested with the scrubber and cyclone in a small experimental station in order to recommend the highest filter efficiency and was tested under the commercial scale barn situation.

Laboratory experiments have been done to select the filter material and the best working conditions. From these experiments StuffNix filter material has been selected at 1.0 m/s air velocity. The laboratory experiments have recognized the highest dust reduction efficiency of wet filter systems to be during 4 m/s air velocity and 1 bar water pressure.

Small scale measurements have been done in the experimental station of the university (Frankenforst farm). In these experiments two filter systems have been tested under different ventilation rates. From these measurements the designed StuffNix filter achieved the highest indoor dust concentration and dust emission reduction efficiency under different air volume rates.

Commercial farm measurements have been done using the designed StuffNix filter. Under these scale experiments the designed filter achieved high dust reduction efficiency as shown in table 6.1.

Table 6.1: Dust reduction efficiencies for StuffNix filter system in commercial barn for laying hens [%]

	Indoor dust concentration	Dust emission rate
TSP	55	72
PM_{10}	63	78
$PM_{2.5}$	57	78

From this investigation a prototype of dry filter system has been designed and fabricated using StuffNix filter material to reduce the indoor dust concentration in laying hen houses besides reducing the dust emission rate. Economic evaluation of this filter must be considered in the following study to estimate the possibility of the farmer to use it. The prototype of the designed StuffNix filter also has a few recommendations which should be considered and modified in further studies. These are described in the following:

- Feather and particle matter accumulated so fast on the filter surface that the passway in the filter is decreased and the pressure drop across the filter increased.
- The filter can easily be cleaned using over pressure and sweeping of the surface with brooms. With high relative humidity though the particle matter in the filter could absorb this humidity and it was not cleaned off easily.
- Collected particle matter on the filter may pollute the body of the worker upon accidental contact with the filter; which may make a high protection level for the person necessary.

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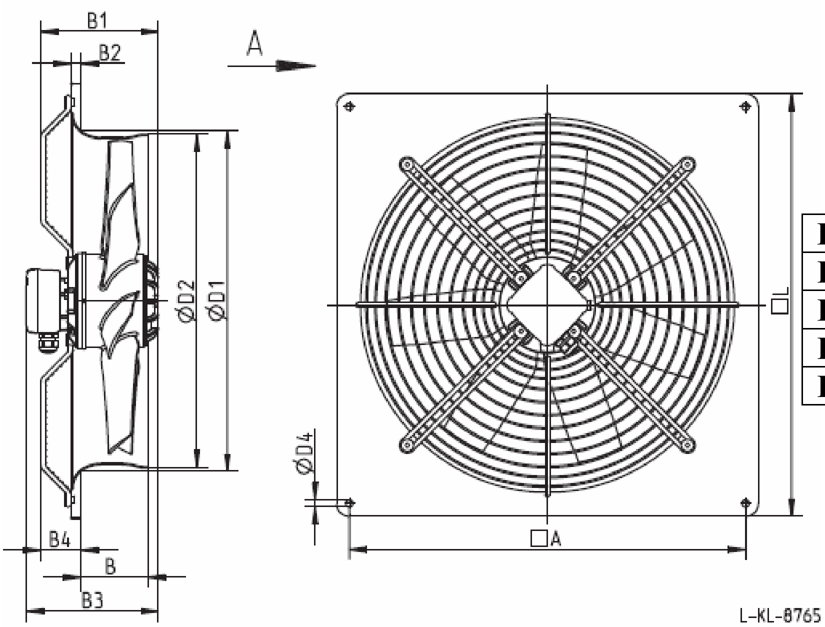
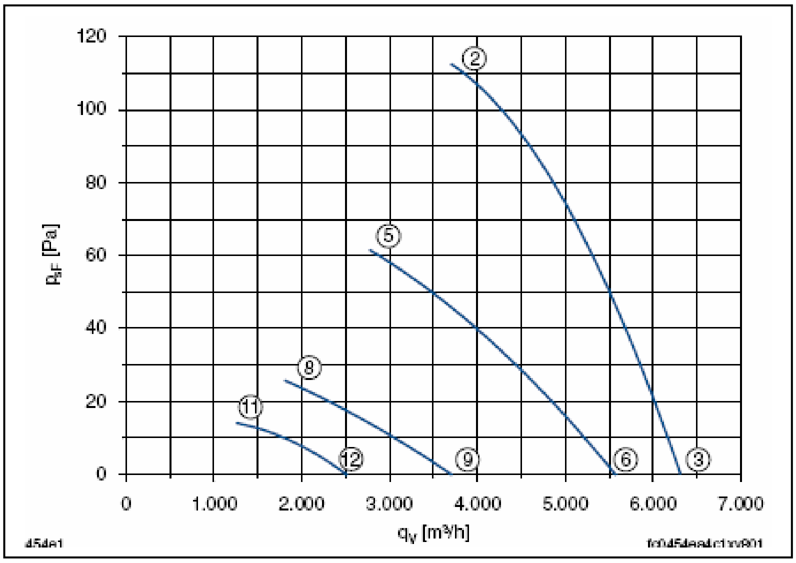
8 Appendices

Appendix 1: Technical data and performance curve for StuffNix filter ventilator

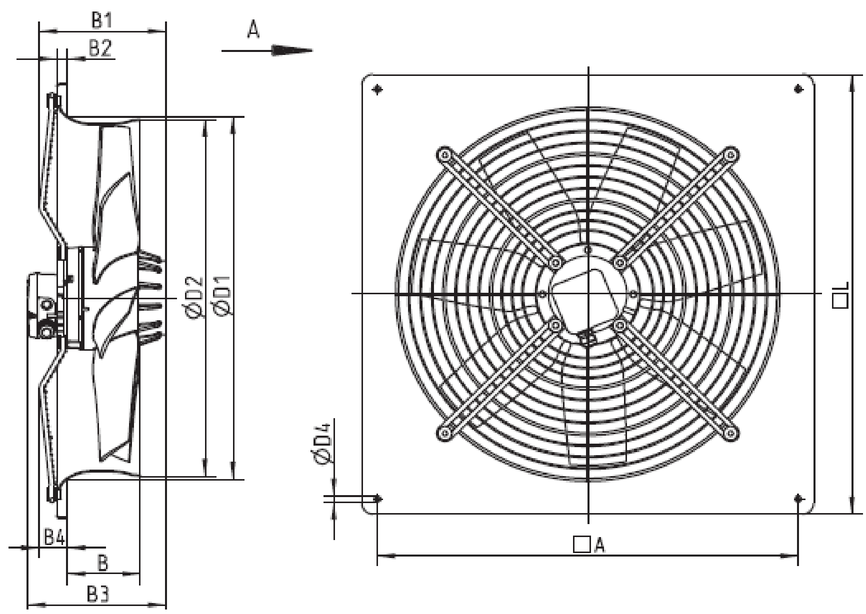


	mm		mm
B	104	**D1**	528
B1	185	**D2**	517
B2	16	**D4**	11
B3	205	**A**	615
B4	62	**L**	655

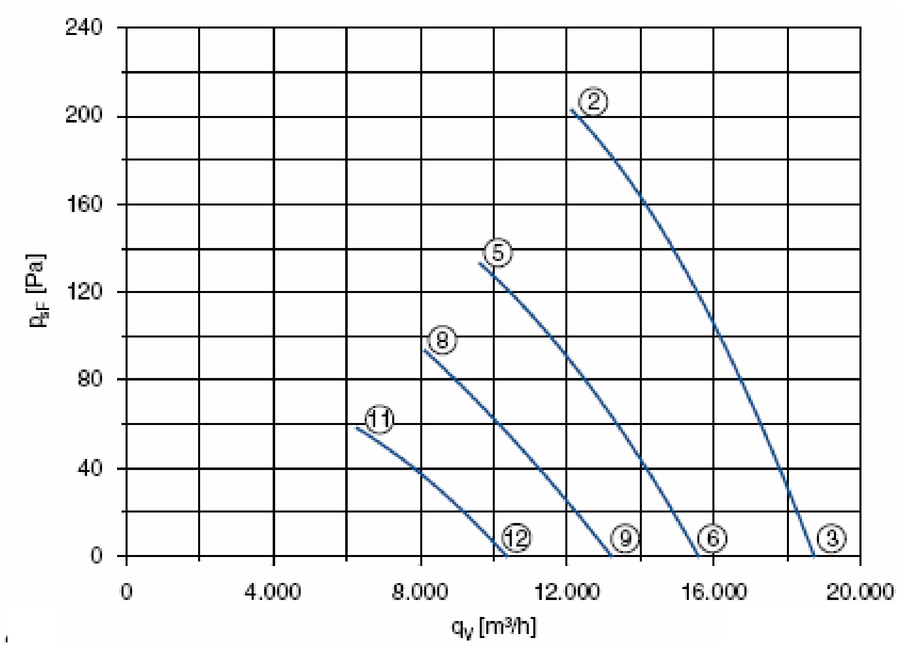


	U	I	P_1	n
	V	A	W	min^{-1}
②	230	1,6	360	1370
③		1,4	320	1390
⑤	160	1,95	300	1060
⑥		1,65	270	1220
⑧	130	1,75	210	700
⑨		1,7	200	820
⑪	105	1,5	135	530
⑫		1,45	135	570

Appendix 2: Technical data and performance curve for wet filter ventilator



	mm		mm
B	130	**D1**	664
B1	225	**D2**	643
B2	20	**D4**	11
B3	246	**A**	750
B4	50	**L**	805



	U	I	P_1	n
	V	A	W	min^{-1}
②	**400**	**3,2**	**1900**	**1360**
③		3,1	1800	1380
⑤	230	3,8	1350	1110
⑥		3,7	1350	1130
⑧	180	3,8	1050	920
⑨		3,7	1000	950
⑪	140	3,4	730	740
⑫		3,4	730	770

Appendix 3: Techanical date for the used sprinkler in the wet filter

UniJet® DÜSENMUNDSTÜCKE

Flachstrahl
TP Mundstücke

TECHNISCHE DATEN

DÜSENKÖRPER T (IG)
ODER

DÜSENKÖRPER TT (AG)

DÜSENFILTER

MUNDSTÜCK
(s. Übersicht)

ÜBERWURFMUTTER

ÜBERSICHT MASCHENZAHL	
Äquivalente Austrittsbohrung (mm)	Empfohlene Maschenzahl
bis 0,46 mm	200
0,47 bis 0,79 mm	100
0,80 mm und größer	50

Spritz-winkel bei 3 bar	Größe*	Äquiv. Aus-tritts-bohrung (mm)	VOLUMENSTROM (l/min)											SPRITZ-WINKEL			
			0.3 bar	1 bar	2 bar	3 bar	4 bar	5 bar	6 bar	7 bar	10 bar	20 bar	35 bar	1.5 bar	3 bar	6 bar	14 bar
110°	11001	0.66	0.12	0.23	0.32	0.39	0.46	0.51	0.56	0.60	0.72	1.0	1.3	94°	110°	121°	124°
	110015	0.79	0.19	0.34	0.48	0.59	0.68	0.76	0.84	0.90	1.1	1.5	2.0	97°	110°	121°	124°
	11002	0.91	0.25	0.46	0.64	0.79	0.91	1.0	1.1	1.2	1.4	2.0	2.7	98°	110°	120°	123°
	11003	1.1	0.37	0.68	0.97	1.2	1.4	1.5	1.7	1.8	2.2	3.1	4.0	99°	110°	120°	123°
	11004	1.3	0.50	0.91	1.3	1.6	1.8	2.0	2.2	2.4	2.9	4.1	5.4	100°	110°	119°	122°
	11005	1.4	0.62	1.1	1.6	2.0	2.3	2.5	2.8	3.0	3.6	5.1	6.7	100°	110°	118°	122°
	11006	1.6	0.75	1.4	1.9	2.4	2.7	3.1	3.3	3.6	4.3	6.1	8.1	101°	110°	117°	122°
	11008	1.8	1.0	1.8	2.6	3.2	3.6	4.1	4.5	4.8	5.8	8.2	10.8	102°	110°	117°	121°
	11010	2.0	1.2	2.3	3.2	3.9	4.6	5.1	5.6	6.0	7.2	10.2	13.5	103°	110°	117°	119°
	11015	2.4	1.9	3.4	4.8	5.9	6.8	7.6	8.4	9.0	10.8	15.3	20	104°	110°	117°	118°
	11020	2.8	2.5	4.6	6.5	7.9	9.1	10.2	11.2	12.1	14.4	20	27	105°	110°	117°	118°
	11030	3.6	3.7	6.8	9.7	11.8	13.7	15.3	16.7	18.1	22	31	40	105°	110°	117°	118°
95°	9501	0.66	0.12	0.23	0.32	0.39	0.46	0.51	0.56	0.60	0.72	1.0	1.3	81°	95°	105°	113°
	95015	0.79	0.19	0.34	0.48	0.59	0.68	0.76	0.84	0.90	1.1	1.5	2.0	82°	95°	105°	113°
	9502	0.91	0.25	0.46	0.64	0.79	0.91	1.0	1.1	1.2	1.4	2.0	2.7	82°	95°	105°	113°
	9503	1.1	0.37	0.68	0.97	1.2	1.4	1.5	1.7	1.8	2.2	3.1	4.0	83°	95°	104°	111°
	9504	1.3	0.50	0.91	1.3	1.6	1.8	2.0	2.2	2.4	2.9	4.1	5.4	84°	95°	103°	108°
	9505	1.4	0.62	1.1	1.6	2.0	2.3	2.5	2.8	3.0	3.6	5.1	6.7	84°	95°	102°	107°
	9506	1.6	0.75	1.4	1.9	2.4	2.7	3.1	3.3	3.6	4.3	6.1	8.1	86°	95°	101°	106°
	9508	1.8	1.0	1.8	2.6	3.2	3.6	4.1	4.5	4.8	5.8	8.2	10.8	87°	95°	100°	105°
	9510	2.0	1.2	2.3	3.2	3.9	4.6	5.1	5.6	6.0	7.2	10.2	13.5	89°	95°	100°	105°
	9515	2.4	1.9	3.4	4.8	5.9	6.8	7.6	8.4	9.0	10.8	15.3	20	90°	95°	100°	105°
	9520	2.8	2.5	4.6	6.5	7.9	9.1	10.2	11.2	12.1	14.4	20	27	90°	95°	100°	105°
	9530	3.6	3.7	6.8	9.7	11.8	13.7	15.3	16.7	18.1	22	31	40	91°	95°	101°	105°
	9540	4.0	5.0	9.1	12.9	15.8	18.2	20	22	24	29	41	54	92°	95°	100°	105°
	9550	4.4	6.2	11.4	16.1	19.7	23	25	28	30	36	51	68	93°	95°	99°	103°
	9560	4.8	7.5	13.7	19.3	24	27	31	33	36	43	61	81	93°	95°	99°	103°
	9570	5.2	8.7	16.0	23	28	32	36	39	42	50	71	94	93°	95°	99°	103°
80°	800050	0.46		0.11	0.16	0.20	0.23	0.25	0.28	0.30	0.36	0.51	0.67	61°	80°	95°	101°
	800067	0.53		0.15	0.22	0.26	0.31	0.34	0.37	0.40	0.48	0.68	0.90	67°	80°	94°	99°
	8001	0.66		0.23	0.32	0.39	0.46	0.51	0.56	0.60	0.72	1.0	1.3	68°	80°	89°	92°
	80015	0.79		0.34	0.48	0.59	0.68	0.76	0.84	0.90	1.1	1.5	2.0	68°	80°	89°	92°
	8002	0.91	0.25	0.46	0.64	0.79	0.91	1.0	1.1	1.2	1.4	2.0	2.7	69°	80°	88°	91°
	8003	1.1	0.37	0.68	0.97	1.2	1.4	1.5	1.7	1.8	2.2	3.1	4.0	70°	80°	87°	90°
	8004	1.3	0.50	0.91	1.3	1.6	1.8	2.0	2.2	2.4	2.9	4.1	5.4	71°	80°	86°	89°
	8005	1.4	0.62	1.1	1.6	2.0	2.3	2.5	2.8	3.0	3.6	5.1	6.7	71°	80°	86°	89°
	8006	1.6	0.75	1.4	1.9	2.4	2.7	3.1	3.3	3.6	4.3	6.1	8.1	72°	80°	85°	88°
	8008	1.8	1.0	1.8	2.6	3.2	3.6	4.1	4.5	4.8	5.8	8.2	10.8	72°	80°	84°	87°
	8010	2.0	1.2	2.3	3.2	3.9	4.6	5.1	5.6	6.0	7.2	10.2	13.5	73°	80°	84°	87°
	8015	2.4	1.9	3.4	4.8	5.9	6.8	7.6	8.4	9.0	10.8	15.3	20	74°	80°	83°	86°
	8020	2.8	2.5	4.6	6.5	7.9	9.1	10.2	11.2	12.1	14.4	20	27	74°	80°	83°	86°
	8030	3.6	3.7	6.8	9.7	11.8	13.7	15.3	16.7	18.1	22	31	40	74°	80°	83°	86°
	8040	4.0	5.0	9.1	12.9	15.8	18.2	20	22	24	29	41	54	74°	80°	83°	86°
	8050	4.4	6.2	11.4	16.1	19.7	23	25	28	30	36	51	68	74°	80°	83°	85°
	8060	4.8	7.5	13.7	19.3	24	27	31	33	36	43	61	81	75°	80°	83°	85°
	8070	5.2	8.7	16.0	23	28	32	36	39	42	50	71	94	75°	80°	83°	86°
73°	730023	0.30		0.05	0.07	0.09	0.10	0.11	0.12	0.14	0.17	0.23	0.31	50°	73°	89°	97°
	730039	0.41		0.09	0.13	0.15	0.18	0.20	0.22	0.24	0.28	0.40	0.53	53°	73°	87°	93°
	730077	0.56		0.18	0.25	0.30	0.35	0.39	0.43	0.46	0.55	0.78	1.0	53°	73°	86°	92°
	730116	0.71	0.14	0.26	0.37	0.46	0.53	0.59	0.65	0.70	0.84	1.2	1.6	54°	73°	85°	90°
	730154	0.81	0.19	0.35	0.50	0.61	0.70	0.78	0.86	0.93	1.1	1.6	2.1	55°	73°	84°	88°
	730231	1.0	0.29	0.53	0.74	0.91	1.1	1.2	1.3	1.4	1.7	2.4	3.1	56°	73°	83°	87°
	730308	1.1	0.38	0.70	0.99	1.2	1.4	1.6	1.7	1.9	2.2	3.1	4.2	58°	73°	82°	86°
	730385	1.3	0.48	0.88	1.2	1.5	1.8	2.0	2.1	2.3	2.8	3.9	5.2	59°	73°	81°	85°
	730462	1.4	0.58	1.1	1.5	1.8	2.1	2.4	2.6	2.8	3.3	4.7	6.2	60°	73°	80°	84°
	730616	1.7	0.77	1.4	2.0	2.4	2.8	3.1	3.4	3.7	4.4	6.3	8.3	63°	73°	79°	83°
	730770	1.8	0.96	1.8	2.5	3.0	3.5	3.9	4.3	4.6	5.5	7.8	10.4	64°	73°	77°	82°
	730924	2.0	1.2	2.1	3.0	3.6	4.2	4.7	5.2	5.6	6.7	9.4	12.5	65°	73°	77°	80°
65°	650017	0.28			0.05	0.06	0.07	0.08	0.09	0.10	0.12	0.17	0.23	44°	65°	77°	86°
	650025	0.33			0.08	0.10	0.11	0.13	0.14	0.15	0.18	0.25	0.34	45°	65°	77°	84°
	650033	0.38			0.11	0.13	0.15	0.17	0.18	0.20	0.24	0.34	0.44	47°	65°	76°	83°
	650050	0.46			0.16	0.20	0.23	0.25	0.28	0.30	0.36	0.51	0.67	48°	65°	75°	82°
	650067	0.53		0.15	0.22	0.26	0.31	0.34	0.37	0.40	0.48	0.68	0.90	50°	65°	75°	81°
	6501	0.66		0.23	0.32	0.39	0.46	0.51	0.56	0.60	0.72	1.0	1.3	51°	65°	74°	80°
	65015	0.79		0.34	0.48	0.59	0.68	0.76	0.84	0.90	1.1	1.5	2.0	51°	65°	74°	80°
	6502	0.91	0.25	0.46	0.64	0.79	0.91	1.0	1.1	1.2	1.4	2.0	2.7	52°	65°	73°	79°
	6503	1.1	0.37	0.68	0.97	1.2	1.4	1.5	1.7	1.8	2.2	3.1	4.0	53°	65°	72°	78°
	6504	1.3	0.50	0.91	1.3	1.6	1.8	2.0	2.2	2.4	2.9	4.1	5.4	53°	65°	72°	76°
	6505	1.4	0.62	1.1	1.6	2.0	2.3	2.5	2.8	3.0	3.6	5.1	6.7	53°	65°	72°	76°
	6506	1.6	0.75	1.4	1.9	2.4	2.7	3.1	3.3	3.6	4.3	6.1	8.1	54°	65°	72°	75°
	6508	1.8	1.0	1.8	2.6	3.2	3.6	4.1	4.5	4.8	5.8	8.2	10.8	55°	65°	71°	74°