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Report 134

Measurement Protocol for Emissions of Fine Dust from Animal Houses

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ANIMAL SCIENCES GROUP
WAGENINGEN UR

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Abstract
Within this study a measuring protocol was developed for determining fine dust emission factors for animal houses

Keywords fine dust, measuring protocol, animal houses

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Titel: Measurement Protocol for Emissions of Fine Dust from Animal Houses
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Samenvatting
In dit onderzoek is een meetprotocol ontwikkeld voor het vaststellen van emissiefactoren voor fijn stof voor stallen

Trefwoorden: fijnstof, meetprotocol, stallen

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Report 134

Measurement Protocol for Emissions of Fine Dust from Animal Houses

Considerations, draft protocol and validation

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October 2008

Summary

The EU has set air quality standards for particulate matter (PM) in the outdoor air smaller than 10 μm (PM10) and smaller than 2.5 μm (PM2.5). These standards are exceeded in some parts of The Netherlands. Also animal houses are a significant source of dust. The present dust emission factors from animal houses, however, are only rough estimates. More accurate data are needed and this requires a well defined measuring protocol. The objective of this study was to determine and to validate a measuring protocol for determining fine dust emission factors for animal houses.

Looking at the air quality standards for outdoor air, we should be able to predict the year average concentration and the number of violations of the 24 hour standard. This means that we want to have a year average emission factor (being the median of 24 h emissions) and the variation around this mean. For the development of a measuring strategy for determining fine dust emission factors, the developed measuring strategy for determining ammonia emission factors for animal housing systems formed the basis. This measuring strategy should take into account the following three variance compounds: the between-farm variance, the within-farm variance, and the instrument measurement variance. Each variance component attributes to the overall measurement variance of the mean emission of a housing system. The proposed sampling scheme for the PM-measurement protocol is based on the same number of locations (n = 4) and samplings within locations (n = 6), as applied in the ammonia and odour protocol. The six measurements should be spread over one year, being randomly taken in subsequent two month periods. By this procedure seasonal variations that influence dust concentrations and ventilation rates throughout a year are equally distributed and well balanced in the sampling scheme. For housing systems with production cycles that affect emission patterns, like broilers or fattening pigs, it is prescribed that measurements are equally divided over the growing period. All measurements will be based on 24 hour sampling periods. This implies that diurnal variation patterns are not contributing to the overall measurement variation. Aim of the PM emission measurements is to get a representative set of data on emissions of animal housing systems. This involves normal management procedures and no exceptional situation within the animal house. When reporting dust emission results, detailed descriptions of the housing system and the performed management should be given.

For air sampling in animal houses the existing standards for sampling outdoor air for determining fine dust concentrations was used as the starting point. These standards are described in NEN-EN 12341 (1998b) for PM10 and in NEN-EN 14907 (2005) for PM2.5. For outdoor air, with changing wind directions and turbulence, a circular slit sampler was developed to sample particles independent from wind direction and with little influence of turbulence intensity. This circular slit sampler is followed by a size separation unit to retain particles larger than the size that should be sampled. For outdoor air the standardized pre-separation is based on the impaction principle. The sampled air is accelerated in narrow tubes and hit on a greased plate. Large particles are trapped on the plate due to their greater inertial, while the smaller particles (PM10 or PM2.5) follow the air stream to a filter where they are collected. Impactor pre-separators (IPS) face the problem of overloading of the impaction plate, especially during long sampling periods, e.g. 24 h. Overloading of the impaction plate causes the so-called bouncing effect; particles trapped on the plate are bounced off again by accelerated new particles. These particles will then follow the air stream to the filter, causing an overestimation of the dust concentration. Cyclone pre-separators (CPS) are less vulnerable for overloading; however, there is no European standard for CPS. Overloading of the impaction plate was tested in a study in a poultry house. In this study the impaction plates were regularly cleaned and greased during the sampling period. For the PM10 impactor no effect of cleaning interval was found on dust concentration. For the PM2.5 impactor dust concentrations significantly decreased with decreasing cleaning intervals, meaning that the impaction plate was overloaded. From this study it was concluded that the PM2.5 impactor is not a suitable pre-separator for dusty environments like animal houses. In a second study the equivalence was tested of CPS with IPS according standard procedures. For PM10 CPS equivalence was proven for PM10 concentrations lower than 100 $\mu g/m^3$. For PM10 concentrations higher than 100 $\mu g/m^3$ CPS did not fulfil the requirements of equivalence (difference between candidate cyclone samplers was on average 6%; this is higher than the requirement of < 5%; the slope between concentrations measured with the candidate cyclone sampler and the standard impaction sampler was 1.2; this fell out of the required range of 0.9 - 1.1). For PM2.5 CPS equivalence was proven for environments with low dust concentrations; in our study outdoor air and a working place environment. For the animal house environments equivalence could not be proven, because of the overloading of IPS.

When using CPS for determining PM10 concentrations in animal houses, correction factors should be used to determine the real values. Two regression lines have been determined, one for measured data within this study in the range < 100 $\mu g\ m^{-3}$ and one with measured data > 100 $\mu g\ m^{-3}$. These regression lines crossed each other at

the X-value (CPS-value) of 222.6 μg m^{-3}. For CPS values below 222.6 μg m^{-3} a correction factor of 1.09 should be used and for CPS values higher than 222.6 μg m^{-3} the following correction should be made: IPS = 0.83*CPS + 57.5 (μg m^{-3}). For PM2.5, in environments with low dust concentrations, the regression coefficient between the concentrations measured with CPS and the concentrations measured with the IPS was not significantly different from 1.0 and the constant was not significantly different from 0, therefore a correction for PM2.5 CPS results is not necessary.

From this study it can be concluded that for animal houses an adapted measuring protocol for PM is needed when compared to the outside air. Impactor plates of the standardized outdoor samplers are easily overloaded, especially for the PM2.5 sampler. Use of cyclones could overcome this problem. Correction factors for PM10, however, are needed to relate the emission results from animal houses, measured with cyclones, with outdoor results measured with the standardized impactor samplers. The measuring strategy that was developed for determining ammonia and odour emissions seems to be suitable for determining PM emissions, as well. 24 h samples should be taken to cover within day variations and measurement days should be spread over the year to cover all the seasons. For animals with a growing cycle the measuring days should also cover the whole growing period. Further research is needed to determine the measuring error when the standard outdoor sampler inlets are used to determine dust concentrations at high air velocities (> 2.0 m/s), e.g. in air channels before and after scrubbers.

Samenvatting

De EU heeft normen opgesteld voor de kwaliteit van de buitenlucht. Er zijn normen gesteld voor deeltjes kleiner dan 10 μm (PM10) en sinds kort ook voor deeltjes kleiner dan 2,5 μm (PM2.5). Deze maximale normen worden in delen van Nederland overschreden. Stallen zijn ook een significante bron van stof. De huidige stofemissiefactoren voor stallen zijn echter zeer ruwe schattingen. Nauwkeuriger data zijn nodig en daarvoor is een goed meetprotocol noodzakelijk. De doelstelling van deze studie was om een meetprotocol te definiëren en te valideren voor het vaststellen van fijnstofemissiefactoren voor stallen.

De vastgestelde normen voor fijnstof in de buitenlucht vereisen dat we jaarrond de fijnstofconcentraties kunnen voorspellen, evenals het aantal keren dat de daggemiddelde norm wordt overschreden. Dat betekent dat we een jaargemiddelde emissiefactor moeten vaststellen (de mediaan van de daggemiddelde emissies) en de variatie rond dit gemiddelde. Voor het ontwikkelen van een meetstrategie voor het vaststellen van fijnstofemissiefactoren namen we de reeds vastgestelde meetstrategie voor bepaling van ammoniakemissiefactoren voor stalsystemen als uitgangspunt. Deze meetstrategie moet rekening houden met de volgende drie variatiebronnen: de tussenbedrijfvariantie, de binnenbedrijfvariantie en de variantie als gevolg van toevallige meetfouten. Elke variantiecomponent draagt bij aan de totale meetvariatie bij de bepaling van een gemiddelde emissie van een huisvestingssysteem. Het voorgestelde bemonsteringsschema voor fijnstof is gebaseerd op hetzelfde aantal locaties (n = 4) en hetzelfde aantal metingen per locatie (n = 6), als toegepast in de meetprotocollen voor ammoniak en geur. De zes metingen moeten verspreid over het jaar worden verricht; dit betekent één meting op een willekeurige dag per 2 maanden. Door deze procedure toe te passen worden seizoensvariaties, die de stofconcentraties en ventilatiedebieten beïnvloeden, meegenomen. Voor stalsystemen met groeiende dieren, zoals vleeskuikens of vleesvarkens, moeten de metingen ook gelijk verdeeld worden over de groeiperiode. Alle metingen zijn gebaseerd op 24-uurs monsternameperioden. Dit voorkomt dat variaties binnen een dag ook bijdragen aan de totale variatie. Doelstelling van de PM emissiemetingen is het verkrijgen van een representatieve dataset voor de stofemissie van een bepaald stalsysteem. Dit betekent dat metingen bij normale managementprocedures en niet tijdens exceptionele situaties moeten plaatsvinden. Bij het rapporteren van emissieresultaten moet de stal en het gehanteerde management nauwkeurig worden beschreven.

Voor het bemonsteren van fijnstof in stallen zijn de huidige standaarden voor het bemonsteren van fijnstofconcentraties in de buitenlucht als uitgangspunt genomen. Deze standaarden zijn beschreven in NEN-EN 12341 (1998b) voor PM10 en in NEN-EN 14907 (2005) voor PM2.5. Voor de buitenlucht, met veranderende windrichtingen en turbulentie, is een monsterkop ontwikkeld met een ronde spleetopening als inlaat. Met deze inlaat kan stof worden bemonsterd onafhankelijk van de windrichting en met weinig invloed van de intensiteit van turbulentie. Na deze inlaat gaat de lucht naar een voorafscheider die deeltjes afscheidt die groter zijn dan de deeltjes die bemonsterd moeten worden. Voor buitenlucht is de genormeerde voorafscheiding gebaseerd op het principe van impactie. Hierbij wordt de stroomsnelheid van de bemonsterde lucht vergroot door de lucht door nauwe pijpjes te leiden. De lucht botst vervolgens op een ingevette plaat. Als gevolg van hun traagheid plakken de grotere deeltjes vast op de plaat, terwijl de kleinere deeltjes (PM10 of PM2.5) de luchtstroom volgen en vervolgens op een filter worden verzameld. Impactor voorafscheiders (IVA) hebben als nadeel dat de impactieplaat snel overbeladen kan raken, vooral tijdens lange monsternameperioden, bijv. 24 uur. Overbelading van de impactieplaat veroorzaakt het ‘bouncing effect’; deeltjes die al geïmpacteerd zijn op de plaat kunnen daar weer vanaf gebotst worden door andere grote deeltjes. Deze deeltjes worden daardoor weer opgenomen in de luchtstroom en opgevangen op het filter. Door het ‘bouncing effect’ wordt de stofconcentratie in de lucht overschat. Cycloon voorafscheiders (CVA) zijn veel minder gevoelig voor overbelading. Er is echter geen Europese normering voor gebruik van een CVA. Het al dan niet overbeladen raken van de impactieplaat is getest in een pluimveestal. Tijdens deze test werd de impactieplaat regelmatig gereinigd en opnieuw ingevet tijdens de monsternameperiode. Voor de PM10 impactor werd geen effect van het schoonmaakinterval op de stofconcentratie gevonden. Bij de PM2.5 impactor nam de stofconcentratie significant af bij kortere intervallen van opeenvolgende reinigingen van de impactieplaat. Dit betekende dat de impactieplaat overbeladen was, waardoor het ‘bouncing effect’ optrad. Uit deze test hebben we geconcludeerd dat de PM2.5 impactor niet geschikt is als voorafscheider in stoffige omgevingen zoals in stallen. In een tweede studie is volgens een standaard procedure getest of de CVA equivalent is aan de IVA. Voor PM10 werd equivalentie aangetoond voor PM10 concentraties lager dan 100 µg m^{-3}. Voor PM10 concentraties hoger dan 100 µg m^{-3} voldeed de CVA niet aan de voorwaarden voor equivalentie. Het verschil tussen twee vergelijkbare cyclonen was gemiddeld 6%, terwijl de eis maximaal 5% is; de helling tussen stofconcentraties gemeten met CVA en met IVA was 1.2; dit valt buiten de vereiste range van 0.9 – 1.1. Voor PM2.5 is equivalentie bewezen voor monsternames in omgevingen met een lage stofconcentratie, in onze studie de buitenlucht en een werkplaatsomgeving. Voor stallen kon de equivalentie niet worden bepaald, aangezien de IVA in deze omgeving zeer snel wordt overbeladen.

Wanneer CVA wordt gebruikt voor bepaling van de PM10-concentratie in stallen, moet men correctiefactoren gebruiken om de werkelijke waarden vast te stellen. Er zijn twee regressielijnen vastgesteld, één met gemeten waarden in deze studie lager dan 100 µg m^{-3} en één met gemeten waarden in deze studie hoger dan 100 µg m^{-3}. Deze lijnen sneden elkaar bij een X-waarde (CVA-waarde) van 222.6 µg m^{-3}. Voor gemeten waarden met de CVA lager dan 222.6 µg m^{-3} moet een correctiefactor van 1.09 worden gebruikt en voor waarden hoger dan 222.6 µg m^{-3} moet de volgende correctie worden toegepast: IVA = 0,83 x CVA + 57,5 (µg m^{-3}). Voor PM2.5, in omgevingen met lage stofconcentraties, was de regressiecoëfficiënt tussen concentraties gemeten met CVA en de concentraties gemeten met IVA niet significant verschillend van 1,0 en de constante was niet significant verschillend van 0, daarom is een correctie voor de PM2.5 CVA concentraties niet nodig.

Uit deze studie kunnen we concluderen dat voor het meten van PM in stallen een aangepast protocol nodig is ten opzichte van de metingen in de buitenlucht. De impactieplaten van de genormeerde monsterkoppen voor de buitenlucht raken snel overbeladen in stallen; dit geldt met name voor de PM2.5 monsterkop. Het gebruik van cyclonen kan dit probleem oplossen. Voor PM10 zijn echter correctiefactoren nodig om de PM emissies uit stallen gemeten met cyclonen te relateren aan de buitenluchtconcentraties gemeten met impactoren. De meetstrategie die ontwikkeld is voor het bepalen van de ammoniak- en geuremissies lijkt ook geschikt voor het bepalen van de PM-emissies. 24-uurs metingen zijn nodig om de invloed van binnendagvariaties uit te sluiten en de metingen moeten gespreid over het jaar plaatsvinden om seizoenseffecten mee te nemen. Voor groeiende dieren moeten de waarnemingen ook gelijk over de groeiperiode verdeeld worden. Verder onderzoek is nodig om de meetfout vast te stellen wanneer gestandaardiseerde luchtinlaten voor de buitenlucht worden gebruikt om stofconcentraties te bepalen bij hoge luchtsnelheden (> 2,0 m/s), zoals in luchtkanalen voor en na een luchtwasser.

Content

Summary

Samenvatting

References

1 Introduction

Air pollution by fine dust (PM10, particles smaller than 10 μm), causes human health problems (Buringh and Opperhuizen, 2002). Therefore, the EU has set air quality standards for maximum PM10 concentrations (EU, 1999). The maximum year round limit was set to 40 μg m^{-3} and the maximum daily limit was set to 50 μg m^{-3}, with a maximum of 35 crossings. Based on new findings policy attention in the EU has shifted towards the finer fraction (PM2.5, particles smaller than 2.5 μm). For PM2.5 the Parliament and Council of the EU agreed on an initial target value of 25 μg m^{-3} from 2010. From 2015, this figure would become a binding limit (European Parliament; The legislative Observatory, 2007). PM10 (and PM2.5) standards are exceeded in some parts of The Netherlands (Anonymous, 2006). Therefore The Netherlands made an action plan to solve this problem. Animal houses in The Netherlands are responsible for approximately 20% of the total primary fine dust emission (Chardon and Van der Hoek, 2002). The other 80% is emitted from traffic and from industry. The present dust emission factors from animal houses are rough estimates. More accurate data are required. However, for animal houses no measuring protocol is available yet for determining the fine dust emission. The objective of this study was to determine and to validate a measuring protocol for fine dust emission from animal houses.

The first part of a measuring protocol is the measuring strategy. For determining ammonia emissions from animal houses a measuring strategy has already been developed (Ogink et al., 2005). For the development of a measuring strategy for fine dust emission, the developed measuring strategy for determining ammonia emissions from animal houses formed the basis. For air sampling in animal houses the existing standards for sampling ambient air for determining fine dust concentrations was used as the starting point. The standard procedure for sampling outside air for determining PM10 concentrations are described in protocol NEN-EN 12341 (1998b). For sampling within chimneys iso-kinetic sampling is necessary, because of the high air flow within these chimneys. With iso-kinetic sampling it is assured that the particles in the sample are representative for the particles in the air. Within this report it will be discussed whether iso-kinetic sampling is needed and possible for animal houses. The measuring protocol should be suitable for measuring dust concentrations after air scrubbing systems, as well. The air after the scrubber is generally saturated with moisture; therefore attention should be paid to prevention of condensation within the sampling head. For determining the mass of dust on the filter we join the existing protocol for mass determination of dust filters (NEN-EN 12341, 1998b; NEN-EN 14907, 2005).

In chapter 2 we answer the question what should be measured. In chapter 3 the measuring strategy is described and in chapter 4 we discuss the sampling equipment that could be used. The specific situation for sampling the dust removal efficiency of air scrubbers is described in chapter 5. Based on chapters 1 to 5 a draft measuring protocol for determining dust emission factors for animal houses is proposed in chapter 6. In chapter 7 the suitability of the standard impactor samplers for outdoor air is tested for the dusty environment of an animal house. Furthermore, in this chapter the equivalence of the cyclone pre-separators for PM10 and PM2.5 is described. The report is finished with a general discussion chapter and a chapter with the general conclusions from this report.

2 What to measure?

Looking at the air quality standards for outdoor air, we should be able to predict the year average concentration and the number of violations of the 24 hour standard of 50 $\mu g\ m^{-3}$ in rural areas. This means that we want to have a year average emission factor (being the median of emissions). We need to know what the distribution of emissions in time looks like, because when doing emission measurements, we obtain the average emission and a standard deviation of emissions. Enough data should be available to detect the kind of distribution of emissions and to derive an estimate of the median of emissions. Calculation of the distributions of outdoor concentrations is in principle possible using the median of the emissions and a model for local dispersion like the New Dutch National Model (Erbrink, 1995).

Talking about 24 average concentrations raises the question how representative an estimated emission based on the product of concentration and ventilation rate is, as both show diurnal fluctuations. Influence of hourly fluctuations of this product on the 24 average emission rate should be investigated.

Deciding to concentrate on the determination of emissions and emission factors does not exclude that we may want to obtain information as well on concentrations inside the animal houses. Indoor concentrations play a role in health of the farmer as well as animal health and welfare. Especially for the farmer information on dust concentration with an averaging time of less than 24 h is interesting as animal activity may increase at entering the animal house and distributing fodder etc. The farmer may be exposed to higher concentrations during his stay in the animal house than the average exposure of the animals.

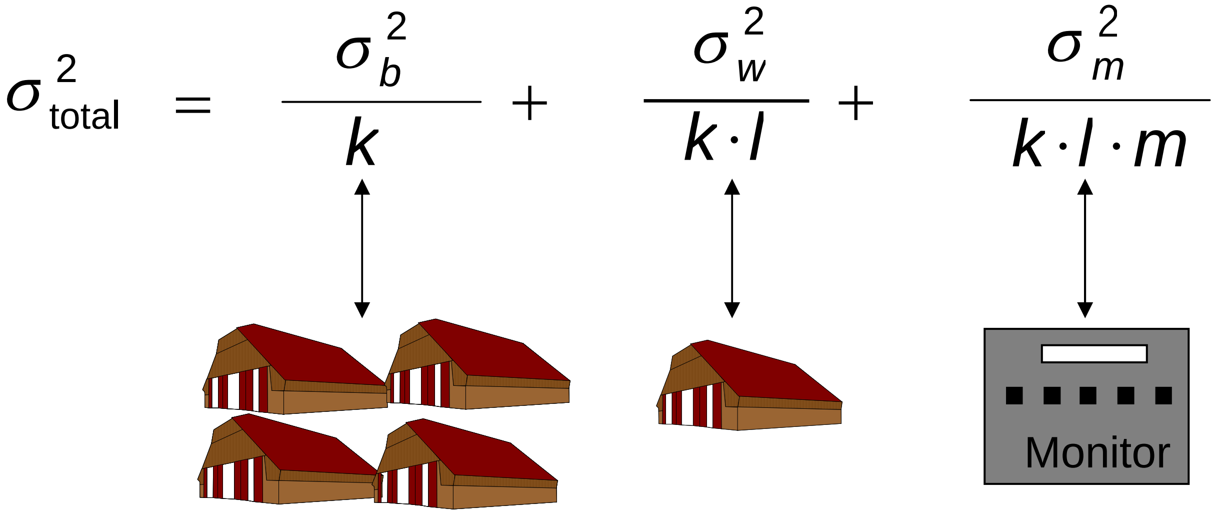
3 Measurement strategy

The measurement strategy for determining the PM10 emission factor of an animal housing system should be focused on achieving a representative sampling procedure that includes all relevant variation sources. An animal housing system is defined here as a group of animal houses that accommodates a specific animal category with a specific pen design that describes the layout of elements of the pen that (potentially) affect the emission of airborne components. Defined in this way it can be understood as a classification of animal houses in systems that have a characteristic pen design with specific emission levels. Classifications may differ between varying gaseous components. In the Netherlands the most important classification scheme of animal housing systems is related to the emission of ammonia, and is described in the Regulation on ammonia and livestock housing systems (Regeling Ammoniak en Veehouderij: Rav, www.infomil.nl). The Rav-classification scheme provides for each main animal category the available housing system and their mean ammonia emission factors for licensing-procedures. Besides pen design, systems may also be defined on basis of manure management or specific end-of-pipe techniques that reduce ammonia emission. For odour emission a more generalized version of the Rav-classification with less categories is used in the Regulation on odour emissions from livestock houses (Regeling Geurhinder Veehouderij, www.infomil.nl), and provides the list of mean odour emissions to be used in licensing-procedures. Both the ammonia and odour emission factors are based on measurement protocols that are designed to give a reliable and, given available means, accurate estimate of the mean emission from a housing system in practice (Ogink et al., 2005). These protocols have recently been modified to include new insights in underlying variance of emission patterns in the sampling scheme. Because emission characteristics of PM (PM10 and PM2.5) are expected to share many elements with gaseous emissions, a similar approach will be followed for setting up the measurement strategy of PM emission as has been applied in the modified ammonia and odour protocols. The main considerations for this strategy are explained hereafter and are based on research experience where ammonia and odour emissions were measured.

Ogink and Klarenbeek (1997) described a variance-component model that comprises the main elements that determine the accuracy of a measurement protocol for emissions. The model was used to evaluate measurement strategies for odour emissions. Ogink et al. (2005) used the same model to explore improved sampling schemes for ammonia emissions of housing systems. The model is based on distinguishing between three variance layers in a nested sampling design:

Between-farm variance (σ^2_b) : variance resulting from factors and variables that cause systematic differences between farm locations within the same housing system. Such factors can be related to different management practices between farms, like different feeding- and ventilation regimes, different hygiene standards, but also small differences in pen layout within the same system.
Within-farm variance (σ^2_w) : variance resulting from factors and variables that cause day to day fluctuations in emissions of a specific farm location. Such factors can be related to seasonal factors that affect ventilation levels and correlated emission levels throughout the year, but also production factors like present animal numbers and mass, feed intake and manure excretion.
Instrument measurement variance (σ^2_m) : variance resulting from random measurement error of instruments used in emission measurements. Both instruments used for measuring concentrations and instruments used for determining air flows are subject to this type of error.

Figure 3.1 Statistical model describing the relationship between the overall measurement variance of the mean emission level of a housing system (σ^2_{total}) and the between-farm variance(σ^2_b), within-farm variance (σ^2_w) and the instrument measurement variance (σ^2_m).



$$\sigma^2_{total} = \frac{\sigma^2_b}{k} + \frac{\sigma^2_w}{k \cdot l} + \frac{\sigma^2_m}{k \cdot l \cdot m}$$

Each variance component attributes to the overall measurement variance of the mean emission of a housing system (σ^2_{total}) as described in the model equation in figure 3.1. The equation reflects σ^2_{total} in a sampling design with k farm locations, l measurement events within each location and m measurements within each measurement event on a location. The model is based on the assumption that variance components are independent, and that farm locations and sampling days are randomly selected. Moreover it is assumed that measurements within locations and within measurement events are independent from each other. In practice it has been shown that day to day measurements of ammonia emission in continuous sampling schemes are subject to strong autocorrelation patterns (De Boer & Ogink, 1994) and thus not fully independent. The same can be expected for other gaseous emissions from animal houses. The model therefore can only be used in sampling schemes where sampling events are sufficiently spread in time to avoid autocorrelation. Such an approach is highly recommended for emission measurements to achieve cost efficient data collection. The model refers to a nested design where a restricted number of farm locations are frequently sampled in time. This approach is normally considered the most practical and cost effective one for emission measurements, because considerable efforts are required in terms of selecting available and suitable farms, and large investments are required for each farm location to install sampling equipment and instruments. This also applies for PM10 measurements where required investments per location are a major factor in available measurement budgets.

The model in figure 3.1 shows that knowledge of the magnitude of the different variance components is required to design an adequate sampling scheme. For PM10 there are no quantitative data available from measurement campaigns that allow estimates for σ^2_b or σ^2_w. For both ammonia and odour emission it was demonstrated by Mosquera & Ogink (2005) and Ogink & Klarenbeek (1997) that both variance components in housing systems for fattening pigs were estimated to vary in the range of 30 - 40%, when expressed as relative standard deviations. These components were as such larger than the instrumental variance components, even for odour measurements. The model shows that the effects of these components can be downscaled by the number of replications k and l. Especially k, representing the number of locations, plays a key role as it affects the contribution of all variance components. For the modified measurement protocol of ammonia (Ogink et al., 2005) and odour it was decided to include four farm locations in the sampling scheme, i.e. k=4. By doing so the model improves the overall accuracy by a factor 2, compared to the earlier design of the ammonia protocol where one farm location was sampled. In both ammonia and odour protocols the number of independent sampling events on a farm location was set at six, i.e. l=6, spread over one year. This number was considered large enough to deal with the within-farm location variance and at the same time ensuring that observations were sufficiently spread in time to be independent from each other. Similarly as required for PM10-measurements the sampling time of one sampling event in the ammonia protocol was set at 24 hours, thus including all diurnal variations.

The proposed sampling scheme for the PM10-measurement protocol is based on the same number of locations and samplings within locations, i.e. k=4 and l=6, as applied in the ammonia and odour protocol. Here, two major considerations play a role:
It is expected that, similarly as for ammonia and odour, for PM10 both σ^2_b and σ^2_w have a substantial magnitude, both likely to be higher than the instrumental variance. Similar factors, as explained before for ammonia and odour, being related to farm management, especially feeding and ventilation regimes, are expected to affect the emission of PM10. It is therefore important that sufficient replications are present in both variance strata. Only after having collected enough data in these strata in different animal categories, it is going to be possible to estimate their variances and subsequently to modify the required number of replications based on these insights.
In practice emission measurements on farm locations will in many cases include all relevant emission components, such as ammonia, odour, greenhouse gases and PM10. Both for reasons of cost efficiency and for the interest of funding parties, measurements of different emission components are normally combined. This means that there is a practical need to harmonize the sampling scheme of these components, unless there is a very compelling reason to apply another scheme. So far, there are no grounds to apply a different scheme for PM10.

In the ammonia and odour protocol, for each location six measurements have to be taken that are spread over one year, being randomly taken in subsequent two month periods. By this procedure seasonal variations that influence dust concentrations and ventilation rates throughout a year are equally distributed and well balanced in the sampling scheme. For housing systems with production cycles that affect emission patterns, like broilers or fattening pigs, it is prescribed that measurements are equally divided over the growing period. Similarly, in cases where regular management practices can be expected to affect emission levels, care should be taken that these practices are incorporated in the sampling scheme in such a way that samplings are well distributed over these management practices.

For reasons explained before, all measurements will be based on 24 hour sampling periods. This implies that diurnal variation patterns are not contributing to the overall measurement variation.

4 Choice of instrumentation

Standards that could be relevant for sampling fine dust in animal houses are standards for sampling fine dust in the open air and standards to sample dust in stacks. Table 4.1 gives an overview of these standards within the EU and the USA. The last standards are less relevant for European animal houses in first view, but the advantage of higher loading capacities of the size selective inlets are favourable for animal houses with sometimes pretty high dust concentrations.

Table 4.1 Overview of European, VDI and US standardized methods to measure fine particulate matter

NEN-EN-13284-1	Station. source emiss.; Determination of mass, gravimetric	2001
NEN-EN 13284-2	Station. source emiss.; Determination of mass, automated	2004
VDI 2066 part 1	Station. source emiss.; Dust in flowing gas; gravimetric, plane filter	1975
VDI 2066 part 2	Station. source emiss.; Dust in flowing gas; gravimetric, tubular filter; low volume	1993
VDI 2066 part 3	Station. source emiss.; Dust in flowing gas; gravimetric, tubular filter; high volume	1994
VDI 2066 part 5	Station. source emiss.; Dust in flowing gas; size selective, cascade impactor	1994
VDI 2066 part 7	Station. source emiss.; Dust in flowing gas; gravimetric, gravimetric; plane filter	1993
40 CFR part 50	Reference and equivalent methods for dust measurements in ambient air	1997
www.epa.gov/ttn/amtic/criteria.html	List of commercial available instruments that comply to US standards for PM10 and PM 2.5	2005
Peters et al.	Design and calibration of the EPA PM2.5 WINS impactor	2001
Kenny	Design and calibration of the VSCC PM2.5 cyclone	2000
NEN-EN 12341-1	Dust measurement in ambient air; gravimetric; impactor ;PM10	2001
NEN-EN 12341-2	Dust measurement in ambient air; automated; impactor ;PM10	2001
NEN-EN 14907	Dust measurement in ambient air; gravimetric; impactor ;PM2.5	2005

In table 4.1 we see standardised methods for outdoor air and for in stack monitoring. Outdoor air is in general characterized by varying wind speeds (sometimes lower, but most of the time higher than 1 m s^{-1}) and low concentrations (< 200 μg m^{-3}). Stack sampling is characterized by high flow velocity in the stack (> 1 m s^{-1}) and medium to high dust loadings. Animal houses differ from these situations. Concentrations are medium to high (300-5000 μg m^{-3}) and air speeds within the animal house are low. Houses with forced ventilation have higher air velocities within the ventilator ducts. The duct length, however, is most of the time too short for representative measurements according to the stack sampling protocols. This forces us to make a dedicated protocol for sampling in animal houses. For this protocol we therefore derive as many items as possible from existing standards and also use instrumentation that is in some way already standardized or that has a documented performance.

Starting with a new field of applications (sampling in animal houses and before and after air scrubbers or bio-filters) we start looking at the efficiency of the entrance of the sampler. Then we will go to the cut-off characteristics of the pre-separator and finally we will end up with the collection medium. In addition some attention is paid to automated sampling of dust, as filter changing, filter conditioning and gravimetric analyses involve a lot of labour costs.

4.1 Required efficiency at the entrance of an inlet

It is a well-known fact, that small particles in air are easily collected in an inlet as they have that low inertia, that they follow the streamlines of the air surrounding them. For larger particles sampling is more complex (Belyaev and Levin, 1974; Ter Kuile, 1983; Hofschreuder and Vrins, 1983). For sampling in a defined flow iso-axiality and iso-kinetic sampling are required. In outdoor air with changing wind directions and turbulence, these requirements cannot be met. Therefore a circular slit sampler was developed to sample particles independent from wind direction and with little influence of turbulence intensity. This circular slit sampler is followed by a size separation unit to retain particles larger than the size that should be sampled (Wedding et al, 1982). For the particle size fractions PM10 and PM2.5 efficiency curves for size separation are defined (ISO, NEN). These efficiency curves were in the past to be met by size selective pre-separators within a certain margin of tolerance (Wedding et al, 1982). The required size separation curve for a PM10 inlet is presented in figure 4.1, for a PM2.5 inlet in figure

4.2. Problems are the not very sharp cut off characteristics of these curves. Instruments that have the same cut-off diameter (50% efficiency) may have a different cut-off curve and show difference in results depending on the size distribution of the aerosol that is sampled. This prompted to strive for a very sharp cut off curve. The WINS impactor (Peters et al, 2001) was the first with a very sharp cut-off curve for PM2.5. This impactor acts as the US standard. This approach was followed by CEN in the design of the EU- PM10 and PM 2.5 inlets.

The important part of the curves is the section where the efficiency is larger than zero percent (here called maximum cut-off diameter) and smaller than 50%. It is easily understood that the **efficiency of the inlet** (slit) should be constant and equal to 100% for particles smaller than the largest value of the particle diameter of the pre-separator efficiency curve not being equal to zero. A sampled fraction of the particles not being constant and equal to 100%, would result in a variable mass of this fraction being forwarded to the collecting medium. The collection efficiency of particles larger than the maximum cut-off diameter is not important as they should be totally collected by the pre-separator.

Figure 4.1 Efficiency curve for PM10 sampling according to ISO, (1995)

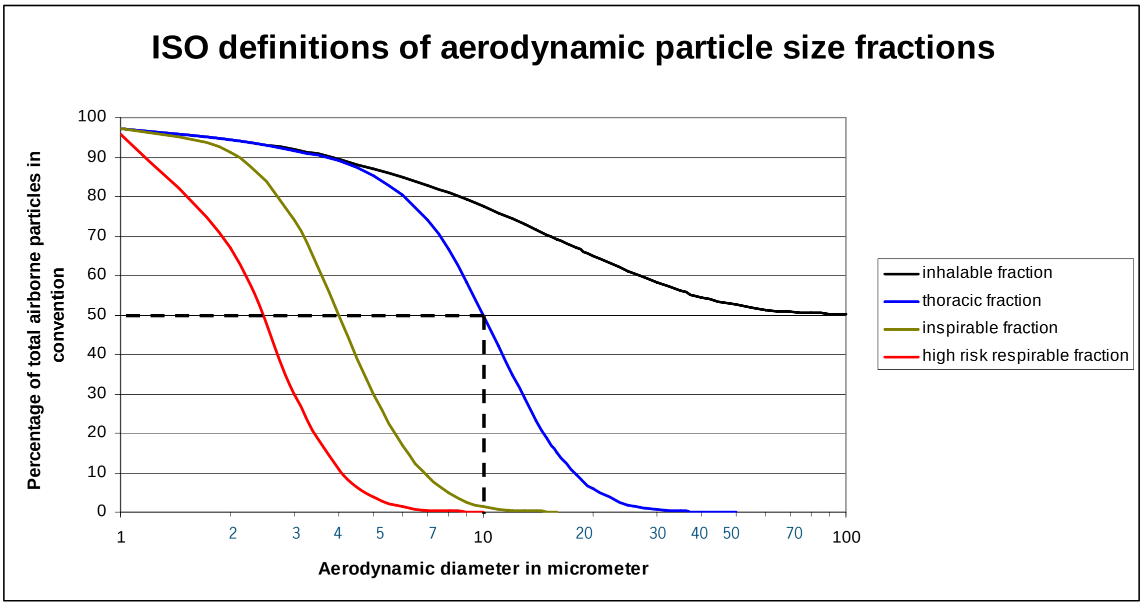
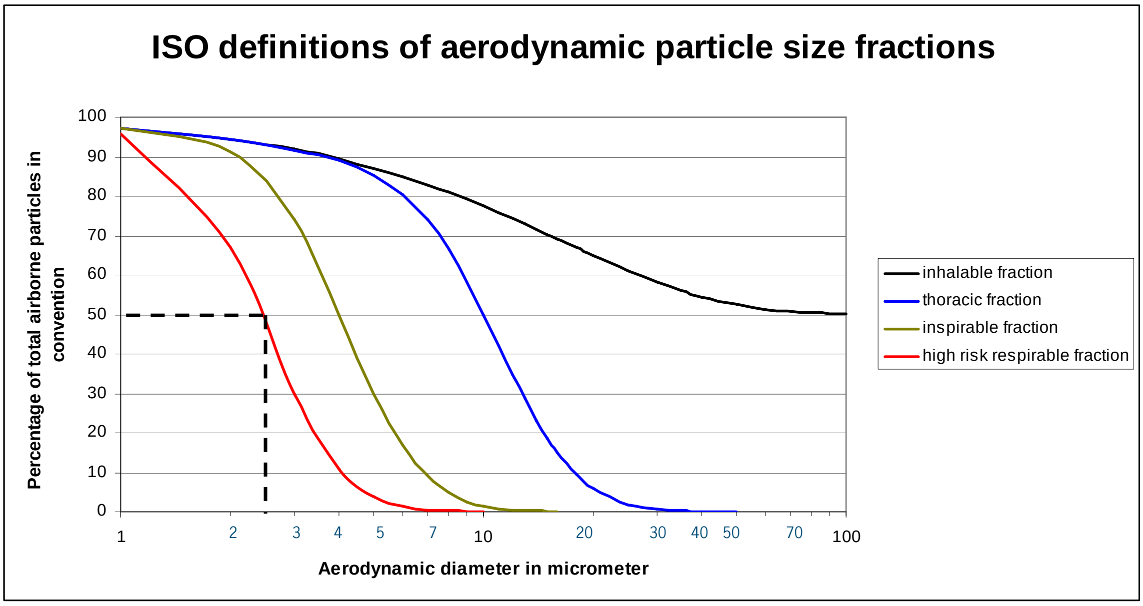


Figure 4.2 Efficiency curve for PM2.5 sampling according to ISO, (1995)



4.2 Choice of a pre-separator capable to cope with high dust loadings

The first pre-separators used in the US to sample PM10 were impactors. A very bulky impactor for the EPA High Volume samplers and a more handy low volume impactor for the Dichotomous sampler (Wedding et al, 1982). A problem with the impactors appeared to be the change in cutt-off characteristics of the impactor by narrowing the impaction nozzles because of dust deposition on the walls of these nozzles and the effect of bouncing of particles on a highly loaded impaction surface (Kenny, 1998). Regular cleaning and the use of a rotation impaction surface (Moudi impactor) to prevent bouncing, were means to overcome this problem. To minimize the effect of a change in cut-off characteristics, it was decided to develop an impactor with very sharp cut-off characteristics. The WINS impactor (Peters et al, 2001) was the first with a very sharp cut-off curve for PM2.5. A graph of the cut-off characteristics is presented in figure 3.3. In this figure the classical PM2.5 cyclone follows the original ISO PM2.5 curve. The Wins impactor clearly has more sharp cut-off characteristics.

Sharp cut-off impactors, however, still have the problem of particle bouncing at high dust loadings. This prompted to the development and standardisation of the very sharp cut PM2.5 cyclone (VSCC) in the US (Kenny, 2000). European standards followed the American standardisation, by starting with standardisation of impactors (CEN-12341, 1998 and CEN-14907, 2005). These standards only presented details on the design of the impactor, not on the related cut-off characteristics. Being equivalent to a sharp cut-off characteristic of 10 µm and 2.5 µm respectively, they should almost mimic the curves for the US samplers.

Considering the safe loading characteristics of 120 μg m^{-3} at a flow of 2.3 m^3 s^{-1} for impactors, a filter loading of 276 μg is possible. A concentration of 200 μg m^{-3} with corresponding loading of 460 μg is expected to be possible. Two problems will arise when dealing with an impactor and higher concentrations like in animal houses; The filter will clog at higher loadings influencing the flow and with that also the cut off characteristics of the pre-separator.

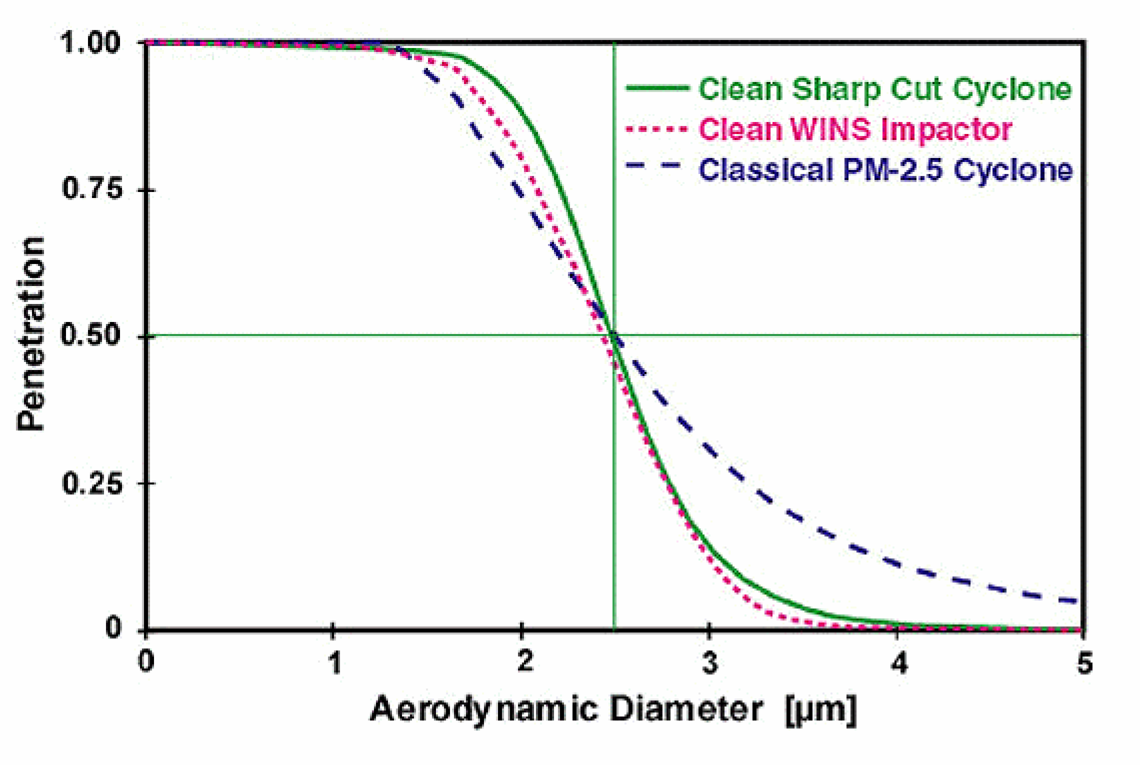
The impaction plate under the jets in the pre-separator will collect that much coarse particles, that bouncing and collecting coarse particles with the fine fraction is possible.

Estimating maximum aerosol concentrations in animal houses as high as 1000 μg m^{-3}, we can sample safely during only 1/5 of every hour = 12 minutes. This can be done by sampling a block of 3 minutes during every quarter of an hour. In this way we obtain a spreading within the hour and still reduce uncertainty in the results from frequent switching on and off of the flow. The timer will be accurate enough, but the flow takes time to reach a certain value. Referring to the outdoor standard, the estimated range in measurable concentrations is 5 – 1000 μg m^{-3}**.** To overcome these problems, we decide to use a VSCC cyclone as a pre-separator. This avoids influence of high dust loadings on the pre-separator. The second choice is to use a tubular filter unit, like described in VDI 2066 Part 3 at the back of the cyclone to have a low pressure drop (large filter surface) at high dust loadings, putting less constraints to the flow regulation of the pump and maintaining a more accurate flow.

Taking this into account and expecting large problems from overloading impactors at the high concentrations of dust in animal houses we chose for the Very Sharp Cut Cyclone (VSCC) instead of the Standardised CEN impactor for PM 2.5. Figure 4.3 shows that it has almost the same cut-off curve as the WINS impactor with very little influence of particle loading on the performance of the instrument (Kenny, 1998).

The problem with overloading and particle bouncing does not only exist for the PM2.5 fraction, but also for the PM10 fraction. For the same reason we would like to use a PM10 cyclone instead of a PM10 impactor. Disadvantage in this case is, that there is no standardised PM10 cyclone in the US. University Research Glassware (URG) sells a low volume (1 m^3 h^{-1}) PM10 cyclone but is only able to provide the relation between 50% cut-off diameter and flow of the cyclone but not able to provide the total efficiency curve. This means that equivalence to the CEN PM10 impactor should be proven.

Figure 4.3 Cut-off characteristics for the classical PM2.5 cyclone (following the ISO curve for the respirable fraction for a high risk population), the WINS-impactor and the Very Sharp Cut Cyclone (VSCC)



4.3 Standard for gravimetric analysis and optical detection

The European standards on air quality for PM 10 and PM 2.5 are expressed in mass per cubic meter air as year average (PM10 and PM 2.5) or day averaged (PM 10) concentrations. This means collection of dust on filters , conditioning of filters before and after loading and weighing under controlled conditions. Details can be found in the description of the standardised methods.
It would be much easier to use an optical method to measure dust concentrations. Advantage would be that it is less labour intensive, gives indications of the trend of the concentration in time and can be used as an alarm system when setting an emergency level on the signal. The main drawbacks are;
Measuring unconditioned aerosol (fluctuating water content).
Not measuring the fine fraction (smaller than 0.3 μm because of the lower optical detection limit), although the mass of these small particles is low.
Possible errors in collection of the larger particles (> 5 μm) because of possible entry problems (see paragraph 3.1 and chapter 5).
An optical diameter is not equivalent to a mass median diameter.

As the size distribution of the aerosol and relative humidity in the animal house will fluctuate, it is no option to use optical instruments for determination of emission factors. These instruments are however very useful as additional instruments to study trends in concentrations and determine the efficiency of abatement measures.

5 Measuring emissions and efficiency from air scrubbers and bio filters

To reduce emissions of ammonia, odour and dust air scrubbers or bio-filters may be placed between the outlet duct of the animal house and the outlet to the open air. Measurements shall be performed at the outlet of these units to determine the emissions to the air. For determining the efficiency of the air cleaning units, additional measurements in front of the filtration unit are needed. The environment for these measurements is demanding for measurement instruments. Air velocities before and after the scrubber can vary very much between scrubbers. Some scrubbers have a large surface area with relatively low air velocities (< 1.0 m/s), while others scrubbers are compact and have a relatively high air velocity (> 2.0 m/s). The geometry of the incoming and outgoing air ducts may be very variable with circular ducts, rectangular ducts or no duct at all, but just an opening above the droplet remover or free air after the bio-filter wall (see figures 5.1, 5.2 and 5.3). For scrubbers with high air velocities of the air (> 2.0 m/s) use of stack sampling procedures is most adequate. However, there is one important requisite when using an in stack sampling procedure: the air velocity during the sampling period should not vary. This requisite can generally only be met in animal houses when samples are taken during short periods (e.g. one hour). For 24 h sampling periods the ventilation rate is generally varying too much for in stack sampling. Important standards for in stack sampling are NEN-EN 13284-1 Determination of low range mass concentration of dust-part 1 : Manual gravimetric method and NEN-EN 13284-2 Determination of low range mass concentration of dust-part 2 : Automated measuring systems. To be able to sample for 24 h periods without stack sampling the air velocity of the outgoing air could be reduced by placing a funnel on the outer layer of the scrubber (see figure 5.4).

Figure 5.1 Chemical air scrubber next to an animal house with circular ducts for the outgoing air

Figure 5.2 Droplet remover of a combined air scrubber where the cleaned air is coming out

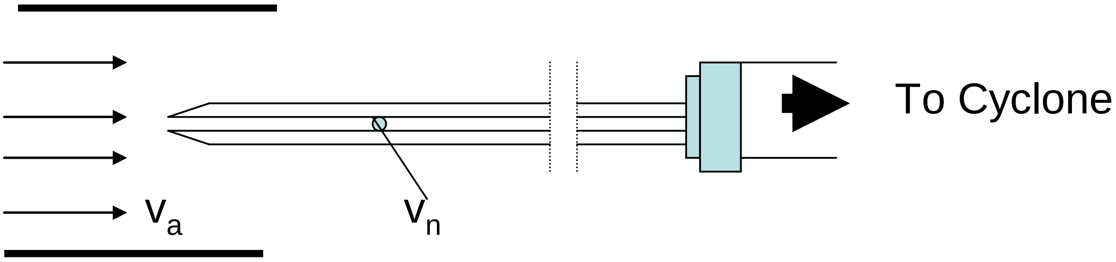
Figure 5.3 Air scrubber next to an animal house with a large surface of the outgoing air. Air is sampled inside tubes placed on the last layer of the scrubber to prevent wind influences

Figure 5.4 Funnel on top of the droplet remover from a combined air scrubber to slow down the air speed

5.1 Sampling theory

At high air velocities (> 2.0 m/s) an outdoor sampling inlet within the duct is less suitable, while 1) it would obstruct the air flow to a large extend giving rise to undefined flow and aerosol patterns in front of the sampler; 2) the high air velocity inside the duct causes unequal sampling efficiencies of the particles in the air. When the air speed can not be reduced by using a funnel, stack sampling during short periods is preferred with inlets according to NEN EN 13284-1. With a horizontal duct, the inlet can be straight (see figure 5.5). The pre-separator and filter unit can be placed outside the duct to prevent these units obstructing the flow. The inlet tube should be as short as possible to avoid important loss of dust between inlet and pre-separator. For a vertical duct, an inlet probe with a bend according to NEN EN 13284-1 can be used.

Figure 5.5 Iso-kinetic sampling from a horizontal duct



The use of a restricted number of straight and 90° bend sharp edged inlets (NEN-EN13284-1) with variable inside diameter would not pose a practical problem, as sampling artefacts are most important for coarse aerosol and we are interested in the PM10 and PM2.5 fractions. Especially for the PM2.5 fraction the non representative sampling of particles larger than approximately 4 μm would not pose too much problems as long as the sampling velocity and velocity of outside air are not too different (see figure 5.6). As the cut-off curve of the PM10 fraction extends up to 30 μm, the representative sampling of this fraction is more critical. Figure 5.6 shows the relation for sampling efficiency in function of an-isokinesis in a qualitative way.

Figure 5.6 Effect of an-isokinesis on the sampling efficiency of particles. All sampling is iso-axial

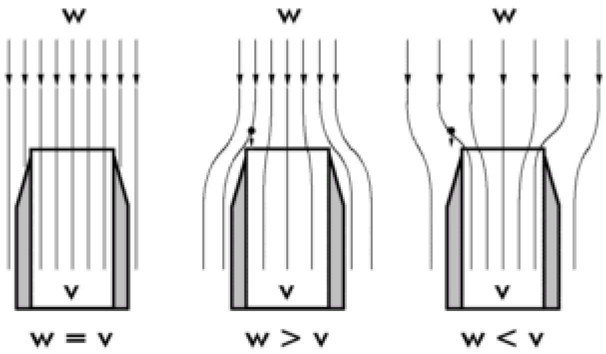
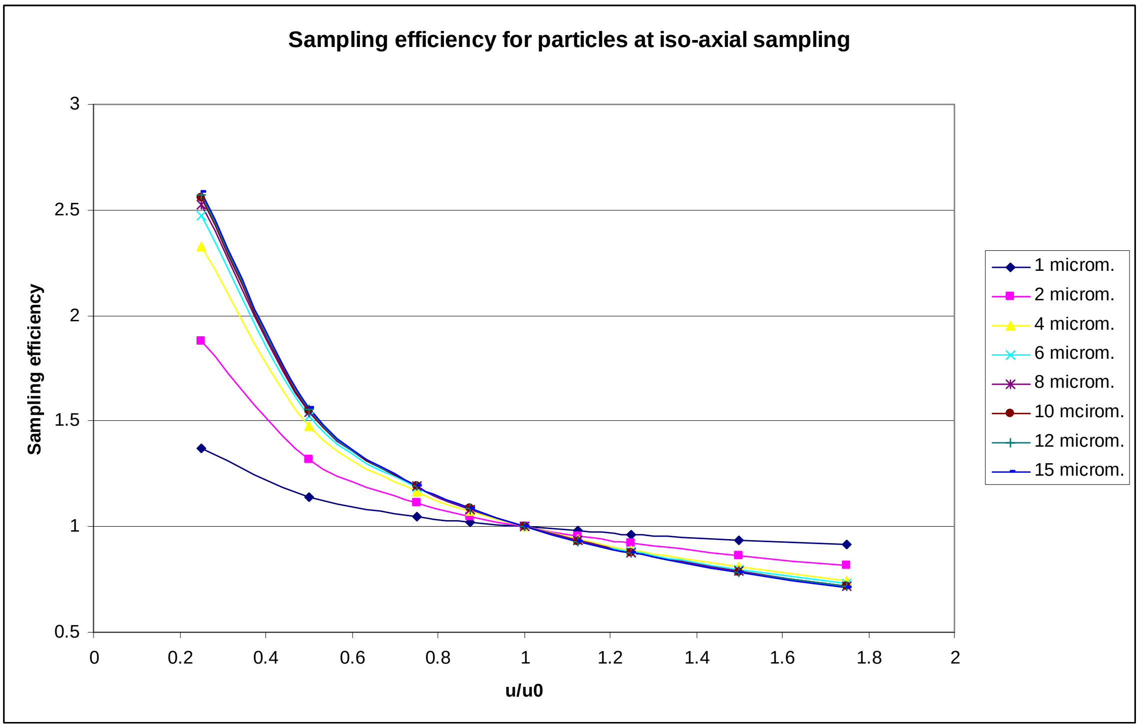


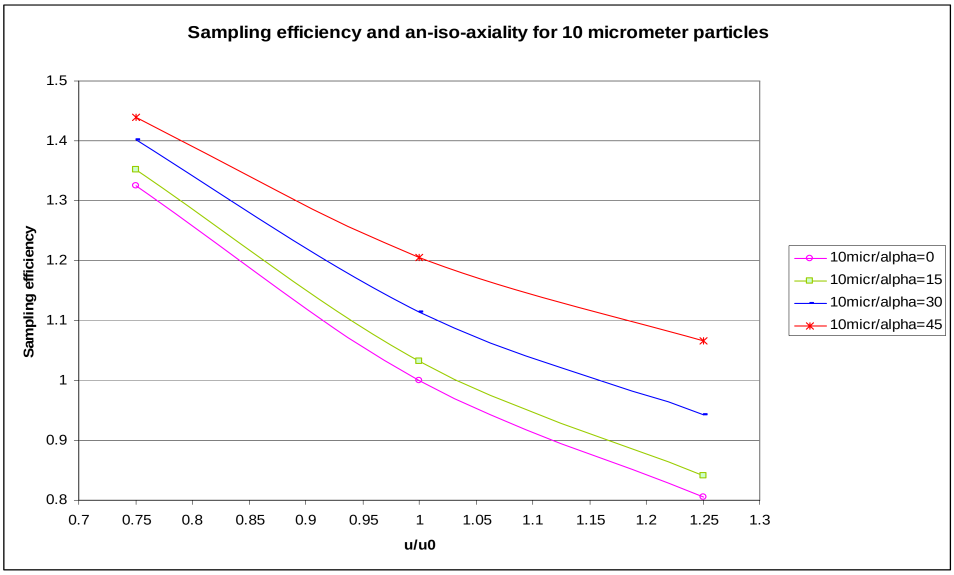
Figure 5.6 shows that we will sample the correct amount of particles, when the flow inside the sampling nozzle will equal that of the surrounding air. When we maintain a too low flow inside the nozzle (W>V) we sample more particles because of inertia of the larger particles. When the sample flow is too high, we will determine a too low concentration. To show the influence of iso-kinesis on the sampling efficiency, sampling efficiencies for a couple of particle sizes and a range of ratios for the sample flow divided by the free air flow are presented in figure 5.7 For all situations iso-axiality is assumed (angle between axis of sampler and axis of duct < 15 ° (NEN-EN-13284-1). Figure 5.7 makes two things clear; larger particles are more influenced by an-isokinesis than small particles and a too high sampling velocity compared to the undisturbed flow gives less deviation from the ideal sampling efficiency of one, than a too low flow ($u/u_0<1$).

Figure 5.7 Sampling efficiency in dependence of particle diameter and ratio of sampling velocity u and external velocity u_0 at iso-axial sampling



Another problem when sampling aerosols from scrubbers is an-isoaxiality. The stack sampling standard (NEN-EN-13284-1) prescribes an angle less than 15°. This condition is easily met when we have a long duct and we have a sampling opening in the duct more than 10 times the diameter of the duct away from a bend or obstruction. Scrubbers will have small length of ducts or even no ducts at all. In this situation there is no guarantee, that the air flow is parallel to the duct and there may be turbulence induced, that hinders correct sampling. The effect of misalignment on the sampling efficiency is shown in figure 5.8. The effect of the angle of yaw is rather complicated and more clear when only calculated for one particle size (e.g. 10 µm).

Figure 5.8 Sampling efficiency depending on ratio of sampling velocity and velocity of the free air stream (u/u0) and angle between sampling tube and direction of the free air stream in degrees for particles of 10 µm



The results in figure 5.8 look peculiar as we find efficiencies larger than 1 for all aspiration ratio's and expect entry problems for these larger particles. This phenomenon occurs because of secondary aspiration. Particles strike the wall of the sampling tube, but bounce of the wall again and enter the tube (Grinshpun et al, 1990). This behaviour of the aerosol entering the tube is unpredictable, so the curves give more an indication of the possible sampling errors than an accurate estimate of the sampling efficiency.

When we consider turbulence a Gaussian fluctuation of the direction of the flow around the mean, we can also use the last equation to make estimates on the influence of turbulence on the errors in sampling. When sampling with a thin walled tube of 1 cm diameter in the mean wind direction with a wind speed of 3-5 m s^{-1}, and 20-50 µm particles, Grinshpun et al, (1990) calculated a reduction in sampling efficiency of 5%, when $-15^{\circ}<\alpha<+15^{\circ}$ (stable conditions), 25-35% when $-45^{\circ}<\alpha<+45^{\circ}$ (neutral conditions), and 40-45% when $-60^{\circ}<\alpha<+60^{\circ}$ (unstable conditions). Reduction of the influence of turbulence is clearly favourable in reduction of sampling errors.

An open outlet of the scrubber/bio-filter facing upwards is most complicated for sampling dust. Gusts of wind may penetrate the outlet area exposing the sampler alternating in the outlet air of the scrubber and ambient air. Iso- axial sampling in the vertical air stream with a 90° bend inlet is possible. Placing a wire mesh over the outlet might help blocking incoming gusts of air. Some optimization is needed for the wire mesh. Filter paper has proven to be very effective in blocking turbulence but has a large pressure drop. Wire mesh is less effective the larger the space between the wires is.

5.2 Sampling equipment for in stack sampling of scrubbers

5.2.1 Behind the scrubber

Nozzle.
We should use a stack sampling inlet of not too small inner diameter to minimise wall effects on the sampling. The inlet should be sharp edged, the area of the wall of the tube should be less than 10% of the total surface of the tube facing the air stream and the angle of the sharp edge of the nozzle should less than 30° (NEN-EN, 13284-1,2001). The nozzle or nozzle tip can be made exchangeable to attain the right flow as the pre-separator requires a fixed and well defined flow.

In stack or out stack pre-separator and filter?
The situation will most of the time be pretty clear. The ducts of an animal house are seldom that large, that a pre-separator and/or filter unit do not obstruct the flow. So we have to place them outside of the stack.

Which fraction to sample?
This is a difficult question. From the theoretical [point of view we can measure 3 fractions PM 10 and 3 fractions PM 2.5;

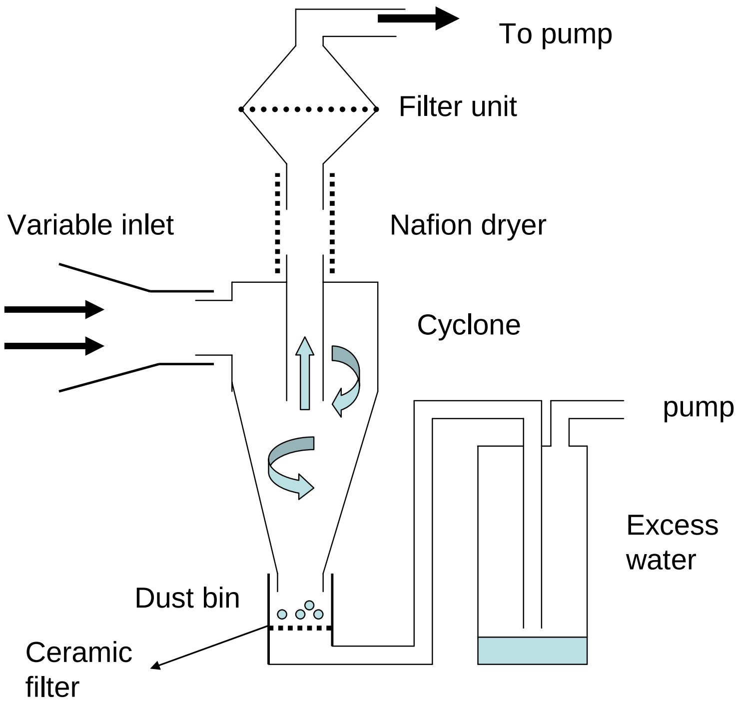
- The wet aerosol as it leaves the scrubber
- Aerosol in equilibrium with the temperature and relative humidity of ambient air
- Dry aerosol

This sequence gives diminishing mass going from wet aerosol to dry aerosol. However, when we first pull this fraction through a pre-separator, we get increasing mass as dry 10 µm particles will absorb some water during the pre-weighing conditioning at 20°C and 50% humidity, whereas wet 10 µm will lose some water during the pre-weighing conditioning. In analogy to sampling in ambient air we will focus on sampling and pre-separation of the wet aerosol followed by standard pre-weighing conditioning (20°C, 50% RH) of the aerosol before weighing.

Choice of pre-separator
The inlet is connected to the pre separator inlet with provisions to have the angle of widening or reducing the diameter to be smaller than 30 °. To stick to existing standards we could use VDI 2066 Dust Measurement in flowing gases; Particle size selective measurement by impaction method-Cascade impactor (1994). In fact we do not need all size fractions and only want the PM10 or PM2.5 fraction separated from the rest. A problem for an impactor can be the large pressure drop with condensation of water from the saturated air. Water in the impactor would obstruct proper functioning.

A cyclone has a less pronounced pressure drop compared to an impactor, resulting in less condensation of water vapour and allows for larger loading with moisture and dust as this is collected in the bin at the bottom of the impactor. The cyclone should always be placed with the coarse dust collection bin downward. Water is caught in the bin as well. When a lot of trouble may be expected from the water from collected droplets and condensation, a bin with water permeable bottom can be used. With a small suction pump connected to the bin, the water is transported to a condensation vessel, preventing interference with the cyclone. A schematic drawing is presented in figure 5.9.

Figure 5.9 Cyclone with variable inlet for iso-kinetic sampling, dust bin with ceramic plate to get rid of excess water, Nafion dryer to dry fine dust and prevent clogging of filter by water and water trap.



Filter unit
As no high dust levels are expected behind a scrubber, a filter unit with plane filter may be used behind the cyclone. A possible problem for all filters may be loading with water, giving rise to increasing pressure drop over the filter and perhaps a drop in flow, when the pump regulation is going out of range. It should be explored if this situation occurs. Placing a Nafion dryer between the cyclone and the filter unit would be an option to get rid of this problem.

The dust bin with ceramic filter and water trap is just an option when water shows to be a problem in the cyclone. This may be dependent on the sampling time. For coupling to an automated sampler, this option might be valuable. The flow through the ceramic or sintered metal filter should be very small (< 1 %) compared to the flow in the cyclone to prevent interference with cyclone performance.

5.2.2 In front of the scrubber

The air in front of the scrubber can be characterized with normal moisture content and high dust concentration. We can use NEN-EN13284-1 for this situation. The approach is similar to the measurements behind the scrubber. The high dust loading forces us in this case to use a cyclone pre-separator anyway. The loading of dust on the filter (up to 120 mg in unfavourable conditions) may pose a problem. Increasing pressure drop may force the flow regulator of the pump out of range with subsequent uncertainty in sampled air volume and change in cut off characteristics of the pre-separator. This situation may be avoided by using tubular filter devices (VDI 2066, 1993). The flow is in this case prescribed by the proper functioning of the pre-separator (16.7 lpm) or 1 m^3 h^{-1}. This is lower than 4 m^3h^{-1} for a 30 mm filter bush as prescribed in VDI 2066. A consequence may be a lower sampling efficiency of the filter bush, stuffed with quartz wool. The VDI standard offers the possibility to place a plane back-up filter behind the filter bush. This is recommended when we use a lower flow (in our case 16.7 lpm).

6 Draft protocol for determining dust emission factors from animal houses

Based on the information in the previous chapters we come up with a draft protocol for determining dust emission factors from animal houses. This draft protocol consists of five parts:

1. Measurement strategy
2. Agricultural context
3. Reference method for sampling and analysis
4. Data analyses and interpretation
5. Equivalence to the reference

The draft protocol only consists of a description of a plan how to measure. Information on the considerations and background information is provided in the previous chapters.

6.1 Measuring strategy

Measurements shall be conducted at **four different locations** with the same animals and the same type of housing. At each location **at least six measurements** are performed with an **averaging time of 24 h**. For animals with a relatively constant emission pattern (no growth cycle) the measurements are distributed **at random** within timeframes of **two months** (one measurement per farm per two months). This procedure allows to include the influence of season on emissions by distributing measurements in time. When animals within the animal house have a growth cycle, emissions will develop during growth. To get at a reliable estimate of median and average emissions, measurements should be **distributed equally** over the growth cycle. This measuring strategy includes daily variations in dust emissions and takes variations with a long cycle time (seasons) into account as well. The influence of periodic activities inside the animal house with high dust emissions, e.g. addition or removal of bedding material, will be difficult to be included in the emission factor. Depending on its potential effect on the dust emission factor, for each activity it should be decided whether it should be included in one of the measurements or not.

Outside the animal house **two sampling units** should be placed to measure the background concentration, one for **PM10** and one for **PM2.5**. Within an animal house or compartment **four sampling units** should be placed, two for PM10 and two for PM2.5. The samplers should be placed at representative places for the outgoing air. The representativeness of the sampling locations should be determined by smoke tests and/or by expert judgment. The chosen sampling locations should always be reported. PM10 and PM2.5 samplers should be placed in pairs to make comparison between the results of these dust fractions possible. During at least 2 out of the 6 measurements per farm **a field blank filter** has to be included. The field blank filter is placed inside a PM10 or PM2.5 sampling head, but this sampling unit is not connected to a pump. In pig houses with forced ventilation, the sampling units shall be placed at a height of **0.1 m below the entrance** of the exhaust ventilation channel and a distance of **0.5 m from the side** of the opening. This is to assure an almost horizontal approach of the air to the samplers, a representative sample of the aerosol leaving the animal house and an air velocity of around 1 m s^{-1} to resemble outdoor air conditions, where the samplers were standardized for.

All variations in emission within one day should be included in the sample. Standards also relate to 24h average values (or year average). Placing the instruments disturbs the animal in usual behaviour. These considerations prompt to use a timer on the instrumentation. The sampling should start when animals are back to normal behaviour. Therefore the sampling should **not start within 1 h** after activities inside the animal house related to the measurements have finished.

6.2 Agricultural context

Aim of the measurements is to get a representative set of data on emissions of animal housing systems. This involves normal management procedures and no exceptional situation within the animal house. In this protocol the agricultural management conditions are prescribed as formulated in annex D of the most recent version of the ammonia measurement protocol for livestock housing (Ogink et al., 2008).

Management conditions are described for the main animal categories and are representative for animal production in the Netherlands. Factors included are:

- Description of the housing management
- Minimum use of the facility since construction.
- Climate management
- Feeding management
- Minimum production standards
- Health status and maximum mortality/culling rates
- Minimum size of the facility.
- Minimum occupancy rate in relation to the allowed number of animals.
- Management parameters that have to be recorded during a sampling period and reported

Besides these factors additional care has to be taken in case of dust measurements that normal procedures with regard to cleaning, providing food and litter are followed. Care has to be taken that no extra measures are taken that eliminate dust emission and are not representative for normal management.

6.3 Reference method for sampling and analysis

As the standardized methods for sampling fine dust (PM10 and PM2.5) in outdoor air do not meet the requirements for high dust loadings, we only use this equipment as a standard for the background measurements outside the animal house. This means that we can refer for background measurements to the standard NEN(CEN)-EN 12341 for PM10 and NEN(CEN)-EN 14907 for PM 2.5. However, when equivalence is proven, we also can use the same equipment as we use for sampling the exhaust air from the animal house.

For the measurements inside the animal house we choose to have a cyclone pre-separator as standardised in the USA, because this device is capable of much higher dust loadings without affecting the performance of the pre-separator (Kenny, 1998). As US standards only describe the instrument and its performance, we will make a protocol for this cyclone that resembles the CEN measuring protocol for PM2.5 (CEN-EN 14907) with the changes indicated below to make the system suitable to measure in animal houses. All descriptions and procedures presented in CEN-EN 14907 (impactor) can be maintained for sampling in animal houses with a VSCC cyclone with the following exceptions (the numbers refer to the chapter numbers of the PM2.5 protocol CEN-EN 14907):

5.1.1 General. Corrosion is an important factor in animal houses. Therefore the inlet, pre-separator and filter holder should preferably be made of **stainless steel** and not of anodised aluminium.

5.1.3 Connecting pipe-work. The connecting pipe-work between inlet and filter holder does **not** need to be **cooled** by ambient air as there is no direct sunshine in the animal house heating this section.

The connection **pipe-work** between inlet and filter holder should be as **short** as possible to minimise aerosol loss.

5.1.4 Filter holder and filter. Material should be conducting and not corroding, which means **stainless steel** or a **conducting plastic** but no polyethylene or PTFE. This is especially important in animal houses with a lot of non-conducting (easy chargeable) dust from organic origin.

5.1.5 Flow control system. The prescribed flow should be maintained within the mentioned **2%** as the flow also determines the cut-off characteristics of the pre-separator. Due to the expected high dust loadings in animal houses a flow control system should be capable of **adjusting the flow** when the pressure drop over the filter increases during sampling.

6.3 Unloaded filter weighing. The standard procedure only provides laboratory blanks (unloaded filters). During transport and periods of passive exposure to air within the animal house (use of a timer) there may be diffusion of gases to the filter (diffusion of particles is much smaller due to low diffusivity) and loading of the filter with other mass than aerosol mass. To study this possible systematic error in mass of the filter, it is recommended to have a blank filter exposed in a sampling unit with a blocked outlet (**Transport and passive exposure blank**) (no pump needed). This transport and exposure blank may be skipped in a future protocol when passive loading has proven not to be important.

6.4 Sampling period. The sampling period should be 24 ± 1 h with an accuracy of ±5 min.

7.2 Maintenance. The standard states maintenance and applying new grease at the impaction plates according to intervals given by the manufacturer or at least every 15th sample. Considering the higher loading with dust around animal houses, maintenance and applying new grease should take place **before every sampling period**

for the background samplers. The cyclone samplers are less sensitive but exposed to high concentrations. For best performance they should also be **cleaned before each sampling period**.

7.4 Field blanks. See passive exposure blank in paragraph 6.3.

8. Expression of results. When it is proven during the period of using this concept protocol that the change in weight of the passive exposed filter blanks is more than 40 μg (the allowed uncertainty in the blank), then at every sampling a passive blank should be included and results should be corrected for the change in weight of the passive blank filter. If the change of weight of passive blank filters is less than 40 μg the use of passive blanks may be skipped in the final version of the protocol for measuring dust emission from animal houses.

9.2. GUM concept. At this very moment, no information is available on the standard deviation of two **collocated** samplers within animal houses. The prescribed need for quantification of uncertainty (see 9.2 and 9.3) forces us to sample with two identical reference samplers simultaneously during the draft protocol. This will at least add one more sampler to the three samplers within the animal house (the PM10 sampler, the PM2.5 sampler and the PM2.5 blank exposure). The sampler to add can be a PM2.5 sampler in view of future standards. To be completely in line with the GUM concept we should also add a duplo PM10 sampler (making a total of 5 sampling heads). Data analysis will show if we may skip these duplicate measurements in the future when standard deviations prove to be constant.

9.3.2.1. Size selection performance. In ambient air, the size distribution of the aerosol is expected to have only a small fraction of particles in the size range of the cut-off diameter of the sampler (in this case 2.5 μm). This may be true for outdoor air, where particles grow into the accumulation mode (0.1- 1.0 μm) and larger particles have a short lifetime because of impaction and sedimentation. The situation within an animal house, being a source of dust, may be different. We do not know the size distribution of generated aerosol. The indicated **uncertainty of 1.5% in cut off diameter for a change of 10 K** in temperature may result in a **larger standard deviation** of measurements.

9.3.2.2. Deposition loss. The standard allows a duct of 3m length between the pre-separator and the filter unit. This is convenient for sampling outdoor air with an inlet above a roof of a measuring shelter and the filter unit within this shelter. Within animal houses we are forced to measure close to the outlets, which are only high in naturally ventilated cow houses. As the aerosol may consist of all kinds of non conducting organic material (skin, straw dust etc.), it may be lost easier because of electrostatic forces. For that reason it is recommended to keep the **distance** between sampler inlet and filter unit **as short as possible** and convenient for sample changing. The maximum length of 3m should no way be exceeded!

9.3.2.5. Change in mass of blanks. Here we stick to the change in procedure described in point 8 of this paragraph.

9.4. Time. For the background measurements using impactors as a pre-separator and the measurements inside the animal house with a cyclone as a pre-separator we both use a sampling period of 24 h. The allowed variation of the sampling period is 0.35%. This means a tolerance of 5 minutes.

9.3.5. Field test uncertainty. The absolute uncertainty is for animal houses probably larger than stated in the outdoor standard because of the possible difference in size distribution between outdoor and indoor air. Relative uncertainty might differ less because of higher filter loadings due to higher aerosol concentrations, provided no overloading of the pre-separator takes place (see 6.3).

9.3.6. Uncertainty table. Looking at the table of individual uncertainty factors, they will remain the same when we apply the proposed changes to the outdoor standard. Applying the proposed changes will not result in an increase of the uncertainty in the field test (u_{field}) of 1 μg m^{-3}, provided the decrease in flow of the cyclone compared to that of the impactor is compensated by the higher filter loading due to higher concentration within the animal house.

6.4 Data analysis and interpretation

Data analysis and interpretation relates to three aspects;

- Control on proper functioning of the instruments, application of corrections, quality control and acceptance or rejection of data.
- Control of the proper management conditions during the measurements.
- Data interpretation in view of emission estimates, and confidence interval for these estimates.

6.4.1 Quality control of functioning of instruments

Quality is performed by following the next steps;

1. Are all questionnaires concerning measurement situation available and filled in? If not the lacking information makes further treatment of the data not needed as they cannot be used.

2. Are all data needed for correction of the measurement situation to STP available (measured temperature inside and outside the animal house, measurements of the temperature of the air in the flow measuring device, atmospheric pressure measured or from a nearby meteorological station)?
3. Preliminary control of the sampled volume by comparing the intended flow times the sampling time with the volume from the gas meter. A small difference is no problem as it will be related to the conversion to STP that should be done. A large discrepancy points at overloading of the filter creating a large pressure drop and resulting in a low flow or failure of the timer.
4. Correct the flow to STP according to the standards EN-12341 or EN- 14907.
5. Determine and register the weighing conditions. They should comply with the standards. Take the needed time to reach equilibrium weight in consideration (longer than 48 h for wet filters).
6. Check the laboratory blank. Difference in mass between subsequent measurements should be within the limits provided by the standards.
7. Determine the change in weight of the transport blank and the exposure blank and subtract the first from the last. When the gain in weight of the exposure blank is negligible (lower than the resolution of the balance and/or lower than the allowed accuracy of the weighing procedure), the exposure blanks can be skipped in the future final dust protocol. When not negligible, there should always be an exposure blank.
8. Calculate the average mass concentration based on corrected mass on the sample filter and the volume (STP) from which it was sampled.
9. Compare the calculated concentration with that of the second (duplo) sample and calculate the relative standard deviation form the set of measured concentrations.
10. Test the conditions prescribed in the standards for the measurements against these standards and conclude whether results can be accepted or should be rejected.

6.4.2 Measuring and management conditions

The management in animal husbandry is subject to continuous change, imposed by new techniques and changing conditions. Management may influence the emissions. To obtain representative and reliable results for emissions of a housing system, management conditions during the measurements should be representative for contemporary practice. Leaving management conditions open would be flexible, but makes the measurements vulnerable to misuse. For that reason we choose for registering the management conditions and compliance of measurement conditions to these registered conditions. This procedure implies temporary revision of the protocol when new management practices emerge. The management conditions are put forward by presenting a range of values or a minimum and a maximum value for each condition. These conditions are chosen in a way to have at least 2/3 of the farms within these conditions (mean + or – one standard deviation of the mean). These Data are based, whenever possible, on KWIN (2005). The most important management conditions are presented in table 6.1.

Table 6.1 Important agricultural and management conditions influencing dust emissions

Item	Considerations
Housing	Consistent with legal regulations Drawings of construction
Climate	Maximum CO_2 concentration within the animal house
Nutrition	Wet or dry feeding Feed composition
Production	Data from KWIN (2005) serve as an average condition SKAL conditions for organic farming
Health	Maximum percentage of dead animals % SKAL standards for biological animal production
Number of animals	Minimum number of animals in an animal house Minimum number related to capacity of the housing
Registration	Specific information related to the animal category Specific information on area and addition of straw Specific information on refreshment of total straw layer

For a detailed description of the agricultural management conditions see annex D of the most recent version of the ammonia measurement protocol for livestock housing (Ogink et al., 2008).

6.4.2.1 Housing

The conditions for housing animals of a certain category are put forward as minimum requirements by law. This requirements result in a number of possible types of housing. The split up of animals in categories is based on this legislation. Measurements should be done in animal houses that are representative for agricultural practice and contain an average number of animals. New animal houses may have different dust emissions from dust from floors and other surfaces that have not been exposed to emissions and fluids as are surfaces in older animal houses. A new animal house may also influence animal behaviour. This asks for at least one cycle of animal growing or presence of animals during a certain period before measurements can be done. For a final version of the protocol, analysis of data will be made. This asks for a thorough description of measuring conditions, including a plan in horizontal view and vertical view of the animal house.

6.4.2.2 Climate

Ventilation may influence dust emission by emanation of fine dust and drying of material. On the other hand ventilation is needed to keep temperature, humidity and CO_2 content between certain limits. The EU defined maximum CO_2 content of 3000 ppm (EU, 1997) is used as a limit value, relating animal CO_2 emissions to ventilation. Temperature is a less suitable limit as pigs in organic farming may create there own microclimate within the straw, differing from that of the surrounding air. Humidity would have a relation to dust emissions, but animals are not very sensitive to humidity. Using humidity would have the risk of optimizing humidity for low dust emissions during the measurements while humidity would be lower under normal conditions. This risk asks for measurements of relative humidity next to temperature to scan for unusual situations during measurements.

6.4.2.3 Nutrition

Nutrition will be a source of dust in animal houses (Aarnink and Ellen, 2006). The fraction of dust originating from feed is dependent on the feed composition and on other conditions like application of straw etc. Important factors influencing dust emission from feed are according to Aarnink and Ellen:

- Moisture content
- Oil or fat content
- Aggregation form (flour, small aggregates, pellets)
- Origin (corn, wheat, rye, sorghum etc.)
- Processing of the food

When we take pigs as an example we can distinguish between feeding with wet feed, dry feed together with a water tap that makes the food wet at eating or dry feed with separated drinking spot. These systems may have different emissions. This asks for registration of the type of feed and feeding system (see 7.4.2.7), as these systems may differ within the same category of animals and the same type of animal house.

6.4.2.4 Production and number of animals

The number of animals within the animal house should be according to normal practice. Productivity should also be at a usual level expressed in kg of milk per year, number of piglets per year, weight gain in kg/day, number of eggs per year for laying hens etc. Averages are presented in KWIN 2005.

6.4.2.5 Animal health

There are no specific demands for animal health during the measurements. One should however realise that animal activity and animal heath are closely related and so will be animal health and dust emissions. Normal veterinary care is assumed during the experiments. Experiments should be stopped when a disease or medication are influencing animal activity. For organic farming SKAL regulations apply. The number of dying animals should be comparable to the country-wide average.

6.4.2.6 Registration

The demands on common agricultural- and management practices require registration of many variables and also registration of unusual circumstances that were met during measurements. As we are in the phase of a draft protocol and careful analyses of gathered data is essential for formulation of a final protocol. This consists of: housing system, feeding system, type of feed, size of the animal house, number of animals, environmental conditions within the house (T, RH and CO_2), manure handling, straw application, animal health etc.

6.5 Equivalence to the reference

In chapter 3 was already mentioned, that existing EU standard measurement procedures for outdoor air are not suitable to measure high dust concentrations for a period of 24 h without switching on and off. At the same time it was concluded, that these gravimetric procedures are very labour intensive. Outdoor measurements are for that reason many times automated using a TEOM instrument or a β-dust monitor. Weak point in the use of an Automated Measuring System (AMS) is the conditioning of the sampled air. High temperatures result in a low relative humidity and low measured weight of moisture, but also in a loss of volatile particulate material. For AMS two questions should be solved;

- What is the optimal conditioning of the instrument regarding gain in weight by moisture and loss in weight by temperature relative to the gravimetric standard?
- What is the ratio between AMS and gravimetric measurements, possibly even specific per source category?

The EU allows the use of AMS provided equivalence is demonstrated. We can apply the same to the measurements for animal houses taking the specific high dust concentration into account. This implies:

- Use of a cyclone pre-separator instead of an impactor to allow for longer sampling times without influence of dust loading of the pre-separator on performance.
- Regular cleaning of the cyclone
- Automatic changing in filter spot at regular intervals. In this case the use of a β-dust monitor is considered. A TEOM would require too much maintenance with high dust loadings.

Equivalence has to be demonstrated in a number of steps in laboratory tests and field tests. Compliance to the gravimetric standard can be demonstrated by the vender of the instrument. This is the usual procedure for outdoor measuring instruments with an appreciable market. The situation is questionable for measurements in animal houses, where only a few institutes have instrumentation and expertise to perform the measurements. It will therefore be thinkable that these institutes have to perform the compliance tests themselves.

6.6 Calculation of PM emission factor

The 24-h PM emission is calculated by multiplying the mean 24-h dust concentration with the mean 24-h ventilation rate. From the 24 (4 farms x 6 measurements per farm) 24-h measurements the mean on log-scale is calculated. By taking the anti-log of this mean the median of the observations is obtained. The calculated standard deviation at log-scale gives an estimate of the variation coefficient at normal scale. The median PM emission per day is multiplied by 365 days and multiplied by the occupation factor. The occupation factor corrects for the days that no or a less animals are present inside the animal house, e.g. between two growing periods. The used occupation factors will be the same as used for determining ammonia emission factors.

7 Validation of samplers

A main part of this chapter will also be published in a scientific journal by Zhao et al. (submitted for publication).

7.1 Objective

The objective of this validation study was to verify the overloading of the greased plate in the standard PM10 and PM2.5 low volume samplers with impaction pre-separators (IPS) as described in NEN-EN 12341 (1998) and NEN-EN 14907 (2005), respectively. Furthermore, results are compared with a pre-separator less sensible for overloading, a cyclone pre-separator (CPS). The reference equivalence test of CPS with IPS was performed based on the EU standard prescription.

7.2 Material and Methods

7.2.1 Samplers

Impaction pre-separator (IPS)

Figure 7.1 shows the used impactor heads for both dust fractions. An IPS consists of a pre-separator and a filter holder. The pre-separator separate the bigger particles from the particles of which the concentration in the air need to be determined. For this, a flat plate is rubbed with a layer of grease and placed underneath the air pipes (see figure 7.1). By the air velocity and the inertia of the particles the bigger particles impact on the plate. The air flow through the sampling head with impactor is 2.3 m^3/h.

Figure 7.1 The left picture shows the complete sampling head; the right picture shows the difference between the size of the openings of the air pipes above the impaction plate (bigger openings for PM10; smaller openings for PM2.5)

Cyclone pre-separator (CPS)

A CPS consists an air cap, a PM10/2.5 cyclone pre-separator (URG corp., USA) and a filter holder (see figure 7.2). A CPS uses centrifugal principle to separate large particles. The air streams are sucked into the air cap then to the pre-separator where a cyclone is formed. Large particles in the air are trapped in a dust chamber due to the centrifugal force, and PM10/PM2.5 particles are following the air stream and collected by a glass fibre filter in the filter holder. The air flow used for CPS is set to 1 m^3/h.

Figure 7.2 The left picture shows the air inlet head, the PM10 cyclone pre-separator, the PM2.5 cyclone pre-separator and the filter holder (from left to right) ; the right picture shows the construction of the air inlet head.

7.2.2 Pumps

For sucking the air through the samplers pumps were used of type Charlie HV (rotating 6 m^3/h; Ravebo Supply b.v., Brielle). These 'constant flow' pumps automatically control the air flow based on the measured temperature at the sampling head. The airflow of these pumps remains constant when the pressure difference over the filter increases. By this control system a stable air flow within 2% of the nominal value could be maintained. The clocks within the pumps were programmed to automatically start and finish during the sampling period.

7.2.3 Filters

Dust was collected on glass fibre filters with a diameter of 47 mm. The unloaded filters were stabilized for 48 h under standard conditions: temperature 20 °C ± 1 °C and 50% ± 1% relative humidity. Each filter was then weighed for 4 times using a precise balance with resolution of 10 µg. The average value was calculated as the filter weight. For the loaded filters, the same weighing procedure was adopted. The weight difference between loaded and unloaded filter equalled the amount of collected dust.

7.2.4 Measurements

Overloading verification

The measurements were conducted for two tests in a layer house. The house consisted of four compartments with approximately 25 layers in each. The floor was covered with straw. In the 2nd test a wooden bed, covering half of the ground, was installed in each compartment and small ventilation openings near the roof were applied. Therefore dust concentrations were far less in the 2nd compared with the 1st test. Six IPSs and 2 CPSs were used in the 1st test, and 8 IPSs (4 PM10 and 4 PM2.5 IPSs) and 4 CPSs (2 PM10 and 2 PM2.5 CPSs) were used in the 2nd test. Greased plates of IPSs were replaced by new ones at different time intervals in order to verify the overloading of IPS under this environment, while CPSs and control IPSs kept sampling without interruption. All samplers were put together but with a certain distance to avoid interference. The measurement schedule is listed in table 7.1.

Table 7.1 Measurement schedule of IPS overloading verification test.

Test	Date	Dust	Sampling time	Plates replacing time interval
1st Test	06-04-2007	PM10	36	12h (2 IPSs), 18h (2 IPSs), Control (2 IPSs and 2 CPSs)
	07-04-2007	PM10	36	12h (2 IPSs), 18h (2 IPSs), Control (2 IPSs and 2 CPSs)
	28-03-2007	PM2.5	8	1h (2 IPSs), 2h (2 IPSs), Control (2 IPSs and 2 CPSs)
	29-03-2007	PM2.5	8	1h (2 IPSs), 2h (2 IPSs), Control (2 IPSs and 2 CPSs)
2nd Test	20-06-2007	PM10	8	0.5h (1 IPS), 1h (1 IPS), 2h (1 IPS), Control (1 IPS and 2 CPSs)
		PM2.5	8	0.5h (1 IPS), 1h (1 IPS), 2h (1 IPS), Control (1 IPS and 2 CPSs)
	21-06-2007	PM10	8	0.5h (1 IPS), 1h (1 IPS), 2h (1 IPS), Control (1 IPS and 2 CPSs)
		PM2.5	8	0.5h (1 IPS), 1h (1 IPS), 2h (1 IPS), Control (1 IPS and 2 CPSs)

Test the comparability of CPS with IPS

96 pairs of 24 h measurements, 48 for PM10 and 48 for PM2.5, were conducted in animal houses (three fatting pig houses, one broiler house and one dairy house), working place environment and ambient air environment. For each pair of measurements, 1 IPS (as reference sampler) and 2 CPSs (as candidate samplers) were used. There were 1200 (80 kg each), 520 (312 pigs were 85 kg, 208 pigs were 45 kg) and 3200 pigs (67.5 kg each) in three fatting pig houses respectively. Before exhausted, the air from each of the houses was sucked through a ventilation room where the dust samples were taken. The broiler house contained 8 compartments, in each of which approximately 2675 broilers were raised on the ground with wood shavings as bedding material. Samples were taken in two of these compartments at 1st, 2nd, 3rd, 5th week of bird age. The dairy house was natural ventilated with approximately 100 dairy cows inside. The working place was a machinery room located at Wageningen University. Farming robots were stored inside. Several people worked in the room daily. Samplers were installed at 1.2 m height in all the locations except in the ventilation room of the pig house with 3200 pigs where samplers were hung in the air at 2.0 to 3.0 m height. The three samplers (1 IPS and 2 CPSs) were kept closely but with a distance of 30 cm between each other to avoid mutual interference. The air speeds near the sampler were from 0.1 to 1.8 m s^{-1} in the measurements.

7.2.5 Data analysis for comparability of CPS with IPS

Concentration data collected were analysed based on the EU standard regulation – “Determination of the PM 10 fraction of suspended particulate matter: Reference method and field test procedure to demonstrate reference equivalence of measurement methods” (NEN-EN 12341, 1998a). Since no specified standard for PM2.5 is available at this moment, similar analysis procedure for PM10 was adopted also for PM2.5 CPS. The only difference was that data for PM2.5 were not separated according to the boundary of 100 µg/m³, but according to the sampling locations (in animal houses, and working place/ambient air). Outliers from both of the datasets for PM10 and PM2.5 were excluded beforehand with Grubb’s test. To be a reference equivalent dust sampler, two requirements need to be met: 1) the two candidate samplers should be comparable to each other; 2) candidate samplers should be comparable to the reference sampler.

Detecting outliers

To detect outliers, a CPS-outlier test was firstly performed in the dataset of CPS validation. *Z* value for each pair of CPS data could be calculated with equation 1,

$$Z_i = \frac{|mean - DF_i|}{SD}$$

Where: “*DF*” is the concentration difference between the two CPSs; “mean” is the mean of *DF* population; “*SD*” is the standard deviation; “i” is the number of the data pair. All *Z* values from the same dataset could not exceed a critical *Z* which could be calculated with equation 2,

$$CriticalZ = \frac{N-1}{\sqrt{N}}$$

In which “*N*” is the number of data. When the *Z* value was higher than the Critical *Z*, the pair of data was recognized as outlier and excluded from further analysis. The Critical *Z* list is presented in table 7.2.

Table 7.2 Critical *Z* value

N	Critical *Z*	*N*	Critical *Z*
3	1.15	22	2.76
4	1.48	23	2.78
5	1.71	24	2.8
6	1.89	25	2.82
7	2.02	26	2.84
8	2.13	27	2.86
9	2.21	28	2.88
10	2.29	29	2.89
11	2.34	30	2.91
12	2.41	31	2.92
13	2.46	32	2.94
14	2.51	33	2.95
15	2.55	34	2.97
16	2.59	35	2.98
17	2.62	36	2.99
18	2.65	37	3.00
19	2.68	38	3.01
20	2.71	39	3.03
21	2.73	40	3.04

CPS-outlier test was done in the whole dataset for both PM10 and PM2.5. Because of severe overloading of PM2.5-IPS in animal house samples, CPS-IPS outlier test was done only for data from work place/ambient air. According to the EU standard regulation, the number of outliers should be lower than 5% of the total number of data.

Test of comparability of candidate samplers (Copied from NEN-EN 12341)

The test focuses on the differences D_i between the concentration values Y_{i1} and Y_{i2}. Ideally both candidate samplers are identical hence probing the same suspended particulate matter (SPM) fraction, implying $D_i = 0$. The procedure is as follows:

Nomenclature	
n	Number of valid pairs
X_i	i-th measured value of the reference concentration
Y_{i1}	i-th measured value of the candidate sampler concentration 1
Y_{i2}	i-th measured value of the candidate sampler concentration 2
$Y_i = (Y_{i1} + Y_{i2}) / 2$	average concentration value of the i-th parallel measurement of the candidate samplers 1 and 2
$D_i = Y_{i1} - Y_{i2}$	difference between the i-th measured value of the candidate samplers 1 and 2
t	test statistic according to the Student t-distribution
CI_{95}	two-sided 95 % confidence interval

(1) average candidate concentration values Y_i below 100 µg/m³

a) Calculate the average concentration Y_i of the i-th parallel measurement;

b) Select all average concentrations $Y_i \leq 100$ µg/m³;

c) The total number of concentration pairs involved is $n_<$;

d) Calculate the absolute standard deviation s_a from:

$$s_a = \sqrt{\left\{\sum D_i^2 / 2n_<\right\}}$$

e) Select the corresponding Student factor $t_{f<;0.975}$, defined as the 0.975 quantile of the two sided 95% confidence interval of the Student t-distribution with $f_< = n_< - 2$ degrees of freedom;

f) Calculate the two-sided confidence interval CI_{95} for the average concentration values $Y_i < 100$ µg/m³:

$$CI_{95} = s_a \cdot t_{f<;0.975}$$

g) Check the comparability of candidate sampler:
If $CI_{95} \leq 5$ µg/m³, the candidate sampler meets the requirement for comparability in this concentration range.

(2) average candidate concentration values Y_i over 100 µg/m³

a) Select all average concentrations $Y_i > 100$ µg/m³;

b) The total number of concentration pairs involved is $n_>$;
c) Calculate the relative standard deviation s_r from:

$$s_r = \sqrt{\left\{\sum (D_i / Y_i)^2 / 2n_>\right\}}$$

d) Select the corresponding Student factor $t_{f>;0.975}$, defined as the 0.975 quantile of the twosided 95% confidence interval of the Student t distribution with $f_> = n_> - 2$ degrees of freedom;
e) Calculate the two-sided confidence interval CI_{95} for the average concentration values $Y_i > 100$ µg/m³:

$$CI_{95} = s_r \cdot t_{f>;0.975};$$

f) Check the comparability of candidate sampler:
If $CI_{95} \leq 0.05$, the candidate sampler meets the requirement for comparability in this concentration range.

When it follows that the candidate sampler does not meet the requirements for comparability, then the candidate shall be rejected as reference equivalent.

Test of comparability of candidate sampler with reference sampler (Copied from NEN-EN 12341)
The test focuses on the relationship between the concentration values obtained from duplicate measurements with the candidate and reference sampler. Ideally the candidate sampler is probing the same SPM fraction as the reference one, implying $y = x$. The pertinent procedure is as follows:

a) Compute the relationship $y = f(x)$ between the candidate (y) and reference (x) concentration values by linear regression analysis;
b) Calculate the two-sided acceptance envelope, i. e.
$y = (x \pm 10)$ µg/m³ for concentration values $x \leq 100$ µg/m³ obtained from the reference sampler, and $y = 0.9\ x$ (µg/m³) respectively $y = 1.1\ x$ (µg/m³) for concentration values $x > 100$ µg/m³ obtained from the reference sampler;
c) Plot onto one graph (in our case, separate graphs were plotted due to the different characteristic of dust in animal houses and working place/ambient air):
- the ideal reference equivalence function $y = x$;
- the two-sided acceptance envelope;
- the measured data pairs $\{X_i, Y_{i1}\}$ respectively $\{X_i, Y_{i2}\}$;
- the calculated reference equivalence function $y = f(x)$;

d) Check of reference equivalence:
If the variance coefficient R^2 of the calculated reference equivalence function is ≥ 0.95 over the relevant concentration range, and the calculated reference equivalence function is bounded within the limits of the acceptance envelope over the relevant concentration range, the candidate sampler meets the requirements for reference equivalence.

When it follows that the candidate sampler does not meet both requirements for comparability, then the candidate shall be rejected as reference equivalent.

7.3 Results

7.3.1 Result of overloading verification test

Results from 1st and 2nd overloading verification tests are listed in tables 7.3 and 7.4. In the 1st test, the average PM10 concentration from IPSs without plate replacing was 84.2% of the concentration from CPSs. While the average PM2.5 concentration from IPSs without plate replacing was 11.9 times higher than the concentration measured with CPSs. Results in the second test showed PM10 and PM2.5 concentrations of IPSs without plate replacing were 0.94 time and 3.5 times of those of CPSs, respectively.

Table 7.3 PM10 and PM2.5 concentrations measured using CPSs and IPSs with different plates replacing time intervals in the 1st test (µg/m³).

Date	Dust	Sampling Time (h)	CPS	IPSs		
				12h replacing interval	18h replacing interval	Without replacing
06-04-2007	PM10	36	1305	1124	1082	1061
07-04-2007	PM10	36	1175	1101	1063	1027
		Average±(SE)	1240±65	1112±12	1073±9	1044±17
				IPSs		
				1h replacing interval	2h replacing interval	Without replacing
28-03-2007	PM2.5	8	446	4631	4832	5546
29-03-2007	PM2.5	8	512	5213	5501	5843
		Average±(SE)	479±33	4922±291	5166±334	5694±149

Table 7.4 PM10 and PM2.5 concentrations measured using CPSs and IPSs with different plates replacing time intervals in the 2nd test (µg/m³)

Date	Dust	Sampling time	CPS	IPSs			
				0.5h replacing interval	1h replacing interval	2h replacing interval	Without replacing
20-06-2007	PM10	8	711	652	624	637	655
21-06-2007	PM10	8	622	564	553	582	593
		Average±(SE)	666±45	608±44	588±36	609±28	624±31
20-06-2007	PM2.5	8	54	132	151	161	165
21-06-2007	PM2.5	8	44	113	133	156	177
		Average±(SE)	49±5	123±10	142±9	158±3	171±6

In figures 7.3 and 7.4 the relationships between dust concentrations measured with IPS and the plate replacing time, together with linear regression lines, are given. The significance test of the regression coefficients is presented in table 7.5.

Figure 7.3 Relationship between PM10 concentration and number of times plates of IPS were replaced (■ CPS, ■ IPS). Sampling durations were 36 h for the 1st test and 8 h for the 2nd test

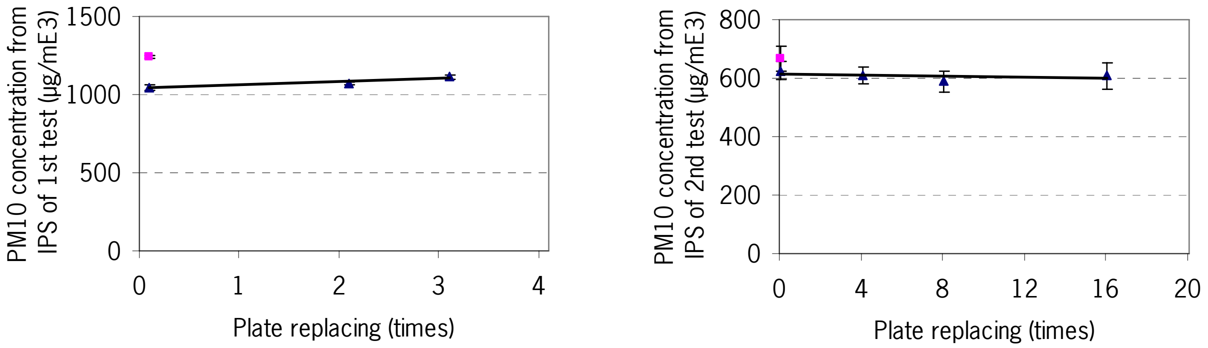


Figure 7.4 Relationship between PM2.5 concentration and number of times plates of IPS were replaced (■ CPS, ▲ IPS). Sampling duration was 8 h.

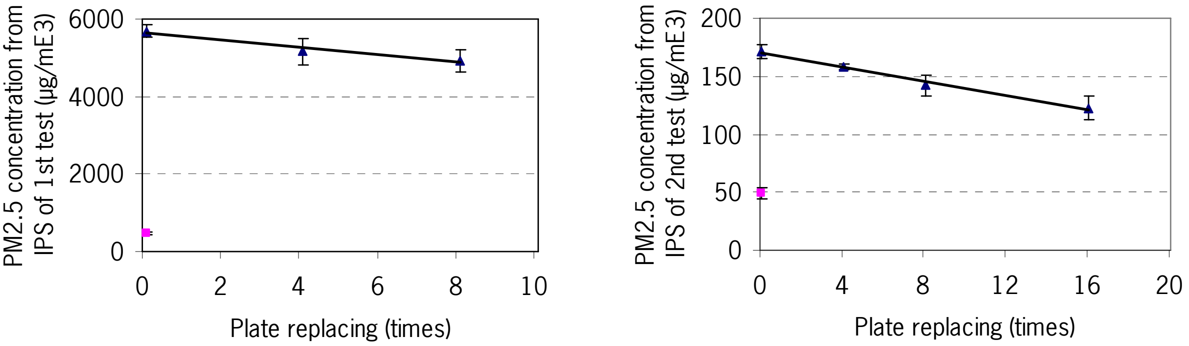


Table 7.5 Significance test for linear regression coefficients of dust concentration against plate replacing time

Dust	Test	Slope	Constant	Standard error	Significance	R^2
PM10	1st test	34.3*	1042.1***	10.5	0.014	0.815
	2nd Test	0.6	609.4***	20.3	0.820	0.009
PM2.5	1st test	-107.7	5620.0***	218.8	0.096	0.539
	2nd test	-3.2**	168.5***	4.7	0.001	0.843

* indicates $p<0.05$; ** indicates $p<0.01$; *** indicates $p<0.001$

7.3.2 Result of comparison of CPS with IPS

7.3.2.1 Detecting outliers

No outliers were detected in PM10 data. Two pairs of PM2.5 data were eliminated as outliers in the CPS-CPS test. No outliers were found in the following CPS-IPS test. The number of outliers accounted for 0% and 4.2% of the total number of PM10 and PM2.5 data respectively, which were within the maximum limit of 5%. The final number of data pairs of PM10 and PM2.5 were 48 and 46. They were both more than 40 pairs, the minimum required number for the EU standard.

7.3.2.2 Comparability of CPSs

The number, range and CI_{95} of data pairs are listed in table 7.6. CI_{95} for the PM10 low concentration group was 2.20 µg m^{-3}, which was within 5 µg m^{-3} boundary. CI_{95} value for the PM10 high concentration group was 6.0%, which slightly exceeded the EU standard boundary of 5%. CI_{95} values for PM2.5 were 2.30 µg m^{-3} and 9.54 µg m^{-3} for working place/ambient environment and animal houses, respectively. In table 4 CI_{95} values are expressed both in absolute values and in relative values.

Table 7.6 Comparability of candidate samplers (also including comparability of reference sampler, IPS, in working place)

Dust	Group	Number of data	Measured range		CI_{95}	Equivalent CI_{95}
PM10	<100 µg m^{-3}	28	4.0	40.6	2.20 µg m^{-3}	(15.3%)
	>100 µg m^{-3}	20	308.4	4464.9	6.0 %	(66.50 µg m^{-3})
	Working place (IPS)	6	4.8	43.1	1.95 µg m^{-3}	(29.7%)
PM2.5	Working place/ambient	19	1.9	42.3	2.30 µg m^{-3}	(31.5%)
	Animal house	27	5.9	178.1	9.54 µg m^{-3}	(20.2%)
	Working place (IPS)	9	4.0	43.4	1.66 µg m^{-3}	(24.7%)

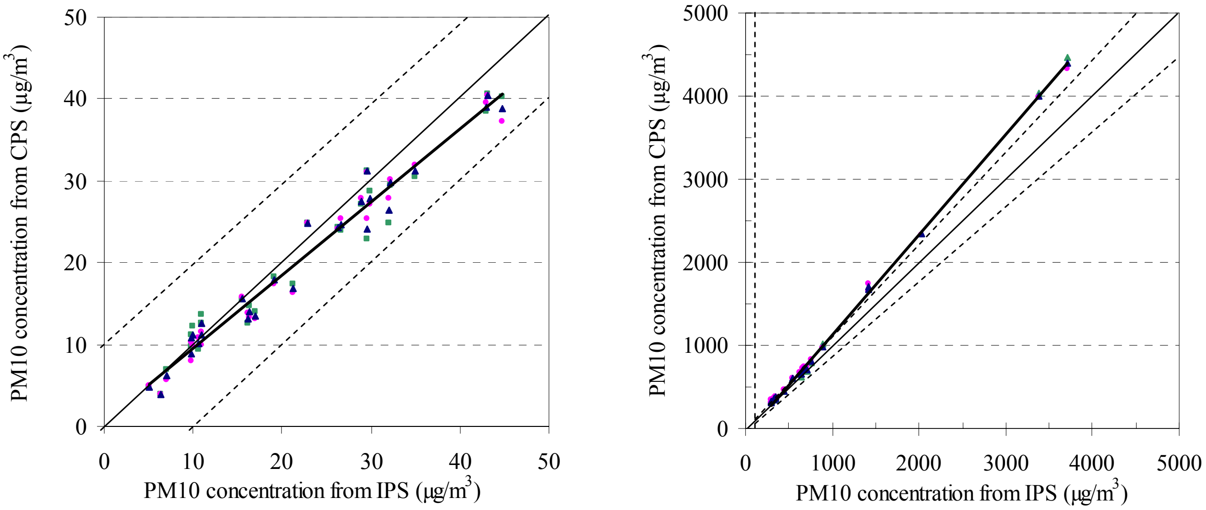
7.3.2.3 Comparability of CPSs with IPS

Figure 7.5 shows the relationship between dust concentrations measured with CPS and IPS. The regression line was drawn from the average concentration of two CPSs in each group. Table 7.7 gives the results from the regression analysis.

Results show that measured values with CPS fell within the acceptable boundaries for PM10 concentrations lower than 100 µg m^{-3}. All data were spread evenly in the range from 0 to 50 µg m^{-3}, but we had no data in the range from 50 to 100 µg m^{-3}. Generally, higher concentrations were obtained with CPS than IPS for PM10 concentrations higher than 100 µg m^{-3}. Most concentrations were lower than 1000 µg m^{-3}. Slopes showed different trends in the low and high concentration groups. The coefficients of determination were both higher than the required 0.95. Combined with the results of the CPS-CPS comparability test, the PM10 CPS totally fulfilled the standard requirements in EU legislation as a reference equivalent dust sampler when sampling in less dusty environments.

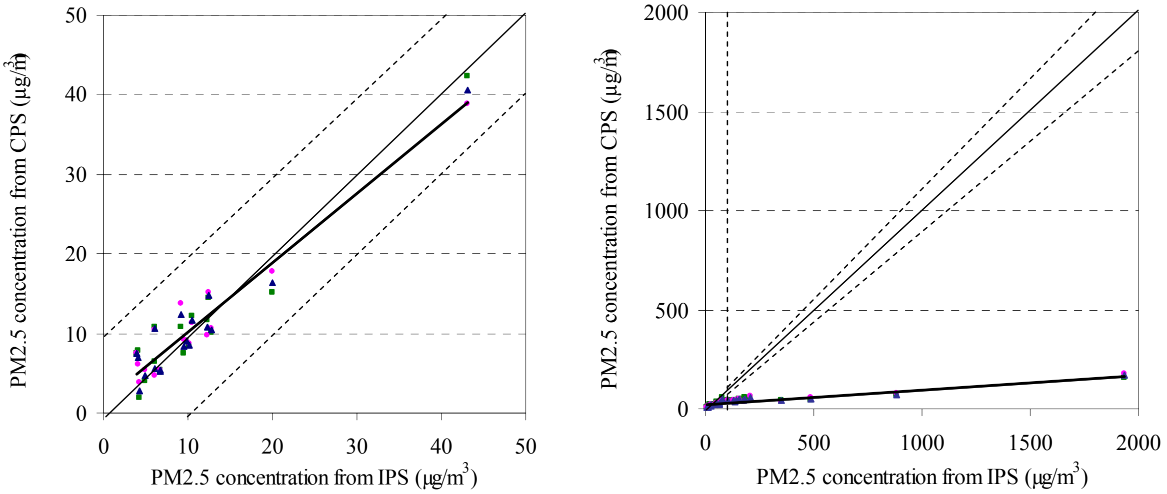
The PM2.5 concentration data from working place/ambient air fitted well within the boundaries. CPS showed also acceptable performance, although the coefficient of determination (0.93) was slightly lower than the required 0.95. Most of the PM2.5 concentration data were between 0 and 20 µg m^{-3}. The slope was 0.87. Due to the severe overloading problem of CPS, the regression line for data from animal houses drifted far away from the PM2.5 boundaries.

Figure 7.5 Average concentrations of CPSs against IPS (—: y=x; - - - : acceptable boundary; —: Linear regression line; ▲ average concentration of CPS; ■ data of CPS$_1$; ● data of CPS$_2$).



(A): <100 µg m^{-3}

(B): >100 µg m^{-3}



(C): Working place / ambient air

(D): Animal houses

Table 7.7 Significance test for regression coefficients

Dust	Data group	Pairs of data	Slope	Constant	R^2
PM10	<100 $\mu g\ m^{-3}$	28	0.89*	0.62	0.97
	>100 $\mu g\ m^{-3}$	20	1.20*	-67.99*	0.99
PM2.5	working place/ambient air	19	0.87*	1.47	0.93
	animal houses	27	0.07*	22.32*	0.86

** indicate significantly different ($P<0.05$)*

7.4 Discussion

7.4.1 Overloading verification

Overloading of the impactor pre-separator was verified by determining the effect of the number of replacements of the greased impaction plates on PM concentrations. In an environment with low dust concentrations, like in ambient air, no effect of plate replacements is expected, because the plate has enough capacity to retain large particles during a 24 h sampling period. In a dusty environment, however, like in animal houses, IPS loses its ability of pre-separation if the overloaded greased plate is not regularly replaced by a clean plate. Because of the bouncing effect, larger particles re-entrain in the air and are collected on the filter. This results in an overestimation of PM concentration. Therefore, overloading can be recognized when dust concentration increases with longer dust collection periods of the impaction plates. This equals with a negative relationship between dust concentration and the number of plate replacements per unit of time.

The PM10 concentrations measured by IPS did not drop by increasing the number of plate replacements. It indicates that the greased plate of PM10 IPS seems not to be overloaded during a 36 h sampling period within such an environment. In the 1st test, IPS with more times of plate replacing collected more airborne particles. It might be caused by the exact location of the samplers or differences between samplers. It could also be caused by the increased sampler operations during plate replacing in such contaminated environment, which provided the chance for particles to fall on the filter directly without passing by the impactor pre-separator of IPS. This effect was assumed to be reduced in the 2nd test because less dust was present.

The PM2.5-IPSs collected 11.9 and 3.5 times the amount of dust compared to CPSs, in the first and second test, respectively. The dust concentrations dropped with shorter duration intervals of plate replacing. The overloading of greased plates of PM2.5 IPSs is notable. It was also shown that the obtained PM2.5 concentrations from IPS increased sharply with increasing dust load in the significance test in table 7.5. In the 1st test, the PM2.5 concentrations were even (a lot) higher than the PM10 concentrations. This might be caused by two reasons. Firstly, the opening of the air pipes for PM2.5 IPS above the greased plate are much smaller than those of PM10 IPS, which leads to reduction of the contact area for bigger particles with the greased plate. The plate would lose binding ability as soon as the small contact area is overloaded. Secondly, the particle-piles formed on the plate could be "exploded" when hit by new-coming big particles. After the "explosions", particles originally bounded on the plate would be re-suspended in the air and collected by the filter. The particles hit the particle-piles with a lot higher speed in PM2.5 IPS than in PM10 IPS because the same volume of air had to go through smaller openings, creating a higher air speed. Therefore "Explosions" were more serious in PM2.5 IPS.

Linear regression models can be obtained between the PM2.5 concentrations and the plate replacing time based on table 7.4, see equation 1 and equation 2.

For 1st test: $y = -107.7x + 5620.0$ (1)

For 2nd test: $y = -3.2x + 168.5$ (2)

Supposing the PM2.5 concentrations from CPSs were the "real values", the plate replacing times of IPSs needed to get the "real values" can be calculated. This calculation shows that during an eight hour sampling period in a poultry house, 48 and 38 times of plate replacing should be applied to IPSs to prevent overloading. That means a clean greased plate would be needed every 10-13 min, which is not realistic for applications. The PM2.5 fraction (F2.5) of total dust in animal houses was estimated to be 8% (Chardon & vd Hoek, 2002). Based on this value together with the airflow rate (AR), the maximum plate replacing interval (T) and the PM2.5 concentration ($C_{2.5}$), a maximum loading of greased plates for particles larger than PM2.5 (ML_{IPS}) can also be estimated with equation 3:

$$ML_{IPS} = C_{2.5} \cdot \left(\frac{1 - F_{2.5}}{F_{2.5}} \right) \cdot AR \cdot T \tag{3}$$

In our case, the ML_{IPS} is estimated as 272μg.

EU standard regulated that the PM2.5-IPS should be operated in less dusty environments, e.g. working place/ambient air, with total dust concentration less than 120 μg m^{-3}. This limitation could be extended to commonly encountered concentrations up to 200 μg m^{-3}. The reason for formulating such a limitation value was from the consideration of no filter clogging and less flow rate variations from the pumps. However, there was no overloading test of greased plates found in this standard. If a 24 hour measurement with PM2.5 IPS in the ambient air is conducted, the upper total dust concentration limit should be 16 μg based on the ML_{IPS} and a proportion of 70% of PM2.5 in total dust in the ambient air. This estimated limit is sharply lower than the standard limit. It should be noted, however, that the particle size distribution of dust in ambient air and in animal houses differs a lot. In the ambient air there are less big particles, so “explosion” of very big particles on the impaction plate has less chance to happen.

7.4.2 Comparison of CPS with IPS

The EU legislation nominated IPS as the standard dust sampler. To be qualified as a “reference-equivalent sampler”, all other samplers have to be submitted to a comparability test. Within this test comparability should be proven between candidate samplers (precision test) and between the candidate sampler and IPS. Ideally, two similar candidate samplers would provide identical results when taking samples in the same environment. But it is impossible to obtain identical result because of system and measuring errors, which could be indicated with CI_{95}. The lower the CI_{95} value the better the precision of the target samplers. The upper limits of CI_{95} for PM10 samplers were set to 5 μg m^{-3} for dust concentrations lower than 100 μg m^{-3} and to 5% for higher concentrations.

PM10 CPS showed quite good precision when sampling in less dusty environments with a calculated CI_{95} in this experiment of 2.20 μg m^{-3}. The data from the less dusty environments came from working place/ambient air and from the dairy farm. The CI_{95} of 6 % for dusty environments, with data from pig and poultry houses, was slightly higher than the standard. The standard CI_{95} value was formulated for less dusty environments, e.g. working place or ambient air. For other environments, like the dusty environment of animal houses, other factors might affect sampler characteristics, such as dust concentration, dust size distribution, dust shape. Perhaps for dusty environments the boundary CI_{95} of 5% should be reconsidered. Boundaries could be determined by testing the comparability of pairs of IPSs in pig and poultry houses.

From the PM2.5-CPS data 45 out of the 46 pairs were < 100 μg m^{-3}. Therefore, it was not reasonable to group the data according to the same criteria as was done for PM10. To be consistent with the CPS-IPS test, these data were split into a working place/ambient air group and an animal houses group. This way of grouping was based on the consideration that the overloading problem with IPS in animal houses was much higher than that in working place/ambient air, where dust concentration was low and PM2.5 proportion was high (Querol *et al.*, 2001). The absolute CI_{95} values showed a big difference between the two groups. The calculated value of 2.30 μg m^{-3} for working place/ambient air is acceptable and within the boundaries (set for PM10). Data from animal houses showed very high absolute CI_{95} values, far exceeding the boundaries.

Linear regression of CPS-IPS test showed good R^2 values for PM10-CPS. The regression line of PM10 concentrations measured by CPS against IPS fell between the two-sided boundary in the range of <100 μg m^{-3} (figure 7.5, A). Combining with the CPS-CPS comparability test results, PM10 CPS fulfils all the requirements to be qualified as an equivalent sampler in this range. In the range of >100 μg m^{-3}, the regression line was out of the boundary, although the coefficient of determination was very high (0.99).

It was suggested in the EU procedure (NEN-EN 12341, 1998) that the measured concentrations should cover a range as wide as possible. Moreover, comparability would be more convincing if the concentration data are spread in an even way in the whole range. In this study data were spread over a wide ranges, however, there was lack of concentration data in the range from 50 to 300 μg m^{-3}. Although it is expected that the relationship between CPS and IPS will not be different within this range, additional collection of data within this range is advisable.

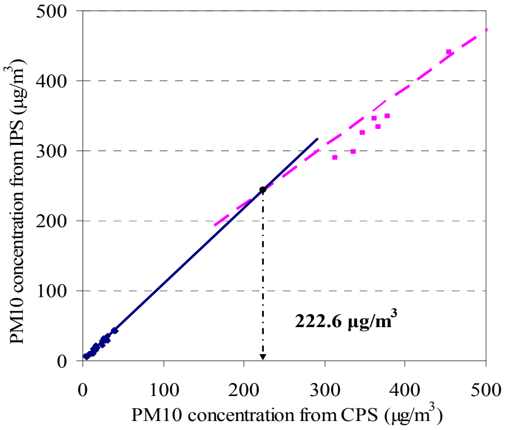
Assuming the reference sampler gave the true PM10 concentration, the slope of the regression line for an ideal candidate sampler against the reference sampler should not be significantly different from 1. Not all the candidate samplers can achieve this. For candidate samplers with slopes significantly different from 1, correction factors should be introduced to calibrate PM10 concentration to the reference sampler. In this study, regression analysis showed different lines for the two PM10 concentration groups. The PM10 concentrations measured with CPS were systematically lower than values measured with IPS in the concentration range <100 µg m^{-3}, but higher in the concentration range >100 µg m^{-3}. Therefore, the calibration should be treated separately. The two regression lines crosses each other at 222.6 µg m^{-3} (Figure 7.6). The equation regressed from data in the range < 100 µg m^{-3} should be used for calibration when PM10 concentration measured by CPS is lower than 222.6 µg m^{-3}. For the higher concentrations, equation regressed from data in the range > 100 µg m^{-3} should be used. The calibration lines are:

$y = 1.0877x$ (x < 222.6 µg m^{-3})

$y = 0.8304x + 57.492$ (x > 222.6 µg m^{-3})

Where x is the concentration measured with CPS; y is the calibrated concentration.

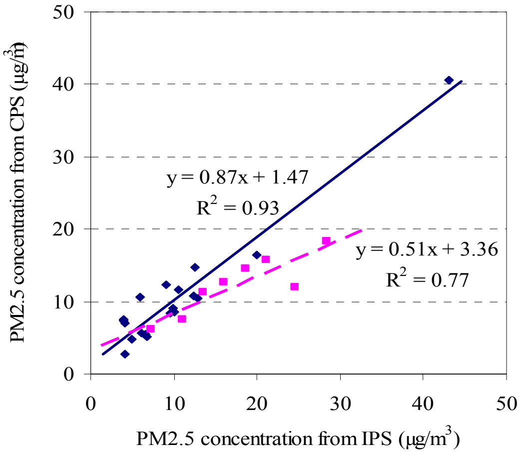
Figure 7.6 Relationships between measured PM10 concentration with cyclone pre-separator (CPS) sampler and impaction pre-separator (IPS) sampler for values <100 µg m^{-3} and for values >100 µg m^{-3} (—: regression line <100 µg m^{-3}; - - - : regression line >100 µg m^{-3}; ♦ data < 100 µg m^{-3}; ■ data >100 µg m^{-3}; notice that only a few data >100 µg m^{-3} are shown).



PM2.5 concentration data from working place/ambient air fell within the boundary, though the R^2 was lower than required (0.93 vs 0.95). The regression line from IPS on CPS was: Y = 1.065 X – 0.827. Both the regression coefficient and the constant were not significantly different from one and zero, respectively. Therefore, when using the CPS for measurements in such environments, calibration is not necessary.

Data from animal houses drifted far away from the boundary due to the overloading problem of IPS. The regression line was rather flat with a slope of 0.07 (CPS on y axis against IPS on x axis). It was highly affected by the data collected in pig and poultry farms with high PM2.5 concentrations. There were still some low concentration data measured by IPS from the dairy farm. The PM2.5 concentrations measured by CPS were quite similar in working place/ambient air and in dairy farm, on average 10.5 µg m^{-3} and 12.3 µg m^{-3}, respectively. It is of interest to look more in detail to the data collected in these two environments (Figure 7.7). The slope of the regression line with only data from dairy farms was 0.51. This was a lot higher than the slope for pig and poultry farms, however, it still is quite different from 1. It indicates that overloading of IPS was still a problem in the dairy farm. In this case, particle size distribution probably played a role. It can be concluded that PM2.5-IPS can not be used in poultry, pig and dairy farms. The question left for future work is whether the CPS gives reliable PM2.5 concentrations in animal houses. The fact that CPS was comparable with IPS in working place/ambient air and the fact that CPS is not easily overloaded give confidence for the CPS to be a reliable PM2.5 sampling method in dusty environments.

Figure 7.7 Relationships between measured PM2.5 concentration with cyclone pre-separator (CPS) sampler and impaction pre-separator (IPS) sampler for working place/ambient air and for a dairy house (—: regression line, working place/ambient air; - - - : regression line, dairy house; ♦ data from ambient air; ■ data from the dairy house).



7.5 Conclusions

The following can be concluded from this validation study:

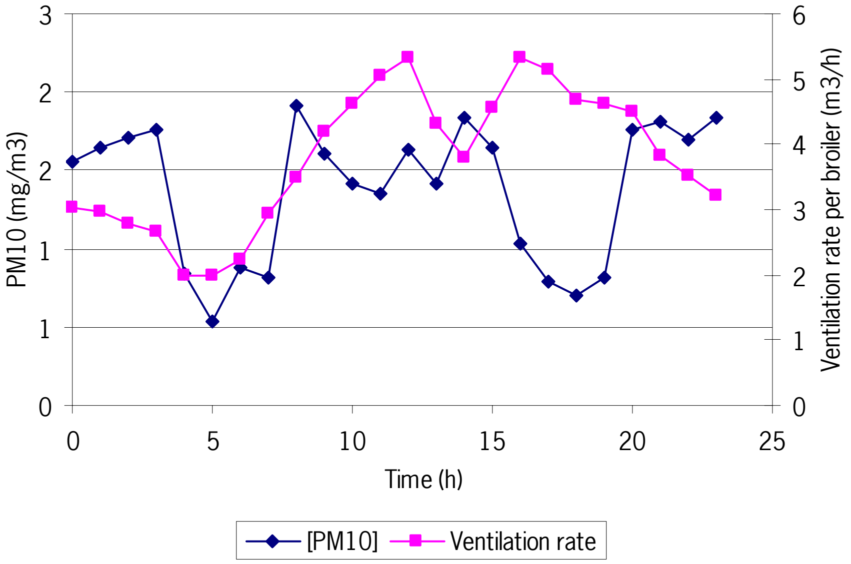
1. PM10 IPS can perform 24h dust sampling without being overloaded in a dusty environment of a poultry house, but PM2.5 IPS is easily overloaded. Therefore, PM2.5 IPS should not be used in dusty environments like animal houses.
2. The maximal loading (*ML*) of the greased plate for particles larger than PM2.5 was estimated to be 272 μg. Based on the *ML* the total dust concentration for an environment where PM2.5 IPS can operate without having an overloading problem should be less than 16μg/m^3. This is far lower than the concentration limit of 200 μg/m^3 in the EU standard.
3. PM10-CPS was proven to be an equivalent sampler in the PM10 concentration range of <100 μg m^{-3}. A very good relationship between PM10-CPS and the reference sampler was also found in the range >100 μg m^{-3}, which data were all from animal houses, though CI_{95} was slightly out of the standard acceptable boundaries. Data of CPS should be corrected with calibration lines in the whole PM10 concentration range.
4. For working place/ambient air the absolute CI_{95} value for the comparison between PM2.5-CPSs was 2.30 μg m^{-3}. Comparison between PM2.5-CPS and PM2.5-IPS showed also comparable data. This means CPS can be used as an equivalent sampler in this environment.
5. For animal houses the absolute CI_{95} value for the comparison between PM2.5-CPSs was 13.10 μg m^{-3}. This is higher than the boundary set for the PM10 standard of 10 μg m^{-3}. PM2.5-CPS was not comparable with PM2.5-IPS because of the overloading of IPS. PM2.5-CPS has a clear higher ability to store the larger particles for a long period of sampling. Although PM2.5-CPS seems to perform well in the dusty environments of animal houses, the real accuracy of this sampler for these environments is still unknown, because of the lack of a reference sampler.

8 General discussion

It is clear from EU legislation that we should measure 24 h average PM emissions of particles smaller than 10 μm (PM10) and particles smaller than 2.5 μm (PM2.5). 24 h averages are needed to determine the number of days the 24 hour standard of 50 μg m^{-3} is exceeded. An important discussion point is whether we should calculate mean dust emissions or median dust emissions from the 24 h data. For ammonia emissions the mean is calculated to determine the emission factor in kg/y per animal. Ammonia is a total load problem (deposition) and for that reason calculating the mean is more appropriate. Dust is a concentration problem, similar to odour. Calculations with spreading models should determine whether certain threshold limits are exceeded. For spreading models input of median emissions are more appropriate, because with these models exceeding frequencies are calculated in time and space.

A point not handled in the previous chapters is the possible difference between estimated emissions based on 24 h average PM concentrations and 24 h average ventilation rates. It can be imagined that high ventilation rates during the day coincide with high dust concentrations, because both are depending on animal activity. In that case the estimated emissions based on 24 h averages will underestimate the real emissions. In figure 8.1 an example is given of the diurnal pattern of PM10 concentrations and ventilation rates in a broiler house. Calculations for the example shown in this figure show that averaging hourly emissions delivers approximately the same PM emissions as multiplying the daily average PM10 concentration with the daily average ventilation rate, 125.6 and 124.9 mg/d, respectively. Although little difference is observed in this case, a possible error caused by multiplying daily means, should be checked for every animal category. So, preferably every 24 h PM sampling should be accompanied with continuous online dust sampling. This can be a rather simple instrument based on light scattering. Results of these online measurements are not meant to determine dust emissions, but only to show the diurnal variation in dust concentrations. The continuous data also give insight in the factors that are influencing these diurnal variations.

Figure 8.1 Diurnal patterns of PM10 concentrations and ventilation rates in a broiler house at a broilers age of 32 days



For determining PM emissions we follow the same strategy as was chosen before for ammonia and odour. By following this strategy the different variance compounds, between farms, within farms and variance caused by the measuring equipment, are accounted for. PM emissions are influenced by other factors than ammonia and odour emissions. For efficiency reasons all emissions (PM, ammonia, odour) will be determined at the same measuring days. Care should be taken that irregular activities or activities with a certain time interval, e.g. once a week, that might have an impact on PM emissions are included in the measuring scheme. Examples of these activities are addition or removal of bedding material. The duration of such activities is generally short. The overall effect on the yearly PM emissions will therefore be small. The effect on the daily emission, however, can be significant. For PM emissions the daily variation is important, as well, while the EU standards are also based on maximum 24 h concentrations.

From chapter 4 and 7 it is clear that impactors are easily overloaded in dusty environments like in animal houses. This is especially true for the PM2.5 impaction sampler, because of the small impaction surface and the high air velocity near the impaction plate. The PM10 cyclone pre-separator was shown to be equivalent with the impactor pre-separator at low dust concentrations (<100 µg/m^3), although the measured values with the CPS were systematically lower than with the IPS. At high dust concentrations (>100 µg/m^3) the cyclone pre-separator gave systematically higher PM10 concentrations. Therefore, when using CPS for determining PM10 concentrations in animal houses, correction factors should be used to determine the real values. The PM2.5 cyclone pre-separator was shown to be equivalent with the impactor pre-separator for environments with low dust concentrations, as well. The regression coefficient between the concentrations measured with CPS and the concentrations measured with the IPS was not significantly different from 1.0 and the constant was not significantly different from 0, therefore a correction for PM2.5-CPS results is not necessary.

A problem that is not fully solved yet is the sampling method that should be used for determining the efficiency of air scrubbers for the removal of dust. When we stick to 24 h sampling, in stack methods seem less suitable, because of the varying ventilation rates and the accompanying variations in air speed in the air channels before and after the scrubber. Further study is needed to determine the sampling error that is made when using the standard outdoor inlets at varying air speeds. Outdoors the wind speed can vary to a large extend varying from less than 1.0 to more than 10 m/s. By doing a series of 24 h measurements the error will be reduced and a good estimate of the real outdoor concentrations can be obtained. In ventilation channels, however, the air velocity might be limited to a certain range, which might cause a systematic error in the measured dust concentrations.

9 General conclusions

From this report it can be concluded that for animal houses an adapted measuring protocol is needed when compared to the outside air. PM2.5-impactor plates of the standardized outdoor samplers are easily overloaded. Although overloading of PM10-impactor plates was not shown within this study, they might get problems in very dusty environments, as well. Use of cyclones could overcome this problem. Correction factors, however, are needed to relate the emission results from animal houses, measured with cyclones, with outdoor results measured with the standardized impactor samplers. The measuring strategy that was developed for determining ammonia and odour emissions seems to be suitable for determining PM emissions, as well. 24 h samples should be taken to cover within day variations and measurement days should be spread over the year to cover all the seasons. For animals with a growing cycle the measuring days should also cover the whole growing period. Further research is needed to determine the measuring error when samples need to be taken in an environment with a high air velocity (> 2.0 m/s).

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