

Size distribution of airborne particles in animal houses

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Abstract: The concentration and size distribution of airborne particles were measured inside and outside typical animal houses such as broilers, broiler breeders (both floor housing with litter); layers (floor housing system and aviary housing system); turkeys (floor housing with litter), pigs: fattening pigs (traditional houses, low emission houses with dry feed, and low emission houses with wet feed), piglets, sows (individual and group housing); cattle (cubicle house), and mink (cages). Using an aerosol spectrometer, particles were counted and classified into 30 size classes (total range: 0.25 – 32 µm). Particles were measured on for two days, one in spring and the other in summer, in two of each species/housing combination during 30 min inside and outside the animal house. Outside temperature and relative humidity were also measured. Particle counts in the different size classes were generally higher in poultry houses than in pig houses, and counts in pig houses were generally higher than those in cattle and mink houses. The particle counts in animal houses were highest (on average 87%) in the size classes <1.0 µm, while particle mass was highest in size classes >2.5 µm (on average 97%). Most particles outside were in the size class <1.0 µm (99% in counts). Mean count median diameter (CMD) of particles inside the animal houses ranged from 0.32 to 0.59 µm, while mean mass median diameter (MMD) ranged from 3.54 to 12.4 µm. Particle counts in different size fractions were highly correlated, with correlation coefficients varying from 0.69 to 0.98; higher coefficients were found for the closer size ranges. Although particle counts in different size ranges varied greatly, for all particle classes, except the particles in the 0.25 – 1.0 µm range, the most variation could be accounted for by species/housing combination and outside temperature and relative humidity. It should be recognized that the measurements were done during short periods of the day and only during the spring and summer period.

Keywords: particle size distribution, animal houses, CMD, MMD, temperature, relative humidity

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1 Introduction

In animal houses, especially those for pigs and poultry, air quality can be seriously impaired by high dust concentrations (Takai et al., 1998; Wathes et al., 1997).

These cause health problems for humans working in this environment (Andersen et al., 2004; Donham et al., 1995; Herr et al., 1999; Pope et al., 2002), and probably also for the animals living in these houses (Al Homidan and Robertson, 2003). In addition, animal houses contribute significantly to particle concentrations in the ambient air through emission of particles with the exhausted air (Seedorf and Hartung, 2000; Takai et al., 1998).

The main characteristics of dust from animal houses are: 1) it is biologically active – the dust contains a

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variety of organic compounds, from the animals themselves (skin, hair, feathers), from feed, feces and bedding material) (Aarnink et al., 1999; Aarnink et al., 2004; Cambra-López et al., 2010; Takai et al., 1998; Welch, 1986) and from microbes (viruses, bacteria, fungi, parasites, dust mites); 2) it is highly concentrated in the air – typically ten or even one hundred times more concentrated in the air of animal houses than in other buildings such as offices (Muller and Wieser, 1987); 3) it spans a wide spectrum of particle sizes and shapes – from less than one micrometer (μm) to one hundred μm in diameter (Cambra-López et al., 2009).

One of the most important characteristic of dust is the size of the airborne particles, because this influences the behaviour and transport of the particles in the air (Wang et al., 2005) and the choice of control technology (Zhang, 2004a). Particle size determines the impact of dust on human and animal health too (Mercer, 1978). Particles are often classified into three size classes: smaller than $10 \mu\text{m}$ (PM_{10}), smaller than $2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) and smaller than $1.0 \mu\text{m}$ (PM_1) respectively. Particles in these size ranges are mainly responsible for health problems because they can travel into the respiratory system (Collins and Algers, 1986). Generally, the smaller the particles are, the deeper they can penetrate into the respiratory system and the greater their impact is on animal and human health.

Some studies have investigated the particle size and size distribution in animal houses, but only for certain animal houses, e.g. pig buildings (Lee et al., 2008; Maghirang et al., 1997); and cattle feedlots (Sweeten et al., 1998) and layer houses (Cao et al., 2009). Lee et al. (2006) investigated the effect of different farm activities on personal exposure to dust in different size ranges on pig, poultry, and dairy farms. Until now, particle size distribution (PSD) had not been investigated in a comparative way, using the same instrument in a wide range of species/housing combinations. Because of variations in space and time in dust concentrations (Maghirang et al. 1997; Van Ransbeeck et al., 2012), in the present study sampling was performed for two times, first during spring and second during the summer, in two animal houses of each species/housing combination.

The objective of this study was to determine the particle size distribution in terms of counts and mass in different types of commercial animal houses in the Netherlands.

2 Material and methods

2.1 Animal houses

PM_{10} mass and particle size distribution (PSD) were determined in 13 different combinations of animal species/housing type in the Netherlands. Each species/housing combination was measured at two farms (replicates) for two days: one in spring, the other in summer. The animal species/housing combinations studied were: broilers (broiler); layers housed in a floor system (layer_floor); layers in an aviary system (layer_aviary); broiler breeders (broiler_breeder); turkeys; piglets; fattening pigs in traditional houses (fat_pig_trad); fattening pigs in modern low-emission housing with dry feed (fat_pig_mod_dry); fattening pigs in modern low-emission housing with wet feed (fat_pig_mod_wet); sows in individual housing (sow_individual); sows in group housing (sow_group); dairy cattle in cubicles (cattle); and mink in cages (mink). The housing systems and conditions of the different animal species are shown in Table 1. The studied farms are representative for the different categories of animals with respect to size (number of animals), animal density, production cycle, climate conditions, housing, feed, and ventilation system. All poultry houses had a bedded floor area. Within the aviary system for layers a part of the manure was regularly removed with a belt system. All poultry, except turkey, and all pig houses were forced ventilated. The houses for turkey, cattle, and mink were naturally ventilated.

2.2 Dust sampling

PM_{10} mass concentrations and PSD in counts were both measured using aerosol spectrometers based on the light-scattering principle. These instruments detect each individual particle by scattered light photometry inside an optical measuring cell. The intensity of the scattered light signal is a measure of the particle's size. PM_{10} mass concentrations were measured with a DustTrak aerosol monitor, model 8520 (TSI inc., 500 Cardigan road Shoreview, MN 55126-3996, USA), which consisted

Table 1 Characteristics of the animal houses (n=26) in this study

Animal type	Animal category	Farm	No. of animals	Animal density (No m ⁻²) ¹⁾	Production cycle (weeks of age)	Sampling moments (weeks of age)	Inside/outside conditions (T, RH)	Housing	Feed	Ventilation	
Poultry	Broiler	1	52 000	20-24	0 – 6/7	4	18.2°C, 52.5%/14.5°C, 47.7%	Floor with bedding	Automatically dispensed crumbs and pellets	Side inlet, fans in end wall	
						5	24.0°C, 67.0%/22.5°C, 57.1%				
		2	2 675			3	20.2°C, 41.1%/18.9°C, 44.4%				
							4	23.2°C, 55.1%/23.5°C, 45.3%			
		Layer_floor	1	3 850	8.8-9	18 – ±75	52	14.8°C, 75.0%/11.4°C, 88.9%	Floor with bedding, slatted hopper, laying nests	Automatically dispensed crumbs and pellets	Side inlet, fans in end wall
				71			18.8°C, 71.7%/15.5°C, 70.8%				
	2		16 500	22			15.5°C, 82.4%/12.5°C, 54.0%				
							31	21.9°C, 52.5%/22.8°C, 39.5%			
		Layer_aviary	1	2 5650	17-18	18 – ±75	52	13.6°C, 72.7%/11.4°C, 88.9%	Floor with bedding, aviary system with manure belts, laying nests	Automatically dispensed crumbs and pellets	Side inlet, fans in end wall
				71			18.2°C, 69.5%/15.5°C, 70.8%				
	2		33 500	50			17.1°C, 68.9%/12.5°C, 54.0%				
							59	24.0°C, 45.6%/22.8°C, 39.5%			
	Broiler_breeder	1	3 698	7.7 - 8.5	20 – 60	29	20.4°C, 47.8%/18.6°C, 28.2%	Floor with bedding, slatted hopper, laying nests	Automatically dispensed crumbs and pellets	Side inlet, fans in end wall	
			39			24.2°C, 57.2%/22.8°C, 56.2%					
2		7 430	27			24.8°C, 40.4%/21.8°C, 40.9%					
						37	24.0°C, 62.6%/20.3°C, 58.9%				
	Turkey	1	4 750	3.0 – 3.4	4/5 – 21	12	16.8°C, 55.6%/14.9°C, 46.1%	Floor with bedding	Automatically dispensed crumbs and pellets	Natural ventilation with open ridge and side inlets	
			20			19.4°C, 70.5%/15.6°C, 50.9%					
2		3 800	10			17.1°C, 56.0%/16.6°C, 25.9%					
						17	20.9°C, 50.3%/22.0°C, 42.3%				
Pigs	Piglet	1	75	2.9 – 3.3	4 – 10/11	4	21.6°C, 83.5%/14.8°C, 33.8%	Partially slatted	Automatically dispensed pellets	Ceiling inlet, fan in ceiling	
						9	23.5°C, 53.4%/19.9°C, 55.2%				
		2	125			6	22.4°C, 83.2%/15.9°C, 67.7%	Fully slatted			Door inlet, fan in ceiling
			8	24.2°C, 66.2%/19.9°C, 53.8%							
		Fat_pig_trad	1	60	1.0 – 1.3	10/11 – 25/27	17	20.8°C, 54.4%/14.8°C, 33.5%	Partially slatted	Automatically dispensed pellets	Ceiling inlet, fan in ceiling
				20			21.4°C, 68.9%/18.0°C, 55.5%				
	2		120	18			21.8°C, 76.8%/15.9°C, 67.7%	Door inlet, fan in ceiling			
			24	24.1°C, 66.2%/19.9°C, 53.8%							
		Fat_pig_mod_dry	1	132	1.0 – 1.3	10/11 – 25/27	22	22.7°C, 53.2%/19.9°C, 48.1%	Partially slatted	Automatically dispensed pellets	Floor inlet, fan in ceiling
				16			24.3°C, 55.2%/25.7°C, 43.9%				
	2		144	20			22.1°C, 50.4%/18.2°C, 42.2%				
							24	26.2°C, 49.1%/26.5°C, 39.5%			
	Fat_pig_mod_wet	1	144	1.0 – 1.3	10/11 – 25/27	22	25.4°C, 64.2%/18.4°C, 64.9%	Partially slatted	Liquid feeding	Floor inlet, fan in ceiling	
			19			22.7°C, 66.9%/18.4°C, 80.5%					
2		120	19			24.1°C, 51.4%/18.2°C, 42.2%					
						24	26.5°C, 62.1%/26.5°C, 39.5%				
	Sow_individual	1	32	0.77	Diverse	Diverse	21.2°C, 60.3%/19.8°C, 57.3%	In crates, partially slatted	Automatically dispensed pellets	Door inlet, fan in ceiling	
			Diverse			22.6°C, 58.8%/20.5°C, 68.0%					
2		145	Diverse			24.4°C, 42.8%/20.3°C, 41.4%	Ceiling inlet, fan in ceiling				
		Diverse	22.4°C, 71.9%/22.3°C, 58.6%								
	Sow_group	1	46	0.4	Diverse	Diverse	19.7°C, 56.6%/22.2°C, 31.2%	Partially slatted with feeding crates	Automatically dispensed pellets	Ceiling inlet, fan in ceiling	
			Diverse			25.7°C, 61.9%/21.6°C, 64.9%					
2		34	Diverse			19.4°C, 82.1%/14.2°C, 33.8%	Valves inlet, fan in ceiling				
		Diverse	23.6°C, 54.4%/19.9°C, 55.2%								
Cattle	Cattle	1	51	0.3 - 0.4	Diverse	Diverse	19.8°C, 51.2%/19.9°C, 56.6%	Cubicle house	Roughage (maize and grass silage) two times /day	Naturally ventilated	
		2	150				18.9°C, 64.6%/20.8°C, 56.1%				With side curtains and ridge
							18.8°C, 46.8%/17.5°C, 45.0%				
							27.9°C, 60.7%/25.4°C, 66.4%				
Mink	Mink	1	9 015	4-5	48 - 52	7	18.9°C, 71.7%/17.9°C, 72.9%	Cages	Feeding wet feed 3 times/day	Naturally ventilated with side curtains and ridge	
						17	22.0°C, 71.3%/22.3°C, 68.6%				
		2	5 086			6	22.9°C, 54.1%/22.5°C, 51.8%				
						20	18.7°C, 68.7%/19.2°C, 67.2%				

Note: ¹⁾ Per m² basic floor space, so excluding floor space at tiers.

of a portable, battery-operated, laser-photometer. The DustTrak provided real-time measurement based on 90° light scattering. This monitor can be used to measure aerosol mass concentrations in the range from 0.0001 – 100 mg m⁻³. The sampling air flow rate was 1.7 L min⁻¹. The monitor was factory calibrated to the respirable fraction of standard ISO 12103-1, A1 test dust (formerly Arizona Test Dust). This allows comparison between measurements.

Particle size distribution in counts was measured with a Grimm instrument, model number 1.109 (Grimm Aerosol Technik GmbH & Co., Ainring, Germany). This portable aerosol spectrometer determines particle counts for 31 size ranges (optical latex equivalent diameter) with lower limits (in µm) of 0.25, 0.28, 0.30, 0.35, 0.40, 0.45, 0.50, 0.58, 0.65, 0.70, 0.80, 1.0, 1.3, 1.6, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.5, 7.5, 8.5, 10.0, 12.5, 15.0, 17.5, 20, 25, 30 and 32. The upper limit of the biggest particle size range (>32 µm) is not well defined and therefore this size range was not included in the analyses. The sampling airflow rate was 1.2 L min⁻¹ and the sampling interval was 1 min. Mean values per location and measuring day for the different size ranges in the analysis were used. The Grimm instrument was size calibrated by the manufacturer by using standard aerosol particles (poly-styrene latex). Before use in this study the device has been cleaned and recalibrated. While this instrument is mainly used for indoor measurements it is not equipped with a dehumidification system. Therefore, outside measurements were never done at humidity levels close to condensation levels. Humidity levels during outside measurements were always lower than 90%.

Air was sampled with the Grimm spectrometer for short periods (60 min) to avoid contamination of the monitor in dusty environments. The Grimm and DustTrak spectrometers were used to sample air both inside and outside each animal house. Inside the house, the samplers were placed at a height of approximately 1.5 m above the floor and as close as possible to the air outlet, but at least 1.5 m from fans. This location was chosen to obtain representative samples of the exhaust air

and to avoid the high air velocities near to the exhaust fans, which would have affected the sampling efficiency (Hinds, 1999). In naturally ventilated buildings, with the air outlet in the ridge, the distance to the air outlet was greater (5 to 8 m). When sampling outside, samplers were placed upwind from the animal house. Sampling inside the animal house started directly after the spectrometers were installed and lasted for 60 min. However, only the data from the last 30 min of each measurement were used. This was done to let the animals go back to normal activity levels again, after being disturbed by the installation of the equipment. In order to avoid possible effects of human disturbance, all measurements were done in daytime between 10:00 a.m. and 15:00 p.m. In Figure 1 the time periods in which the samplings were done are given in relation to the diurnal pattern of PM₁₀ concentrations for the various animal categories (Winkel et al., 2011). These diurnal patterns were not determined on the same days as the measurements in this study. Outside sampling start immediately (within 30 min) after inside sampling finished.

2.3 Environmental parameters

Temperature and relative humidity inside and outside the animal house were recorded every minute during each sampling, using temperature and relative humidity sensors (Escort iLog data logger, Askey Leiderdorp, the Netherlands). Per measuring day, average inside and outside temperature and relative humidity were calculated for each type of animal house for the period during which the dust was sampled: see Table 1.

2.4 Data analysis

Particle mass in the different size ranges was calculated as Equation (1):

$$M_i = \frac{1}{6} \pi (d_i 10^{-3})^3 \rho_i F_i \quad (1)$$

where, M_i = mass of particles in size range i , mg m⁻³; d_i = midpoint diameter (mean diameter between upper and lower limits) of particles in size range i , µm; ρ_i = density of particles in size range i , mg mm⁻³; F_i = number of particles in size range i per unit of volume, L m⁻³.

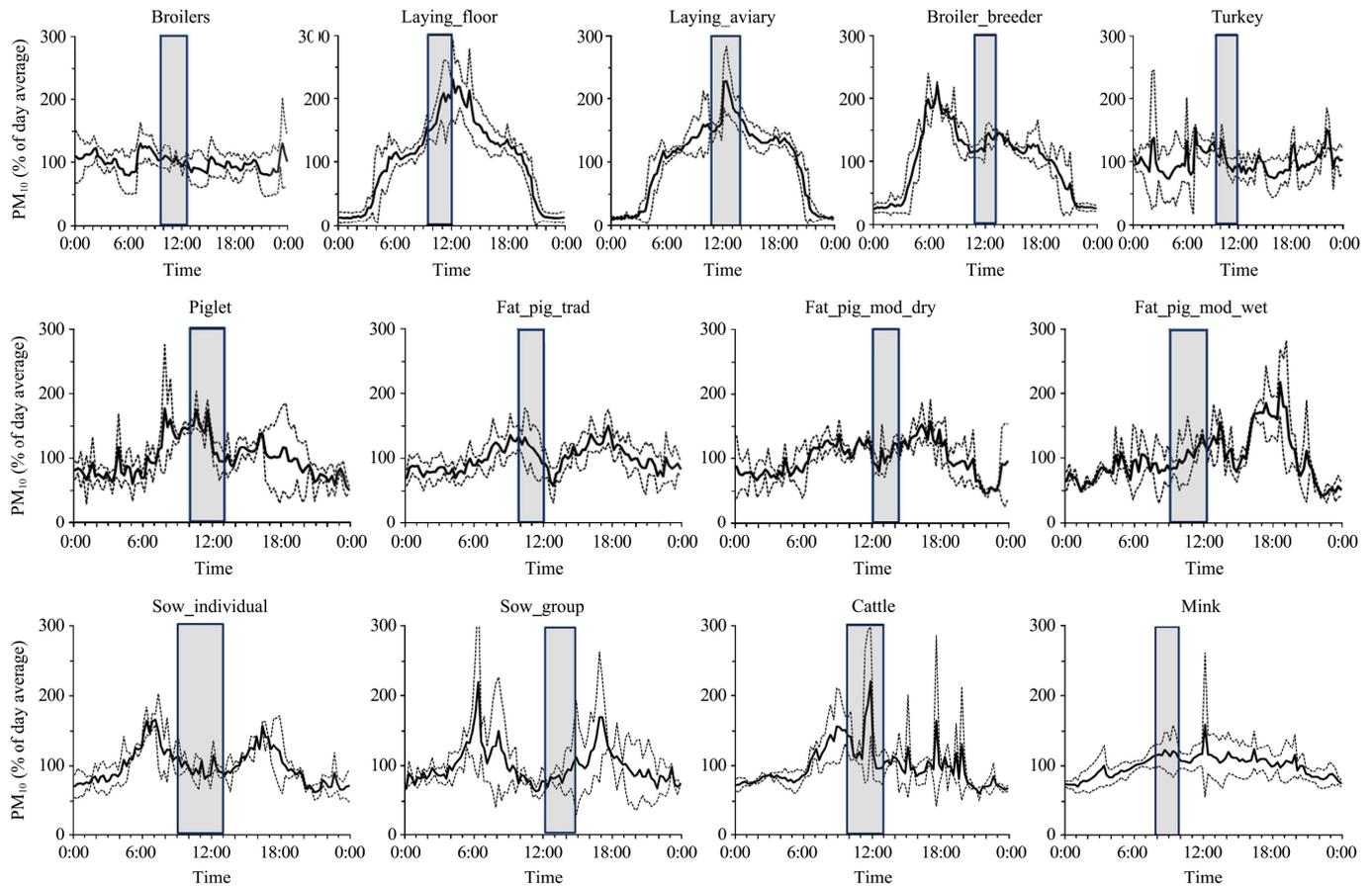


Figure 1 Time periods in which the samplings were done, given in relation to the diurnal pattern of PM_{10} concentrations, measured with the DustTrak, for the various animal categories. The PM_{10} concentrations are given as percentage of the 24 h mean value. The dotted lines give the 95% confidence intervals (Winkel et al., 2014)

Equation (1) assumes that particles in all size ranges were spherical with a density of 1 mg mm^{-3} . The particle counts and mass of the 30 measured size ranges were pooled to form four classes of particulate matter concentration: $0.25 - 1.0 \mu\text{m}$ (PM_1); $1.0 - 2.5 \mu\text{m}$ ($PM_{1-2.5}$); $2.5 - 10 \mu\text{m}$ ($PM_{2.5-10}$); and $10 - 32 \mu\text{m}$ (PM_{10-32}). After \log_e -transformation, the data in these size ranges were analysed with the ANOVA statistical procedure, to determine the effect of animal category on counts and mass. Multiple comparisons were made with Bonferoni's two-tailed t-test. Differences with P-values less than 0.05 were considered to be statistically significant. In addition, correlation coefficients between particle counts in different size ranges were calculated and the effects of outside climate (T, RH) on particle counts in different size ranges, count median diameter (CMD), and mass median diameter (MMD) (after \log_e -transformation) were estimated with multiple linear regression with groups (species/housing combination).

Parallel lines were calculated within the multiple linear regression analysis because the model was not significantly improved by including interactions in the model ($P > 0.05$). The data were analysed using Genstat software (Genstat, 2008).

The particle size distribution can be reported in different ways and characterized using different equations for particle numbers and mass. To standardize the measured values, the equations given by Zhang (2004a) were used. The following Equation (2), Equation (3), Equation (4) and Equation (5) were used to describe particle size distribution:

- Count median diameter (CMD, μm)

Though most particle size distributions are skewed, with a long tail to the right, the median is often used. The CMD of particles is defined as the diameter below which half of the particles in the sample are smaller and above which half are larger. Equation (2) was used to calculate the CMD.

$$CMD = \exp \left[\frac{\sum F_i \ln d_i}{N} \right] \quad (2)$$

where, F_i = number of particles in size range i , $L m^{-3}$; d_i = midpoint diameter of particles in size range i , μm ; N = total number of particles (sum of all size ranges), $L m^{-3}$.

- *Standardized number fraction distribution* (Δf_i , μm^{-1})

The size classes (Δd_i) for which the number of particles is counted with the particle-sizing instrument do not have uniform ranges; some ranges are much greater than others. Especially for line graphs, fractions should be standardized. The standardized number fraction can be calculated using Equation (3).

$$\Delta f_i = \frac{F_i / \Delta d_i}{N} \quad (3)$$

where, Δd_i = difference between upper and lower limits of size range i , μm .

- *Mass median diameter (MMD)*, μm)

Similar to the CMD, the MMD is the particle diameter below which half of the mass of the particles in the sample comprises particles with smaller diameters and above which half comprises particles that have larger diameters. MMD can be calculated using Equation (4).

$$MMD = \exp \left(\frac{\sum F_i d_i^3 \ln d_i}{\sum F_i d_i^3} \right) \quad (4)$$

- *Standardized mass fraction distribution* (Δf_{mi} , μm^{-1})

The standardized mass fraction is defined in a similar way as the standardized count fraction. It can be calculated using Equation (5).

$$\Delta f_{im} = \frac{m_i F_i / \Delta d_i}{M} \quad (5)$$

where, m_i = midsize particle mass of size range i , mg ; M = total mass of the particle population, $mg m^{-3}$.

3 Results

3.1 PM_{10} mass concentration

Mean PM_{10} mass concentrations were highest on poultry farms (0.83– 4.60 $mg m^{-3}$), followed by pig farms (0.13 – 1.62 $mg m^{-3}$), cattle farms (0.02 – 0.12 $mg m^{-3}$) and mink farms (0.04 – 0.12 $mg m^{-3}$). Figure 2 shows the mean PM_{10} mass concentrations for the different animal species/housing combinations. PM_{10} mass

concentrations were highest in layer_floor (3.78 $mg m^{-3}$) followed by layer_aviary (2.81 $mg m^{-3}$), turkey (1.87 $mg m^{-3}$), broiler (1.42 $mg m^{-3}$), piglet (1.15 $mg m^{-3}$), broiler_breeder (0.89 $mg m^{-3}$), fat_pig_trad (0.87 $mg m^{-3}$), fat_pig_mod_dry (0.65 $mg m^{-3}$), fat_pig_mod_wet (0.47 $mg m^{-3}$), sow_group (0.30 $mg m^{-3}$), sow_individual (0.18 $mg m^{-3}$), mink (0.07 $mg m^{-3}$) and cattle (0.07 $mg m^{-3}$). Outside PM_{10} concentrations averaged 0.08 $mg m^{-3}$ (range 0.01 to 0.25 $mg m^{-3}$).

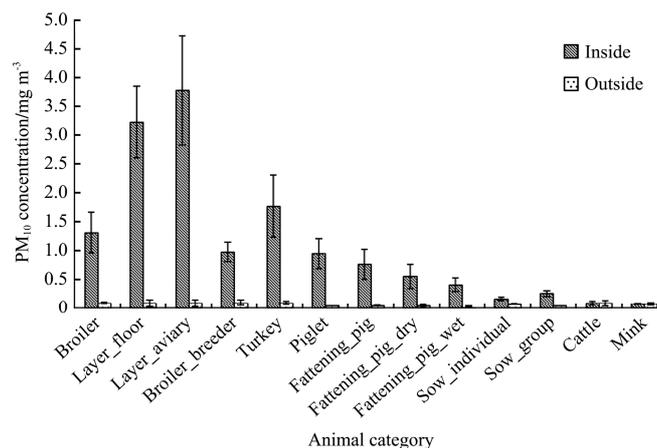


Figure 2 Estimated means (bars) and standard errors (given as lines on top of the bars) of PM_{10} dust concentrations, measured with the DustTrak, for 5 species/housing combinations for poultry, six for pigs, one for cattle and one for mink

3.2 Particle size distribution

3.2.1 Number distribution

Of the particles inside the animal houses, most (86.8% on average) were in the PM_1 class, 5.5% on average were in the $PM_{1-2.5}$ class, 7.4% on average were in the $PM_{2.5-10}$ class, and 0.2% on average was in the PM_{10-32} class. In the outside air, even more (on average, 99.2%) of the particles were in the PM_1 class; 0.7% of particles were in the $PM_{1-2.5}$ class, 0.1% on average was in the $PM_{2.5-10}$ class, and 0.005% on average was in the PM_{10-32} class. On average, outside air contained fewer particles than the inside air, especially in the larger size ranges. The number of PM_1 particles in the outside air was 52.0% of that in the inside air. The corresponding figures for the other particle size classes were 5.6% for $PM_{1-2.5}$, 0.7% for $PM_{2.5-10}$, and 1.1% for PM_{10-32} . The counts of particles in the different size ranges for the different animal species/housing combinations and outside are given in Table 2.

Table 2 Estimated mean particle counts (particles cm^{-3}) in the different size ranges and count median diameter for the different animal species/housing combinations. Standard errors of means are given between brackets ⁽¹⁾

Animal category	0.25- 1.0 μm	1.0- 2.5 μm	2.5- 10 μm	10- 32 μm	CMD ⁽²⁾ μm
1 Broiler	416 ^{ab} (143)	19.8 ^{bcde} (12.8)	34.7 ^{def} (19.8)	1.5 ^{de} (0.6)	0.44 ^{abcde} (0.04)
2 Layer_floor	683 ^b (164)	69.7 ^{de} (15.9)	102.4 ^{ef} (23.7)	2.1 ^e (0.7)	0.59 ^c (0.03)
3 Layer_aviary	763 ^b (107)	83.4 ^c (19.9)	111.7 ^f (27.1)	1.6 ^{de} (0.2)	0.57 ^{de} (0.03)
4 Broiler_breeder	128 ^a (16)	12.4 ^{bcde} (2.1)	17.3 ^{def} (2.9)	0.6 ^{cde} (0.1)	0.54 ^{cde} (0.03)
5 Turkey	395 ^{ab} (85)	41.6 ^{cde} (11.2)	33.4 ^{def} (10.7)	1.1 ^{de} (0.3)	0.48 ^{bcde} (0.04)
6 Piglet	207 ^{ab} (58)	14.9 ^{bcd} (6.0)	24.1 ^{def} (8.4)	0.9 ^{de} (0.3)	0.49 ^{bcde} (0.03)
7 Fat_pig_trad	234 ^{ab} (30)	11.4 ^{bc} (4.5)	16.1 ^{cde} (6.1)	1.0 ^{cde} (0.4)	0.43 ^{abcd} (0.03)
8 Fat_pig_mod_dry	239 ^{ab} (54)	5.2 ^{ab} (1.8)	9.0 ^{cd} (3.6)	0.8 ^{cde} (0.3)	0.38 ^{ab} (0.04)
9 Fat_pig_mod_wet	208 ^{ab} (68)	4.7 ^{ab} (0.8)	7.4 ^{cd} (1.6)	0.5 ^{cde} (0.1)	0.39 ^{abc} (0.04)
10 Sow_individual	232 ^{ab} (65)	2.1 ^{ab} (0.4)	1.9 ^{bc} (0.3)	0.1 ^{bc} (0.02)	0.33 ^a (0.009)
11 Sow_group	194 ^{ab} (46)	4.4 ^{ab} (1.0)	4.9 ^{cd} (1.2)	0.3 ^{cd} (0.06)	0.36 ^{ab} (0.01)
12 Cattle	177 ^a (103)	1.5 ^a (0.7)	1.1 ^{ab} (0.9)	0.04 ^b (0.02)	0.32 ^a (0.006)
13 Mink	380 ^{ab} (75)	0.9 ^a (0.1)	0.13 ^a (0.03)	0.004 ^a (0.001)	0.32 ^a (0.008)
1-13 Overall mean, in counts	327 (78)	20.9 (6.0)	28.0 (8.2)	0.80 (0.24)	0.43 (0.03)
1-13 Overall mean, % of total counts	86.8	5.5	7.4	0.2	
14 Outside	179 (24)	1.2 (0.3)	0.19 (0.02)	0.009 (0.001)	0.32 (0.03)

Note: 1) Means within a column lacking a common superscript letter are significantly different ($P < 0.05$).

2) CMD = count median diameter (see Equation (2)).

Table 2 shows that for all particle size range the average numbers of particles were higher in poultry houses than in pig, cattle and mink houses, with one exception: broiler_breeder houses had particle counts similar to those of pig houses in all size ranges. On average, particle counts in pig houses were higher than those in cattle and mink houses for all particle size ranges except for PM_1 . The number of particles in the PM_1 class in pig, cattle and mink houses did not differ much from the number of particles in the PM_1 class measured outside these houses.

The CMD of particles in this study (Table 2) averaged from 0.32 μm to 0.59 μm . The mean CMD of particles was 0.53 μm in poultry houses, 0.40 μm in pig houses, 0.32 μm in cattle houses, 0.32 μm in mink houses and 0.32 μm in outside air. The CMDs of particles in layer_floor houses and layer_aviary houses were significantly higher than those in most pig categories and higher than those in cattle and mink farms.

There were significant correlations between the number of particles in the different size fractions ($P < 0.001$). Correlation coefficients were 0.82 between PM_1 and $\text{PM}_{1-2.5}$, 0.82 between PM_1 and $\text{PM}_{2.5-10}$, and 0.69 between PM_1 and PM_{10-32} . The correlation coefficient between $\text{PM}_{1-2.5}$ and $\text{PM}_{2.5-10}$ was 0.98, between $\text{PM}_{1-2.5}$ and PM_{10-32} it was 0.80, and between $\text{PM}_{2.5-10}$ and PM_{10-32} it was 0.84.

Figure 3 shows the standardized number fraction of particles in poultry, pig, cattle, and mink houses. For comparison, the standardized number fractions for outdoor particles are given in each sub-figure, for comparison. For all animal house categories and also for all outside samples, the largest fraction of particles was in the size range 0.25 – 0.30 μm . Number fractions decreased sharply with increasing particle size. For pig and poultry houses, two small peaks were observed: one between 0.65 to 0.70 μm , and one between 2.5 to 3.7 μm . It is obvious from Figure 3 that inside the animal houses, especially those for poultry and pigs, the number fractions of the larger particles were much higher than outside.

3.2.2 Mass distribution

As shown in Table 3, particle size distribution in mass is dominated by particles in the size range $> 2.5 \mu\text{m}$. On average, 0.5% of particle mass was found in PM_1 , 2.1% in $\text{PM}_{1-2.5}$, 52.6% in $\text{PM}_{2.5-10}$, and 44.8% in PM_{10-32} . For outside air, 11.0% of particle mass was found in PM_1 , 5.9% in $\text{PM}_{1-2.5}$, 17.1% in $\text{PM}_{2.5-10}$, and 66.0% in PM_{10-32} . On average, compared with inside air, outside air contained less particle mass in the different size ranges: 30.8% of the mass of inside PM_1 particles, 3.9% of the mass of inside $\text{PM}_{1-2.5}$ particles, 0.45% of the mass of inside $\text{PM}_{2.5-10}$ particles, and 2.0% of the mass of inside PM_{10-32} particles.

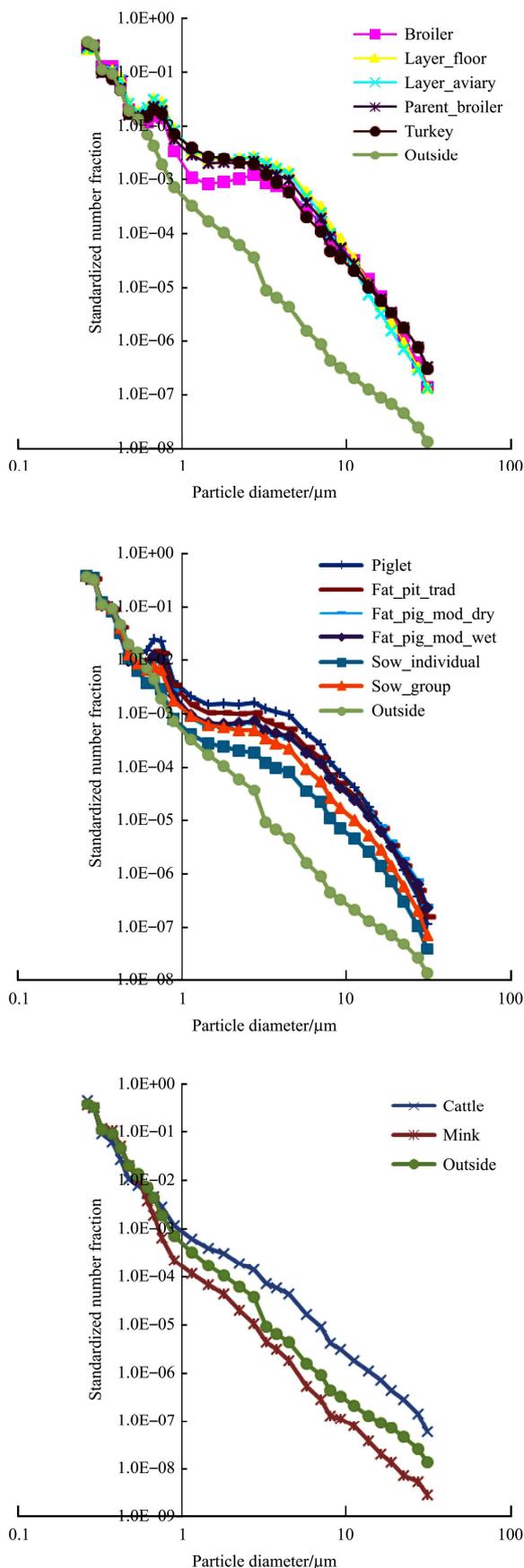


Figure 3 Standardized number fraction (at log10-scale) of particles in the different size ranges (at log10-scale) in 5 species/housing combination for poultry (top), six for pigs (middle) and for cattle and mink (bottom)

Table 3 Mean mass distribution (mg m^{-3}) of particles in the different size ranges and mass median diameter for the different animal species/housing combinations. Standard errors of means are given between brackets ⁽¹⁾

Animal category	0.25-1.0 μm	1.0-2.5 μm	2.5-10 μm	10-32 μm	MMD ⁽²⁾ / μm
1 Broiler	0.019 ^{bcd} (0.009)	0.064 ^{defg} (0.04)	2.10 ^{de} (1.09)	2.36 ^d (0.96)	10.11 ^b (0.43)
2 Layer_floor	0.042 ^{cd} (0.01)	0.210 ^{fg} (0.05)	5.72 ^e (1.63)	2.99 ^d (0.79)	7.66 ^b (0.03)
3 Layer_aviary	0.048 ^d (0.008)	0.246 ^g (0.06)	5.63 ^e (1.21)	2.51 ^d (0.38)	7.32 ^b (0.18)
4 Broiler_breeder	0.007 ^{ab} (0.001)	0.038 ^{cdefg} (0.007)	0.96 ^{cde} (0.18)	1.07 ^{cd} (0.19)	9.94 ^b (0.19)
5 Turkey	0.019 ^{bcd} (0.004)	0.117 ^{efg} (0.033)	1.51 ^{de} (0.46)	2.24 ^d (0.45)	10.53 ^b (0.57)
6 Piglet	0.01 ^{abc} (0.003)	0.044 ^{def} (0.017)	1.59 ^{de} (0.53)	1.33 ^{cd} (0.43)	9.29 ^b (0.67)
7 Fat_pig_trad	0.009 ^{abc} (0.003)	0.034 ^{cde} (0.013)	1.07 ^{cde} (0.41)	1.62 ^{cd} (0.65)	10.26 ^b (0.69)
8 Fat_pig_mod_dry	0.007 ^{ab} (0.002)	0.016 ^{bcd} (0.006)	0.68 ^{cd} (0.27)	1.44 ^{cd} (0.61)	12.39 ^b (0.47)
9 Fat_pig_mod_wet	0.006 ^{ab} (0.0009)	0.014 ^{bcd} (0.003)	0.52 ^{cd} (0.11)	0.92 ^{cd} (0.22)	11.47 ^b (0.46)
10 Sow_individual	0.005 ^{ab} (0.001)	0.006 ^{abc} (0.0009)	0.12 ^{bc} (0.02)	0.21 ^{bc} (0.03)	10.67 ^b (0.37)
11 Sow_group	0.005 ^{ab} (0.001)	0.012 ^{abcd} (0.003)	0.29 ^{cd} (0.07)	0.49 ^{cd} (0.12)	10.86 ^b (0.75)
12 Cattle	0.004 ^a (0.002)	0.004 ^{ab} (0.002)	0.058 ^{ab} (0.04)	0.094 ^b (0.05)	10.96 ^b (2.03)
13 Mink	0.009 ^{abc} (0.002)	0.002 ^a (0.0003)	0.005 ^a (0.001)	0.008 ^a (0.003)	3.54 ^a (1.23)
1-13 Overall means (mass)	0.015 (0.004)	0.062 (0.018)	1.56 (0.52)	1.33 (0.37)	9.62 (0.61)
1-13 Overall means, % of total mass	0.5	2.1	52.6	44.8	
14 Outside	0.0045 (0.0009)	0.0024 (0.0005)	0.0070 (0.0006)	0.027 (0.004)	9.15 (0.63)

Note: 1) Means within a column lacking a common superscript letter are significantly different ($P < 0.05$).

2) MMD = mass median diameter (see Equation (4)).

The standardized mass distributions for the different animal species/housing combinations are shown in Figure 4. From this figure it is clear that the standardized mass distribution is very different from the standardized count distribution. Unlike the standardized count distribution, the standardized mass distribution of particles inside had a very different pattern than the pattern outside. Because the outside air contained relatively high numbers of small particles and very few big particles, the contribution of the small particles to mass was relatively large; by contrast, the mass of inside particles was dominated by the bigger particles. The standardized

mass fraction was especially high in the size range from 2.5 – 10 μm . Peaks in standardized mass fractions occurred in the size range 4.0 – 6.5 μm in all cases, except for mink. The standardized mass distributions of particles inside cattle and mink houses were very similar to those outside.

The MMD inside animal houses averaged from 3.54 μm to 12.4 μm for the different animal species/housing combinations; outside, the average MMD was 9.15 μm . The MMDs in poultry (9.11 μm), pig (10.8 μm) and cattle (11.0 μm) houses were significantly higher than the MMD in mink houses (3.54 μm) ($P < 0.05$).

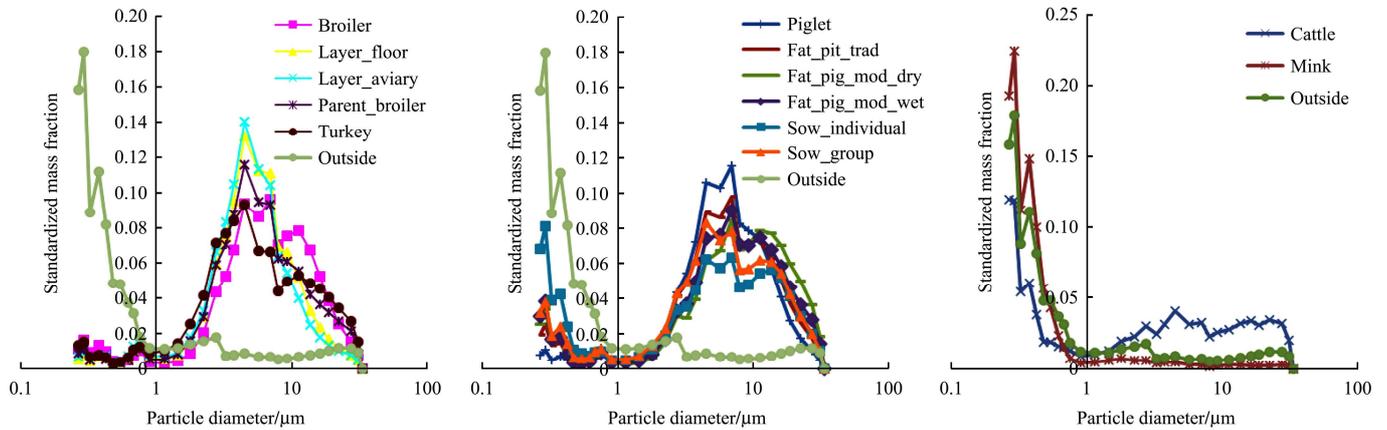


Figure 4 Standardized mass fraction of particles in relation to particle diameter (at log10-scale) in 5 species/housing combinations for poultry (left), six for pigs (middle) and for cattle and mink (right)

3.2.3 Effect of outside climate on particle size distribution inside animal houses

In Table 4 the results of the multiple regression analyses are given. This model accounted for 85% to 91% of the variations in counts in $\text{PM}_{1-2.5}$, $\text{PM}_{2.5-10}$, and PM_{10-32} , for 36% of the variation in counts of PM_1 , for 81% of the variation in CMD, and for 62% of the variation in MMD.

Particle numbers in PM_1 were not influenced by outside temperature; particle numbers in $\text{PM}_{1-2.5}$, $\text{PM}_{2.5-10}$, and PM_{10-32} , however, were significantly influenced by outside temperature. Higher outside temperatures gave lower particle counts in these size ranges. Outside relative humidity did not have a significant effect on particle counts in all size ranges. Count median diameter was significantly influenced by outside temperature and relative humidity. At higher outside temperature and humidity levels CMD became smaller. Mass median diameters were not affected by outside temperature and relative humidity.

Table 4 Linear effects (regression coefficient: rc) of outside climate (Temp., RH) on particle counts in different size ranges and on count (CMD) and mass (MMD) median diameter (after log_e-transformations) inside the animal house. The standard errors of rc and the probability that rc is not different from 0 are given

Size range, CMD, MMD	Temp. outside			RH outside			R^2 (2)
	rc	s.e.	P (1)	rc	s.e.	P (1)	
0.25-1.0 μm	0.009	0.028	0.75	0.006	0.007	0.40	0.36
1.0-2.5 μm	-0.108	0.028	<0.001	-0.012	0.007	0.10	0.85
2.5-10 μm	-0.110	0.029	<0.001	-0.012	0.007	0.10	0.91
10-32 μm	-0.098	0.030	0.003	-0.011	0.008	0.17	0.89
CMD	-0.021	0.005	<0.001	-0.004	0.001	0.01	0.81
MMD	0.001	0.013	0.94	-0.004	0.003	0.23	0.62

Note: 1) A P-value < 0.05 is considered to be statistically significant, meaning there is a significant linear effect of T, RH on log_e (particle count, CMD, MMD).

2) R^2 is the variance accounted for with the multiple regression models with outside T and RH as variables and species/housing combinations as groups.

3.3 Comparison between PM_{10} measurements with the DustTrak and with the Grimm

In Figure 5 a comparison was made between the PM_{10} measurements with the DustTrak and with the Grimm. From these results it can be seen that the results of Grimm and DustTrak have a stronger deviation from the line $Y = X$ at higher dust concentrations. The higher dust concentrations are especially found in the poultry houses.

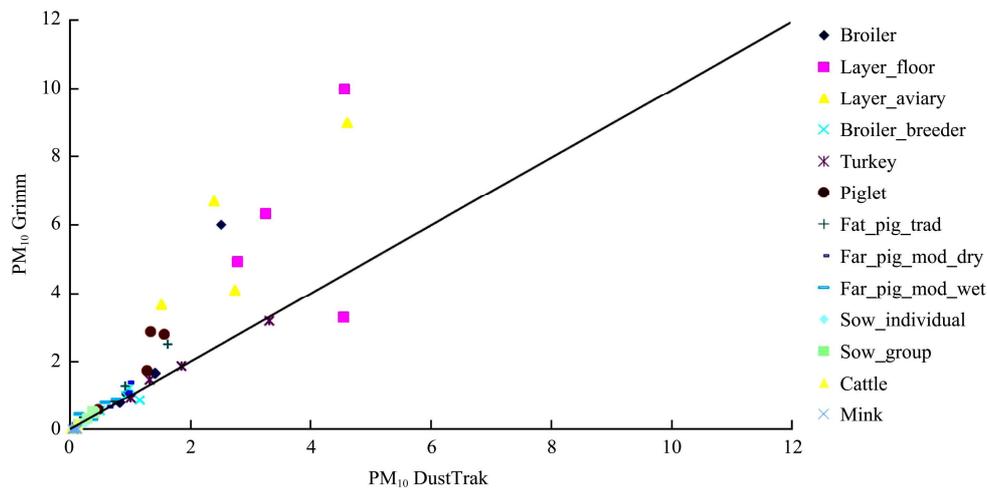


Figure 5 Comparison between PM10 measurements with the DustTrak and with the Grimm

4 Discussion

The results for PM₁₀ mass concentrations and particle counts in the different size ranges show that concentrations were highest in poultry houses, followed by pig houses, and were lowest in cattle and mink houses. Takai et al. (1998) found the same ranking order for concentrations in poultry, pig, and cattle houses in different livestock buildings in Northern Europe. The high dust concentrations in poultry houses are most probably related to the presence and use of litter. The scratching, dust-bathing and other activities of the poultry cause dust particles to be formed, especially from manure and feathers (Cambra-Lopez et al., 2011), and to be suspended in the air. In layer houses with battery cages, where no litter is present and where there is no contact between animals and their manure, much lower dust concentrations were reported (Takai et al., 1998). The low dust concentrations in cattle and mink houses are probably the result of a low dust production in combination with a high ventilation rate in the open naturally ventilated buildings.

The results showed that the number of particles smaller than 1.0 μm in pig, cattle and mink houses did not differ much from the number of particles in this size range measured outside. This corroborates the hypothesis that the small particles in animal houses mainly come from outside (Zhang et al., 1998). The particle counts in mink and cattle houses were more or less similar and not very different from the particle counts

outside for all particle size ranges.

In this study we found totally different particle size distributions of counts and mass, especially in poultry and pig houses. Inside the animal houses, most particles in the counts (on average, 87%) were in the PM₁ class, yet this particle size accounted for only 0.5% of the particle mass. On average, only 7.6% of the number of particles inside the animal houses was $>2.5 \mu\text{m}$, yet this particle size accounted for 97% of the particle mass. In the outside air 99% of the number of particles was found in the PM₁ class, but these particles accounted for only 11% of the particle mass. The very small contribution of the number of particles in PM₁₀₋₃₂ (0.005%) to total number of particles in the outside air contributed greatly to particle mass (66%). It should be noted that when calculating particle mass distribution from particle count distribution it was assumed that the density of the particles was 1 mg/mm^3 and that the particles were spherical (shape factor of one). Both density and shape can vary, however, depending on the source of dust (Cambra-Lopez et al., 2011) and probably also depending on how the dust is generated. Simplistic assumptions were made about density and shape because the contribution of each dust source to the particles in the different size ranges was unknown. The shape factor gives the relationship between the observed diameter by the measuring equipment in a two dimensional view and its diameter in a three dimensional view (Cambra-López et al., 2011). Generally, the density and the shape factor of dust particles are both higher than one. McCrone (1992)

reported densities of 1.2 g cm^{-3} for feathers, 2.6 g cm^{-3} for feed, 1.3 g cm^{-3} for hair, 1.5 g cm^{-3} for manure and wood shavings, 1.4 g cm^{-3} for skin, and 2.1 g cm^{-3} for outside particles. Zhang (2004b) reported shape factors of 1.06 for feathers and wood shavings, 1.08 for feed and outside, 1.15 for poultry manure, 1.36 for pig manure, and 1.88 for skin. When calculating the mass of a particle, the volume of an assumed spherical particle should be multiplied by the density and be divided by the shape factor, so these factors will to some extent cancel out each other.

The results showed the highest CMD for poultry ($0.53 \mu\text{m}$), followed by pigs ($0.40 \mu\text{m}$), while the CMD of particles inside cattle and mink houses were similar to the CMD of particles in the outside air ($0.32 \mu\text{m}$). The MMDs for particles inside poultry, pig and cattle houses were very similar ($9.11 - 11.0 \mu\text{m}$), while the MMD for particles in mink houses were clearly lower ($3.54 \mu\text{m}$). The relatively high MMD for outside particles ($9.15 \mu\text{m}$) is probably caused by some small particles in the highest size ranges causing a big increase in the MMD. In the atmospheric air large amount of very small particles ($<1.0 \mu\text{m}$) are present, but few in the larger size ranges. Therefore a few extra particles in the largest size ranges have a big effect on MMD. The MMD of particles greatly depends on the maximum size ranges of the particles collected. Within this study the upper limit was $32 \mu\text{m}$. In their study, Jerez et al. (2009) analysed particles up to a diameter of $600 \mu\text{m}$ and found the average MMD of particles leaving a building for growing-finishing pigs was $26.8 \mu\text{m}$ – much larger than that found in this study ($10.3 - 12.4 \mu\text{m}$). Lee et al. (2008) also found larger MMDs (ranging from 9 to $25 \mu\text{m}$) for particles in different pig houses. Their maximum measurable particle size ranged from 600 to $1,200 \mu\text{m}$. Maghiran et al. (1997) found a mean MMD for piglets of $13 \mu\text{m}$, measured with an eight-stage cascade impactor with a maximum measurable size range of $>21.3 \mu\text{m}$. This compares with the mean MMD of $9.3 \mu\text{m}$ we found for particles in piglet houses. Sweeten et al. (1998) found MMDs for cattle feedlot dust of $9.5 \mu\text{m}$ for total dust and of $6.9 \mu\text{m}$ for PM_{10} dust. The mean MMD we determined in cattle houses was $11.0 \mu\text{m}$. There are

several possible reasons for the relatively low values found in the study by Sweeten et al. (1998), one of the main reasons being the relatively large amounts of manure that probably dustify in the feedlot system.

In this study, the particle size distribution in different animal houses during daytime at “normal” activity levels of the animals was determined. Normal activity means that animals were not disturbed by human activities or other disturbing effects from outside. However, animals have their own activity pattern, as well. Ideally, particle size distribution should be determined during 24 h periods, at different locations inside the animal house, at different locations with similar species/housing combinations, and during different seasons of the year. This study was limited in terms of giving information on variations during the day (samples were taken for only half-hour periods), variations between locations inside the animal house (only one spot was sampled), and seasonal variations (measurements were only done during the spring/summer period). Within these study comparison measurements at different locations with various species/housing combinations during a similar time period of the day was performed.

In Figure 1 the periods in which the measurements were done are shown against the diurnal background PM_{10} concentrations for the different combinations of animal species/housing type. For broilers, turkey, fattening pigs, sows and mink, measurements were done during a period in which PM_{10} concentrations were close to the average of the day. For broiler breeders and cattle, the PM_{10} concentrations during the measuring period were slightly above the average of the day; while the houses for layers and piglets were being sampled during periods in which PM_{10} concentrations were $1.5 - 2.0$ times above average. These differences should be considered when comparing data between different species/housing combinations. However, as can be seen from Tables 2 and 3, the differences between species/housing combinations are much greater than the diurnal variations within species/housing combinations.

Large variations in particle concentrations occurred not only between animal species/housing combinations but also between farms of the same category and within

farms (two measurements at different moments), as shown by the relatively high standard error of means (s.e.m., Table 2). This agrees with the findings of Martin et al. (1996) who also reported large variations in dust particle concentrations between animal houses. They suggested that this was caused by the fact that each animal farm has its own control and managing practices and its own details in housing design. Another reason for the variations within farms of the same category in our study was the fact that farms were sampled on different days and at different moments in the production cycle. These factors can have a large effect on the ventilation rate and thereby on the dilution of particles with fresh air.

Measuring dust concentrations at only one spot within an animal house, as we did, will also have implications for our findings. Maghirang et al. (1997) found significantly higher total dust concentrations ($<100 \mu\text{m}$) above the pens than above the alley; however, the respirable dust fraction (particles $<4.0 \mu\text{m}$) did not show any significant spatial variability. Jerez et al. (2009) concluded from their study in a swine building that larger particles were re-entrained in the air by animal activity, but settled again before they reached the ventilation outlet. Van Ransbeeck et al. (2012) found relatively small spatial variations when compared to daily variations (within and between days). In our study dust concentrations were measured close to the ventilation outlet to get a sample that was representative of the dust particles that are emitted to the outside air.

Our measurements, which were all made during spring and summer, are representative only for that period. Various studies have shown that dust concentrations are generally higher during the winter than during the summer, especially in pig and poultry houses (Lee et al., 2008; Roumeliotis and Van Heyst, 2007; Takai et al., 1998). The variations in temperature and relative humidity, however, enabled us to estimate temperature and humidity effects on particle counts and count and mass median diameter of particles inside the animal house. These calculations showed that the effects of outside temperature were very similar for particle counts in the different size ranges $>1.0 \mu\text{m}$. Counts in these

size ranges were decreased by approximately 10% for every 1°C rise in outside temperature. This can be explained by the higher ventilation rates at higher temperatures diluting the particle concentrations inside the animal house. Also Papanastasiou et al. (2011) found, in a house for sheep and goats, a negative correlation between (inside) temperature and particle mass concentration in the different size areas. The numbers of particles $<1.0 \mu\text{m}$ were not affected by outside temperature within this study, while Papanastasiou et al. (2011) found a negative correlation. Within our study concentrations of particles $<1.0 \mu\text{m}$ were very similar outside and inside the animal house and therefore it was logical that the number of these particles inside was not affected by ventilation rate. The CMD of inside particles was significantly affected by the outside temperature. This is to be expected, given the previously mentioned effects of outside temperature on particle counts in size ranges $<1.0 \mu\text{m}$ (no effect) and on particle counts in size ranges $>1.0 \mu\text{m}$ (negative effect). The particle counts in the different size ranges inside the animal house were not significantly affected by outside relative humidity, although there was a tendency ($P=0.10$) for counts for $\text{PM}_{1.0-2.5}$ and for $\text{PM}_{2.5-10}$ to be lower at higher humidity levels. Papanastasiou et al. (2011) found a positive correlation between inside relative humidity and mass concentration of small particles ($<2.5 \mu\text{m}$) and a negative correlation between humidity and larger particles ($>2.5 \mu\text{m}$). The negative correlation with larger particles was confirmed within this study. For the positive correlation for smaller particles the former mentioned authors indicated that this could be caused by formation of fine secondary particles. This could, however, not be confirmed in this study. The decrease in the CMD of particles inside the animal house with increasing outside relative humidity might be caused by big particles settling faster at higher humidity levels or, as was also mentioned by Papanastasiou et al. (2011), by the fact that particles are less easily re-suspended in the air at higher humidity levels. The MMD was not affected by outside temperature or humidity. Cao et al. (2009) also found no significant effect of season (fall, winter, spring) on MMD for total dust particles in a

high-rise barn for layers.

We found significant correlations between the numbers of particles in the different size fractions. Correlation coefficients varied from 0.69 to 0.98 between PM_1 , $PM_{1-2.5}$, $PM_{2.5-10}$, and PM_{10-32} , with higher coefficients for size ranges that were close in size. This means that higher or lower dust concentrations generally give higher or lower particle concentrations in the whole range of particle size ranges. This was one of the assumptions when setting-up this study and using only short measurement period.

The comparison between the two aerosol spectrometers for the PM_{10} mass concentration showed good agreement in the lower concentration range up to 2.0 mg m^{-3} , but higher deviation from the line $Y = X$ at higher concentration levels. From this study it cannot be concluded which of the two spectrometers give the highest accuracy. To determine this a comparison should be made with reference samplers as was done in the studies of Zhao et al.(2009) and Van Ransbeeck et al. (2013). These results imply that care should be taken when using these kinds of equipment for determining absolute dust concentrations values. Spectrometers can be used for relative comparisons and for determining diurnal variations, but are not very suitable for determining absolute values. In the latter case parallel measurements with reference samplers, for calibration, are necessary.

This study shows that although large variations occur in particle counts in different size ranges and in CMD and MMD, most of the variation, except in the case of PM_1 , could be accounted for by species/housing combination and outside temperature and relative humidity.

5 Conclusions

From this study the following can be concluded:

- There are large variations in particle counts and mass in the different size ranges not only between and within animal species/housing combinations but also between farms of the same category and within farms.
- In terms of counts and mass, the dust concentrations in the different particle size ranges are generally higher in poultry houses than in pig houses, and are generally higher in pig houses than in cattle houses and mink houses.
- Particle counts and mass in mink and cattle houses were more or less similar to the particle counts and mass in outside air for all particle size ranges.
- Particle size distribution differs totally when expressed in counts or in mass, especially in poultry and pig houses.
- Particle counts in different size fractions were highly correlated. This means that higher or lower dust concentrations generally give higher or lower particle concentrations in the whole range of particle size ranges.
- Although large variations occur in particle counts in different size ranges and in CMD and MMD, most variation, except for PM_1 , could be accounted for by species/housing combination and outside temperature and relative humidity.

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