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Particulate matter reduction in exhaust gas from poultry keepings

Jochen Hahne, Julian Rump

In extensive test runs, the particulate matter reduction of different scrubbers for poultry exhaust air cleaning was investigated with aerosol spectrometers. The attainable particulate matter reduction depended on treatment setup and kind of the water distribution systems which may produce water aerosols and partially result in negative separation efficiencies at particle size diameters < 2.5 µm. At particle size diameters of 2.5–3.0 µm, the mean separation efficiency varied between 5.6 and 73.1% among the experimental plants. The separation efficiency generally increased with the particle size and varied between 56.4 and 97.6% at particle diameters of 6.5–7.5 µm. A constant positive particulate matter reduction over all particle sizes was only achieved using water distribution systems with a low operating pressure of 0.1–0.2 bar. The highest separation results among the scrubber systems were achieved in combination with a dry working dedusting unit. In comparison to the experimental plants with scrubbing units, the dry working electrostatic precipitator consistently showed higher particle separation efficiencies, even with shorter residence times. Especially at particle sizes < 3 µm, the dry working electrostatic precipitator outmatched all the scrubber systems.

Keywords
Particulate matter, aerosols, separation, exhaust air treatment, poultry keeping

Livestock in Germany ensures the production of high-quality and well-priced food, but also causes relevant odor, ammonia and particulate emissions. Exhaust air treatment systems are increasingly used to reduce these environmental impacts. In poultry keeping, single or two-stage scrubbers are used particulary (DLG-Prüfberichte 5952, 6254, 6260, 6271, 6344, 6212, 6397, 6406). If these systems are operated according to specification, extensive particulate matter reduction is ensured. For example, separation efficiencies between 70.7 and 87.9% were measured for total dust, 82.2–91.7 for PM_{10} and more than 98% for $PM_{2.5}$ (DLG-Prüfbericht 6406). During scrubber operation, aerosols are released which may contain bioaerosols besides dissolved nitrogen compounds. Actual measurements showed a relative bioaerosol proportion of 14% in the $PM_{2.5}$ fraction and 39% in the PM_{10} fraction (Gärtner et al. 2017). Measurements bei Clauß, Thuenen Institute (2018, personal communication) showed comparable results for laying hens with 15 and 35% and turkeys with 10 and 35% respectively. Clauß, Thuenen-Institute, estimates the relative proportion of bioaerosols in fraction > PM_{10} for poultry keeping with 60–65%. These results match separation efficiencies for total bacterial count amounting to 79–98 % which, for example, was determined in keepings for laying hens (DLG-Prüfberichte 6397 und 6406). Emission control measurements on biofilters and biotrickling filters in Bavarian livestock keepings have shown separation efficiencies of more than 90% for bioaerosols. The separation efficiency, however, decreased with increasing volume flows and accordingly shorter retention times (Bayerisches Landesamt für Umwelt).

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It was the aim of the work to measure the particulate matter emission of different test facilities with regard to the particle size range. These results should be the basis for a better process technology which improves the particulate matter and nitrogen separation one the on hand and reduces the release of aerosols and bioaerosols on the other. Another aim was the construction and operation of an electrostatic precipitator for particulate matter reduction to assess the potential of this method for poultry keeping.

Material and methods

The experiments for particulate matter reduction were carried out in three different test facilities under practical conditions using exhaust air from laying hen keeping. The raw gas composition and the particle number concentration was subject to daily and annual fluctuations and animal keeping conditions as well (Table 1). The data of particle number concentration was rounded in view of measuring accuracy.

Table 1: Composition and fluctuation range of raw gas from poultry housings (n = 99)

Parameter	Mean	Minimum	Maximum
Ammonia in ppm	4.1	0.3	25.7
Carbon dioxide in ppm	1,737	512	2,519
Relative humidity in %	54.0	42.7	69.1
Temperature in °C	20.0	18.5	23.9
Particle number concentration, rounded > 0,25 µm in 1/L	173,000	18,000	532,000

The raw gas from the laying hen stables showed with mean values between 9,000 and 46,000 per liter relative high particle number concentrations (≤ 0,45 µm). Up to a particle size of 3.5 µm, particle number concentrations remained with 900–3,000 particles per liter at a relatively constant level. Above a particle size of 5 µm, the particle number concentration rapidly decreased to values < 300 particles per liter (Figure 1). For experiments with the electrostatic precipitator (test facility 4) ambient air was enriched with dust which had been collected from the dust filter fleece of test facility 3 over a longer period.

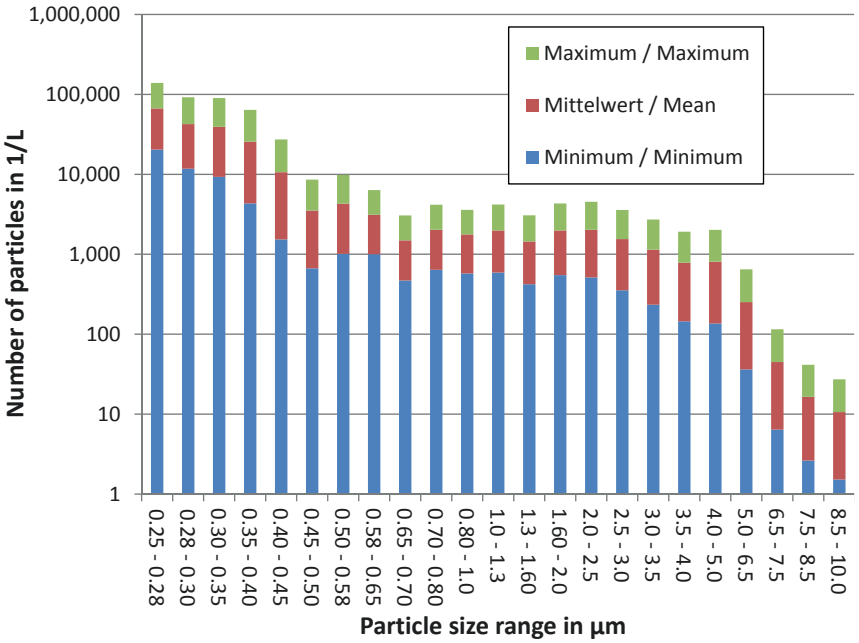

Figure 1: Mean particle size distribution in the exhaust air of laying hen keeping

For particulate matter measurement in raw and clean gas, two identical aerosol spectrometers (Grimm, Portable Aerosol Spectrometer, Model 1.109, Ainring) were used. The simultaneous measurements were executed for at least 60 minutes, whereat single meaurements of one minute were summarized to mean values. The comparability of both aerosol spectrometers was checked after each measurements via reference measurement with purge air. For further assessment, the daily generated results were averaged again. The measurements in the test facilities were carried out from December 2016 to January 2017 (test facility 1, n = 13), from July 2015 to March 2016 (test facility 2, n = 54) and from October 2016 to April 2017 (test facility 3, n = 32). Both experiments with the electrostatic precipitator were carried out over 45 and 59 minutes, respectively, on two different days and evaluated in the same way.

The test facilites 1–3 were operated with overpressure using a pressure stable ventilator (400 m³/h at 550 Pascal (Pa); Hürner Funken, Mücke) which was controlled by a frequency converter (Danfoss, Norborg). An ultrasound gas meter (Sick Maihak, Hamburg) was used for detection of the air velocity in the raw gas. The volume flow was then calculated from the inner diameter of the raw gas pipe (100 mm) and the air velocity. Gas temperatures and humidities were measured with probe systems (Vaisala, Vantaa). For the detection of pressure drops pneumatic working senors were used (halstrup walcher, Kirchzarten).

Test facilities and test conditions

The test facility 1 (Figure 2) consisted of three moistened cleaning stages (2, 3 und 4) filled with plastic packing (25 mm Hiflow rings). While the first cleaning stage was permanently operated with a rigid irrigation system and an irrigation density of 4 m³/(m² h), the following two cleaning stages were operated with a mobile irrigation system, analogous to test facility 2. The irrigation density was also 4 m³/(m² h) but the power-on time of each sprinkler was only 50 %. The layer thickness of the carrier material was 150 mm in the cleaning stages 1 and 2 and 100 mm in cleaning stage 3.

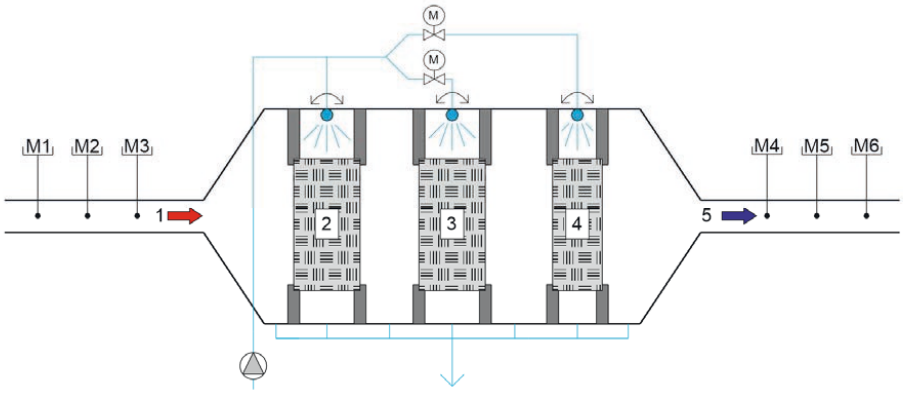

Figure 2: Schematic diagram of the experimental plant 1 (1: raw gas; 2: first cleaning stage; 3: second cleaning stage; 4: third cleaning stage; 5: clean gas; M1: particles in raw gas; M2: humidity in raw gas; M3: temperature in raw gas; M4: Temperature in clean gas; M5: particles in clean gas; M6: humidity in clean gas)

Test facility 2 (Figure 3) consisted of three cleaning stages. The first dry cleaning stage (2) was filled with wood chips (layer thickness 150 mm), while the following cleaning stage (3) filled with wood chips (150 mm) was irrigated intermittently with an irrigation density of 0.016 m³/(m² h). The final cleaning stage was equipped with a rigid irrigation system and filled with plastic carrier material (25 mm Hiflow rings). The irrigation with acidic washing liquid and an irrigation density of 4 m³/(m² h) operated permanently.

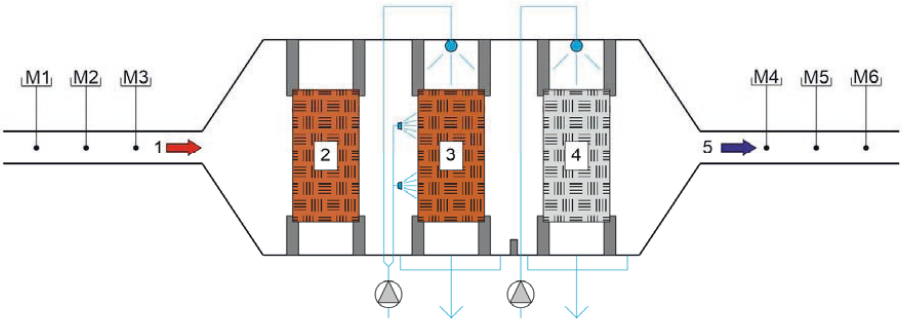

Figure 3: Schematic diagram of the experimental plant 2 (1: raw gas; 2: first cleaning stage; 3: second cleaning stage; 4: third cleaning stage; 5: clean gas; M1: particles in raw gas; M2: humidity in raw gas; M3: temperature in raw gas; M4: Temperature in clean gas; M5: particles in clean gas; M6: humidity in clean gas)

Test facility 3 (Figure 4) consisted of a dry dedusting unit (2) and two downstream working cleaning stages which were irrigated intermittently (3 and 4). For the removal of coarse dust particles a commercially available filter fleece (Typ HS-15/150, Luftfilterbau GmbH, Kiel) was used in cleaning stage 1. The automatically working fleece regeneration started when the pressure drop exceeded 80 Pa in this unit. The pressure drop of the unloaded system was 40–50 Pa. Both following cleaning units, equipped with 25 mm Highlow rings, were irrigated with mobile irrigation systems (Typ Zoom-Max, Gardena GmbH, Ulm) and worked with irrigation densities of 4 m³/(m² h). The power-on time was, however, only 30 minutes per hour.

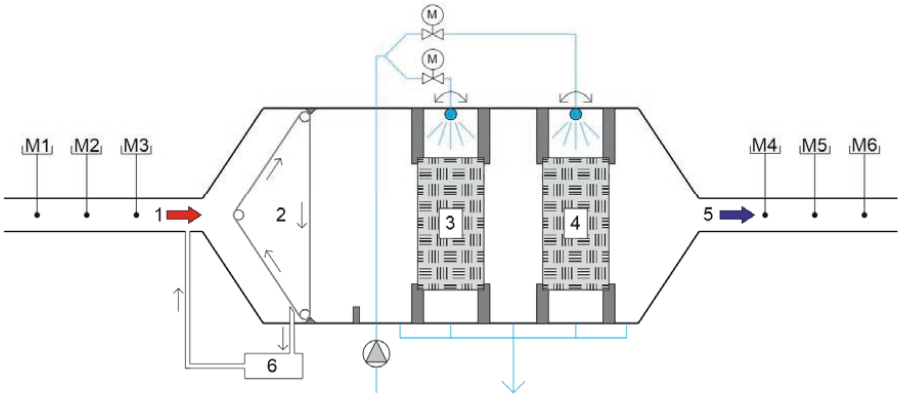

Figure 4: Schematic diagram of the experimental plant 3 (1: raw gas; 2: dedusting unit; 3: second cleaning stage; 4: third cleaning stage; 5: clean gas; 6: fleece cleaning; M1: particles in raw gas; M2: humidity in raw gas; M3: temperature in raw gas; M4: Temperature in clean gas; M5: particles in clean gas; M6: humidity in clean gas)

An electrostatic precipitator (Figure 5) was used as test facility 4. The cleaning unit consisted of a vertical aluminium pipe (d = 200 mm, l = 1,704 mm). The raw gas was sucked through the test facility via a pressure-stable ventilator (790 m³/h at 240 Pa; Funken Kunststoffanlagen, Hennef Sieg) which was controlled by a frequency changer (Hitachi, Chiyoda). Then, the air flow passed a honeycomb grid to generate a laminar flow in order to ensure a correct measurement of the flow velocity by means of a hydrometic anemometer (Ahlborn Mess- und Regelungstechnik, Holzkirchen). After measuring of the flow velocity (M1) particles were metered into the gas flow (M2). For this purpose, a rate-controlled particle feeder (Palas, Karlsruhe) was used. After passing the raw gas measuring point (M3), the air flowed at an angle of 90° into the measurement section (l = 1,704 mm). After another 90° direction change the outlet gas passed the measuring point for clean gas particle number concentration. In addition to that, the pressure drop of the electrostatic precipitator was measured (halstrup-walcher, Kirchzarten). The required high-voltage (DC) provided by a high tension generator (iseg Spezialelektronik, Radeberg) was measured with a multimeter (Voltkraft, Wollerau).

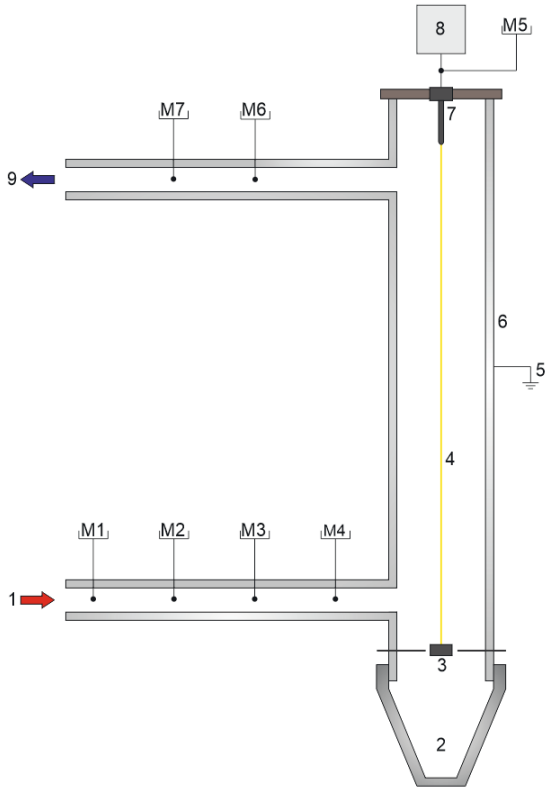

Figure 5: Schematic diagram of the experimental plant 4 (1: raw gas; 2: dust bunker; 3: fixed weight; 4: spray electrode; 5: earthing; 6: collection electrode; 7: isolator; 8: high voltage transformer; 9: clean gas; M1: flow velocity; M2: particle dosing feeder; M3: particle in raw gas; M4: pressure difference raw gas; M5: multimeter; M6: pressure difference clean gas; M7: particle in clean gas)

The relevant test conditions are specified in Tables 2–5. It must be pointed out that the mean air flow in the electrostatic percipitator was significantly higher with 2.7 m/s than in the other test facilities 1–3 with 0.7–0.74 m/s. Nevertheless the mean pressure drop of the electrostatic precipitator was comparatively low with 37.5 Pa. The mean particle number concentrations were lower at the experiments with electrostatic precipitator, but the particle size distribution in the collected dust was absolutely comparable to the particle size distribution in the raw gas. Nearly 72% of the particle number concentration in the collected dust was in a size range between 0.25 and 0.45 µm, while 87% was in the raw gas of the laying hen keeping.

Table 2: Test conditions at the experimental plant 1 (n = 13)

Parameter	Mean	Minimum	Maximum
Flow velocity in m/s	0.70	0.69	0.71
Pressure loss in Pa	29	24	38
Relative humidity, raw gas in %	50.7	43.0	60.7
Temperature in raw gas in °C	19.2	18.7	20.2
Particle number concentration, rounded > 0,25 µm in 1/L	149,000	33,000	227,000

Table 3: Test conditions at the experimental plant 2 (n = 54)

Parameter	Mean	Minimum	Maximum
Flow velocity in m/s	0.72	0.61	0.83
Pressure loss in Pa	99	60	175
Relative humidity, raw gas in %	55.4	45.0	69.1
Temperature in raw gas in °C	20.4	19.3	23.9
Particle number concentration, rounded > 0.25 µm in 1/L	159,000	18,000	337,000

Table 4: Test conditions at the experimental plant 3 (n = 32)

Parameter	Mean	Minimum	Maximum
Flow velocity in m/s	0.74	0.69	0.80
Pressure loss in Pa	96	69	119
Relative humidity, raw gas in %	53.0	42.7	63.1
Temperature in raw gas in °C	19.6	18.5	20.9
Particle number concentration, rounded > 0.25 µm in 1/L	208,000	67,000	532,000

Table 5: Test conditions at the experimental plant 4 (n = 2)

Parameter	Mean	Minimum	Maximum
Flow velocity in m/s	2.67	2.63	2.70
Pressure loss in Pa	37.5	35.0	40.0
Applied voltage in kV	26.69	26.69	26.69
Particle number concentration, rounded > 0.25 µm in 1/L	117,000	40,000	193,000

Results

The test facilities 1–3 operated with irrigated srcrubber units producing fine aerosols which were detected as particles by the aerosol spectrometers. In average (n = 2), the measurements with testing facility 3 and filtered ambient air showed a production of particles in particle size ranges between 0.5 and 5 µm. An explicit increase by eighteen to fiftyfold was registered at particle sizes < 2 µm (Figure 6). At particle sizes between 2.0 and 4.0 µm the particle number concentration was higher by a factor of 2 up to 6 in relation to the filtered ambient air. Above a particle size of 5 µm there was no particle production found anymore.

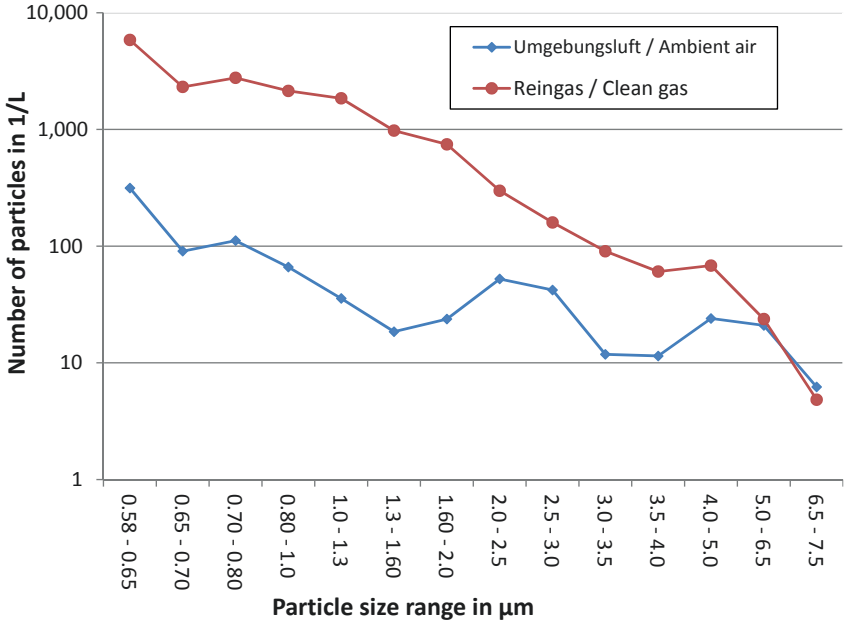

Figure 6: Particle production by sprinkling in experimental plant 3 using filtered ambient air as raw gas

Test facility 1

During operation of test facility 1, a mean raw gas cooling of 2 °C and a 48% uprating of the relative humidity was measured (n = 13). The clean gas temperature was 17.6 °C and the relative humidity amounted to 99.5 %. A positive particle separation in average was only achievable at a particle size of more than 2.5 µm with raw gas particle number concentrations of 149,000 ± 63,000. The separation efficiencies varied between 5.6% (particle size 2.5–3.0 µm) and 56.4% for the particle size range of 6.5 to 7.5 µm (Figure 7).

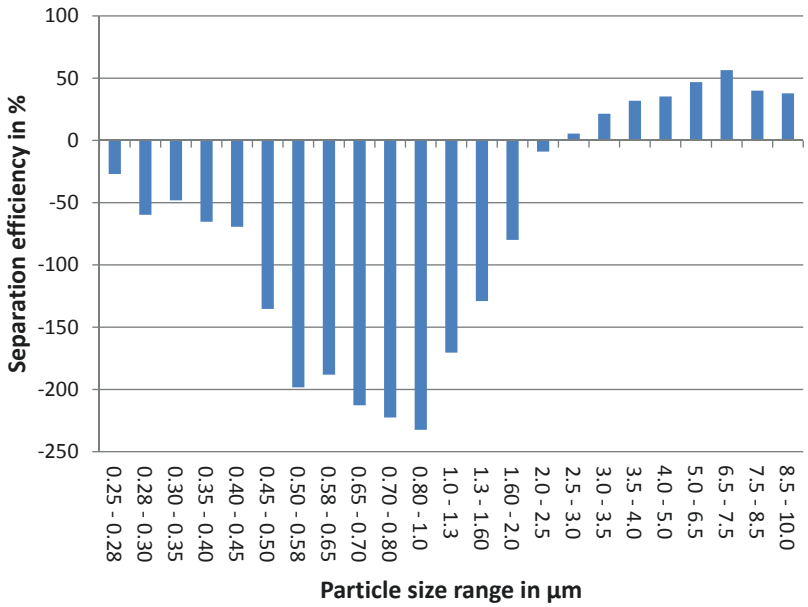

Figure 7: Mean particle separation at experimental plant 1

The dissatisfying particle separation may be due to the formation of water aerosol by the irrigation system operating with pressures between 0.5 and 0.7 bar. For the assessment, it was supposed that the signal strengh of solid particles in the raw gas and the signal strength of water aerosols formed during exhaust air treatment is equivalent.

Test facility 2

During operation of test facility 2, a mean raw gas cooling of 2.5 °C and an increase of 35.5% in relative humidity was measured (n = 54). The clean gas temperature was 17.9 °C and the relative humidity amounted to 90.9 %. At particle number concentrations of 159,000 ± 89,000 per liter the mean separation efficiency (n = 54) by a comparable filter surface load of 2.576 m³/(m² h) was clearly better over all particle sizes in test facility 2 compared to test facility 1. While the mean separation efficiency for a particle size range of 2.5–3.0 µm was 5.6% for test facility 1, it was 43.3% for test facility 2. Also for the particle size range of 6.5–7.5 µm the mean separation was clearly better with 83.2% than in test facility 1with 56.4%. The working pressure of the rigid irrigation systems was between 0.1 and 0.2 bar and may have contributed to a lower water aerosol formation and, thus, to a comparatively better particle separation as well. Another important aspect is the achieved relative humidity in the clean gas which was lower with 90.9% only compared with the results of the test facilities 1 and 3. Condensation of water vapor is unlikely under these conditions. This is supported by the predominantly positive separation results for particle sizes < 1.3 µm.

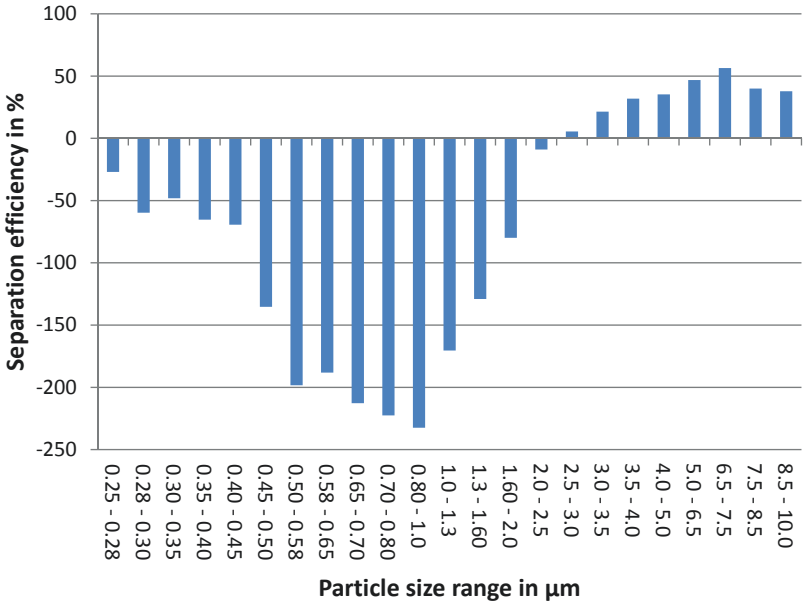

Figure 8: Mean particle separation at the experimental plant 2

Test facility 3

During operation of test facility 3, a mean raw gas cooling of 2.8 °C and an increase of 46.8% in relative humidity was measured (n = 32). The clean gas temperature was 16.9 °C and the relative humidity amounted to 99.8 %.

Analogous to the results of test facility 1, a considerable production of particles < 2.0 µm was detected. However, with maxim values of −79 % (particle size range 0.5–0.58 µm), it was lower than in test facility 1 with values up to −243 % (particle size range 0.8–1.0 µm). An essential reason for the water aerosol production may also be attributed to the working pressure of 0.5 to 0.7 bar in the irrigation system in spite of its intermittent operation. A positive particle separation was measured from a particle size range > 2.0 µm with 54.1% (Figure 9). The mean separation efficiency (n = 32) for a particle size range of 2.5–3.0 µm was 73.1% and increased to 97.6% for a particle size range of 6.5–7.5 µm.

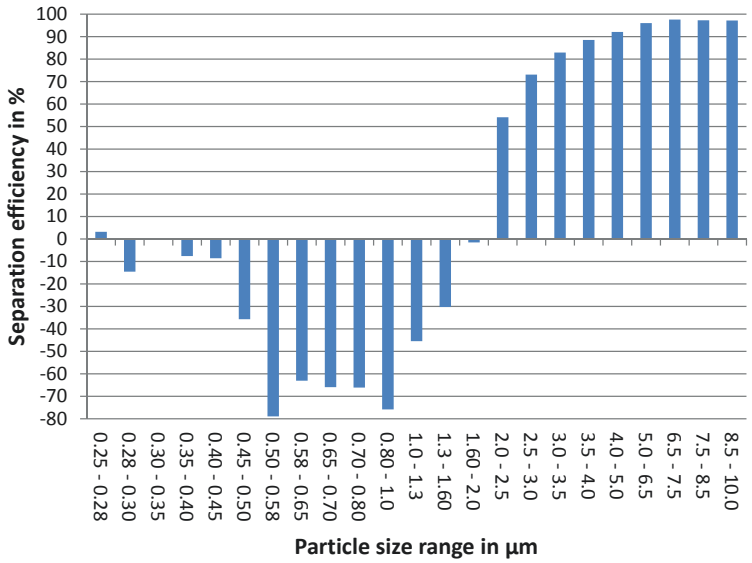

Figure 9: Mean particle separation at the experimental plant 3

Test facility 4

The initial tests for particle separation in a home-made electrostatic precipitator showed significantly higher separation results compared to the scrubber systems (Figure 10). Due to the dry operation of the system, no water aerosols were produced and the mean particle separation was 68.1% even at a particle size range of 0.25–0.28 µm. At a particle size range of 2.5–3.0 µm, the separation was 90.6% and for a particle size range of 6.5–7.0 µm 98.8%.

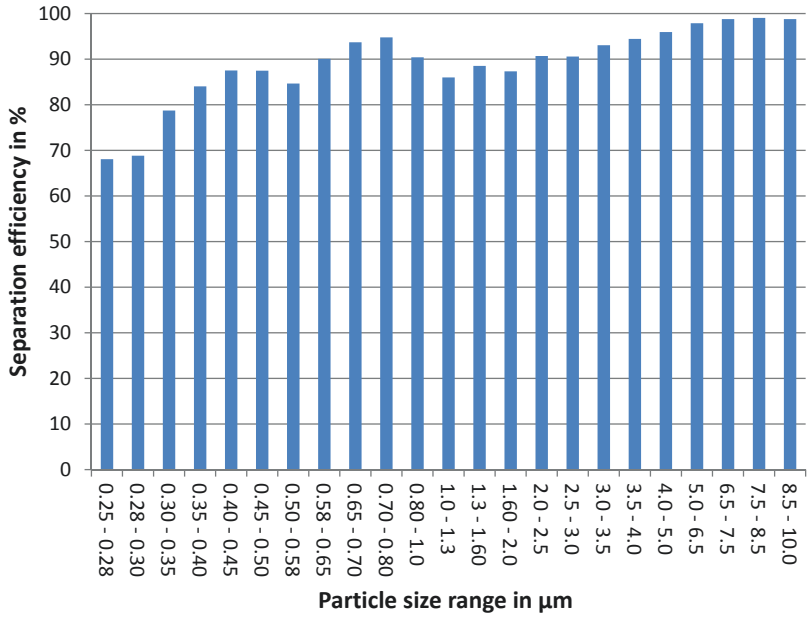

Figure 10: Mean particle separation at the experimental plant 4

The comparative analysis of the achieved separation results showed for selected particle size ranges a substantially higher separation efficiency of the electrostatic precipitator compared to scrubber systems (Figure 11). Both tests with the electrostatic precipitator do not allow a prediction concerning the long term performance of the system. Without regular cleaning of the precipitator an increasing covering of the collecting electrode could lead to a reduction of particle separation.

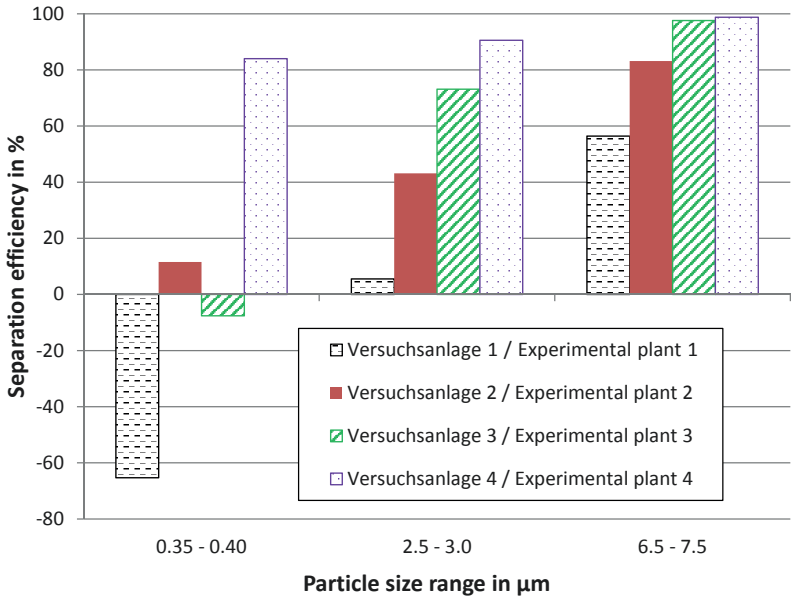

Figure 11: Comparison of particle separation at the different experimental plants

Only for a particle size range of 6.5–7.5 µm, test facility 1 with three irrigated stages without droplet catcher achieved a considerable particle separation. A nearly permanent positive and more effective particle separation was achieved in test facility 2 with two wood chips stages and a final scrubber stage. For particles > 3.0 µm, the separation efficiency of test facility 3 with filter fleece and two subsequent scrubber stages was nearly comparable with the results of the electrostatic precipitator, but not for lower particle sizes < 3.0 µm.

Discussion

The results for particle separation with scrubbers show that these systems contribute to water aerosol emissions up to particle sizes of 5.0 µm, especially when irrigation systems were used at working pressures > 0.5 bar. For spraying towers and packed columns cut sizes between 0.7 and 14 µm were measured. The cut size describes the particle diameter at which 50% of all particles can be separated (VDI-RL 3679 Blatt 1). At best, the cut sizes were 6.5–7.5 µm (test facility 1), 3.0–3.5 µm (test facility 2) and 2.0–2.5 µm in test facility 3. The cut size of the electrostatic precipitator, however, was < 0.25 µm.

But also for particle size ranges of more than 10 µm, a quantitative separation was not achieved. The separation efficiency for the particle size range of 8.5–10 µm varied between 37.8% (test facility 1), 80.2% (test facility 2), 97.2% (test facility 3) and 98.8% for the electrostatic precipitator. For the assessment of these results, however, it should be taken into account that the particle number concentration in this fraction with less than 20 particles per liter was very low (Figure 1). It can be assumed that the particles could not be separated quantitatively from the raw gas. It is unlikely that these particles were produced during irrigation because all irrigation systems only created particles < 5 µm.

Besides the evaporation, the release of water aerosols caused an increased water loss which had to be compensated by fresh water supply. The water loss conditioned by evaporation and water aerosol release amounts to 0.05 m³ per animal place and year for laying hens and 0.02 kg m³ per animal place and year for broilers. Water loss can be reduced by using an improved operation design and selecting a water distribution system with low working pressure.

Besides water also dissolved nitrogen compounds as ammonium (in chemical scrubbers) and ammonium, nitrite and nitrate (in biological scrubbers), respectively, can be released into the environment. On the basis of current DLG test results, the nitrogen loss via aerosol release is comparatively low with 0.05–0.08 mg N/m³ clean gas (DLG-Prüfbericht 6406). The aerosol proportion in view of nitrogen losses, however, can become more important by decreasing NH_3 concentrations in raw gas and higher concentrated nitrogen concentrations in the washing liquid.

DLG tested scrubbers enable a reduction of bioaerosol emission in a range of 90% (DLG-Prüfbericht 6397 and 6406). With a proper operation of exhaust air treatment systems which preferably secure an extensive particle reduction starting from 2.5 µm a corresponding reduction of bioaerosols can be expected, because bioaerosols can predominantly be verified in major particles sizes (Gärtner et al. (2017) and Clauß, Thuenen-Institute (personal communication).

The comparatively high void fractions of the packing in test facility 1 probably is the reason for the marginal particle separation efficiency. This becomes apparent by means of the low pressure drops compared to the test facilities 2 and 3 (Tables 2–4). A sufficient bioaerosol reduction would be questionable in exhaust air treatment systems operating analog to test facility 1.

The comparatively very good particle separation efficiencies of the electrostatic precipitator have to be assessed in view of the overall targets of exhaust air treatment (particulate matter, ammonia and odor reduction). Because an electrostatic precipitator can not contribute to relevant ammonia and odor reduction, its use can only be one treatment step and has to be combined with an additional treatment for nitrogen and odor removal. The latter might contribute again to an aerosol production if scrubbers are used for it. However, for particlulate matter reduction an electrostatic precipitator might be an interesting option, for example, in view of cleaning of circulating air in stables in combination with an activated carbon filter for ozone reduction.

Conclusions

Properly operating exhaust air scrubbers ensure effective reduction of particles with particle size diameters > 5 µm, but also contribute to the release of water aerosols with smaller particle sizes. These aerosols may contain dissolved microorganisms and nitrogen compounds. An essential starting point to reduce the emission of these aerosols are water distribution systems with low working pressure.

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Authors

Dr. Jochen Hahne is research associate at the Thuenen Institute of Agricultural Technology, Bundesallee 47, 38116 Braunschweig, Email: jochen.hahne@thuenen.de

Julian Rump is certified technician and contributed to this work as a former colleague.