Reducing Dust and Gas Emissions using an Aerodynamic Deduster

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ABSTRACT

Dust and ammonia are two major air pollutants that are emitted from confinement animal feeding operations (CAFO) as well as odor. Many air-cleaning technologies are available, but most of them are not applicable for CAFO pollutant control not only because they are out of typical CAFO owners’ budget, but also because few of them are able to reduce the emission of these three pollutants simultaneously. There is a need for a cost effective device that can reduce simultaneously dust, ammonia and odor. The diffusion-coagulation-separation (DCS) system was developed based on this need. Performances of two prototypes are summarized in this paper followed by an update of the latest field evaluation of a vertical prototype of simpler structure. Comparison between the performances of two field-scale prototypes was provided for future system optimization. The vertical prototype contains fewer concentric multi-annual dedusters, which decreased slightly the dust removal efficiency. On the other hand, the gas removal efficiency increased significantly due to the longer residence time for gas removal. What is more, the vertical DCS is simple in structure and cost less in manufacture and operation. The design of next generation DCS system was recommended based on the field evaluations of these two pilot scale prototypes. A vertical setup is recommended in favor of long residence time, little space requirement, and higher stack for faster emission dilution. In addition, more nozzles at the lower stage and longer separation section are recommended. The next generation DCS, prototype #3, is expected to have higher efficiency for both dusty and gaseous pollutants without increasing too much cost.

Keywords: Dust emission, ammonia emission, air cleaning, diffusion-coagulation-separation (DCS) system, and deduster

INTRODUCTION

Dust and toxic gases emitted from confinement animal feeding operations (CAFO) have been major concerns to the public, scientists, and government agencies. Primary health problems are associated with CAFO indoor environments stem from a complex mixture of hazardous airborne dust particles carrying ammonia, bacteria, and odor. Possibilities for control of dust emission have been extensively reviewed (Carpenter 1986, Dawson 1990, Zhang 1999, Tan and Zhang 2002). Common strategies for dust control include source control, ventilation, and dust separating from the air stream with air cleaning devices including cyclones, filtrations, wet scrubbers, electrostatic precipitators (ESPs), and so on. However, devices that are applicable for CAFO dust control are limited due to the special property of CAFO indoor air and the limitation in most owners’ budget. Therefore, a facility that can simultaneously reduce the emission of dust and ammonia is desired.
Advances in air cleaning technologies have made a cost-effective device possible for CAFO emission control by combining the following technologies. An aerodynamic deduster as shown in Figure 1 was developed by Christianson et al. (1999). Laboratory test results showed that this uni-flow aerodynamic deduster could efficiently separate the particle at a cut size of 1 or 4.5 μm, depending on the particle sizing instruments, and the dust collection efficiency based on mass was over 85% at a pressure drop of about 150 Pa. Although only dry particles were tested in lab, the deduster was anticipated to be able to separate other particulate matters including CAFO dusts and liquid droplets from air stream, because it operated at a non-contact format. In addition, wet scrubbers have been proved able to remove gaseous pollutants. Therefore, it is possible to remove part of the odorous gases while removing dusts by combining the wet scrubber with the aerodynamic deduster, because gaseous and fine particles can be captured by large particulates such as water droplets by taking advantage of the diffusion of gas molecules and small particles and the coagulation among particles in various sizes.

![Figure 1. Aerodynamic deduster](image)

A diffusion-coagulation-separation (DCS) system is developed based on the principle described above. It combines the technologies of aerodynamic deduster and wet scrubber. Before this paper, two prototypes, laboratory scale- and field scale- prototypes, have been developed and tested in lab and field, respectively. The corresponding design and test results have been reported elsewhere (Zhang et al. 2002), and a summary is provided as following

**LABORATORY SCALE PROTOTYPE**

The laboratory scale prototype was developed base on the 288 cfm uniflow aerodynamic deduster. The prototype was built by attaching a wet-scrubber (diffusion-coagulation section) in the front of the deduster (see Figure 2). The wet scrubber was a metal elbow acting as a hood. The laboratory test results showed that the prototype diffusion-coagulation-separation air cleaner (DCS) could effectively remove both dust and ammonia from an air stream. The overall dust removal efficiency was 85% and 57% ammonia removal was observed at the combination of 60% power with 10 ppm NH₃ concentration.
FIELD-SCALE PROTOTYPE #1

Based on the 288 cfm bench scale prototype, a 4,000 cfm pilot scale prototype #1 was designed and fabricated. As shown in Figure 3, prototype #1 contained three concentric annual dedusters. The outer cylinder of a smaller deduster serves as the inner cylinder of a bigger one. Therefore, the total air delivery is increased without increasing the overall volume of the unit. The diameter of the exhaust fan is 21”.

Figure 3. Schematic of the 4,000 cfm deduster

The water reclamation efficiency test showed that about 90% water could be collected by the catch basin and water collection box. The water loss was less than 10%. The air flow rates of the DCS at different power levels are shown in Figure 4. The air flow rate decreases as the static pressure increases.
Field evaluation results showed that the dust mass removal efficiency was 91% at 60% power and 89% at 100% power respectively. There was a reduction in NH$_3$ observed at different power level. The ammonia removal efficiency was about 25%. Due to the low NH$_3$ field concentration in summer, it was difficult to evaluate the ammonia removal efficiency. It is worthy to note that the total dust mass removal efficiency was higher than a deduster without a wet scrubber section, because particle reentrance was greatly reduced.

The preliminary results indicated that the longer the retention time is, the higher the gas removal efficiency. However, the residence time was limited by the horizontal setup. A vertical DCS is recommended in order to attain longer residence time. In addition, four sets of concentric dedusters made the system complex and expensive in construction and maintenance. A DCS with fewer vanes is expected for the consideration of investment. This paper summarizes and updates the development of DCS system as a cost effective device for emission reduction of dust and toxic gases from CAFO.

**VERTICAL PROTOTYPE**

Based on previous studies, another vertical field scale prototype (prototype #2) was developed. The total height of this prototype is about 15 ft (4.5 m). The outer tube is 30” in diameter. As shown in Figure 5, it contains four parts connected via flanges: an elbow, diffusion and coagulation section, separation section, and an exhaust fan. To differentiate it from its predecessor, this prototype is termed vertical prototype, because it was mounted vertically with fewer space requirement. For comparison purpose, the exhausting fan that was also used in horizontal prototype was used in the vertical prototype to maintain a 4,000 cfm capacity. A variable frequency controller was connected to the fan to adjust the power and speed of the fan.
The main purpose of this prototype was trying to achieve same even better performance with simpler structure. Instead of three sets of dedusters as in the horizontal deduster, the vertical one is composed of two concentric annual dedusters. The outer cylinder of a smaller deduster serves as the inner cylinder of a bigger one. Therefore, the total air delivery could be increased without increasing the overall volume of the unit. The polluted air enters the system via the elbow, which changes the airflow direction from horizontal to vertical. Diffusion and coagulation section was made of plastic, inside which are only three BETE PJ40 nozzle installed at different elevation along the centerline of the tubes. Mist was generated by these nozzles when water was supplied. Gas molecules and fine particles diffuse to liquid mists, and small particles coagulate with (attract to) each other to form larger particulates. The amount of nozzles in the vertical prototype is much less than that in the horizontal one. It was expected to reduce significantly the water consumption by reducing nozzle amount. Large particles and droplets are separated from the air stream when the mixture enters the separation section. Instead of 3 sets of vanes in prototype #1, there are only two sets of vanes in prototype #2, which reduced much labor and cost in manufacture. The vanes are manufactured by Bob’s machines shop, and they were glued on the tubes. Two sets of vanes, big vanes and small vanes, are employed in the collection zone. Big vanes are located between the outer tube and the mid-tube, and the small vanes are located between the mid-tube and the inner tube.

FIELD EVALUATION

The DCS system was mounted on the sidewall of a swine building at Moorman swine research farm. Spray water was supplied by the onsite water line without pressure control, trying to operate as close to real situation as possible.
Dust removal efficiency measurement

The inlet and outlet dust concentrations were measured using two identical dust collection systems, which are similar to that developed by Wang et al. (1999). Each system contains three glass fiber filters, three filter holders, three critical venturi, an electrical air pump, and some plastic tubing. The pore size of the filters is 0.8 µm. Filters were 37 mm (in diameter) filter holders. Both the filters and their holders are from Millipore Aerosol Analysis Monitor, Inc. Critical venturi connected to downstream of the filters and the pump was used to keep the constant air flow rate of 20 l/s for each filter.

Both dust collection systems were calibrated in BESS lab before they were put in field, one for inlet and the other for the outlet of the vertical deduster. The system for inlet was placed inside the building to measure dust mass concentration, and the one for outlet was placed on a frame above the exhaust fan. The filter surfaces were kept perpendicular to air flow. After both systems running simultaneously for 24 hours, the filters were dried in TCC laboratory and weights recorded. The weight collected at inlet or outlet of DCS was obtained by averaging the dry dust weights on three filters in corresponding dust collection system. Then the dust removal efficiency of prototype #2 was calculated using the following equation.

\[
\eta_{dust} = \left(1- \frac{Average \ outlet \ dust \ mass}{Average \ inlet \ dust \ mass}\right) \times 100\% \tag{1}
\]

Ammonia removal efficiency measurement

Ammonia concentration was measured manually using colorimetric gas detector tubes for ammonia with an aspirating pump. The ammonia detector tubes are Precision Gas Detector Tubes Nos. 105SC, 120SD, and 182U from Matheson-Kitagawa, Inc, N.J. Their range is 0.2-20 ppm with a detectable limit of 0.1 ppm. The scale of the detector is marked as 1, 2, 4, 6, 8, …, 20 in ppm. The aspirating pump is 1 pump stroke also from Matheson-Kitagawa, Inc, N.J.

The inlet and outlet ammonia concentrations were measured to estimate the gas removal efficiency of prototype #2. Preliminary tests showed that the gas concentration at either inlet or outlet was not uniformly distributed, several sampling points were selected and the average concentrations were used for calculating the ammonia removal efficiency.

\[
\eta_{NH_3} = \left(1 - \frac{Average \ outlet \ NH_3 \ concentration}{Average \ inlet \ NH_3 \ concentration}\right) \times 100\% \tag{2}
\]

Since a gas detector tube can only be used once, only five or six of the representative points (see Figure 6) at each surface were sampled considering that the ammonia detector tubes are relatively costly.
RESULTS AND DISCUSSION

The dust removal efficiencies at different fan power levels are shown in Figure 7. The dust removal efficiency was about 71%, 77%, and 75% when the fan operated at 60%, 80%, and 100% of its full power, respectively. Since these data were obtained under different operation conditions such as different humidity, temperatures, and wind speeds, it is temporarily concluded that the overall dust removal efficiency of the DCS falls in the range of 70%-80%. It also indicated that the fan power level had slight influences on the dust removal efficiency; this confirmed the similar results obtained from prototype #1, where dust removal efficiency changed from 91% to 89% when fan power varied from 60% to 100%.

Note that the sampling location inside the building is 3 ft away from the inlet surface, where the air velocity is much lower than that at the DCS inlet surface. According to Bernoulli equation,

\[ P + \frac{1}{2} \rho v^2 + \rho gh = \text{constant} \]  

[3]

air was compressed while flowing towards the inlet surface of the DCS system. Therefore, the dust concentration sampled should be lower than that entering the DCS system, which means that the overall dust collection efficiency might be less estimated and the real dust removal efficiency could be higher than 80%. Further quantitative investigation is needed for testing conclusion.

Figure 6. Potential ammonia concentration sampling points on the imaginary surfaces of inlet and outlet.
Figure 7. Dust removal efficiency vs. fan power level.

Figure 8. NH$_3$ removal efficiency vs. fan power level.

Ammonia removal efficiencies at different fan power levels are shown in Figure 8. The data were obtained from the same tests, and there were no obvious changes in operation conditions. The highest ammonia removal efficiency of 38% was obtained at the 80% fan power level. The efficiency was barely the same at 60% and 80% power levels, but that was much lower at 100% power level. The overall trend indicated the relationship between the gas removal efficiency with residence time.

There was only one nozzle at each stage, and spray was not able to cover all the cross section of the outer tube. As illustrated in Figure 9, the outer tube of the DCS is 30”, but the coverage of a single nozzle spray was only 24” in diameter. There was a large fraction of the pollutants that could not be captured by the droplets at first time. The gas removal efficiency could have been higher if more nozzles had been installed on the same level.

Figure 9. Schematic of the spray coverage problem
Ammonia concentration was less than 4 ppm due to the limited amount of pigs in the swine building, and the high ventilation rate in the early summer. The ammonia removal efficiency could be higher if more pigs had been housed or in winter, when ammonia concentration is usually higher.

By the way, maldistribution of ammonia distribution at the inlet surface was observed. Awareness should be taken in future measurements. Table 1 summarizes the ammonia concentrations (in ppm) at different sampling points. The average values are illustrated in Figure 10. Higher concentration was found at the bottom edge of the inlet surface than other points.

Table 1. Ammonia concentration maldistribution at the DCS inlet (ppm)

<table>
<thead>
<tr>
<th>Fan Power</th>
<th>P0</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 %</td>
<td>2.8</td>
<td>2.0</td>
<td>3.0</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>80 %</td>
<td>2.5</td>
<td>2.2</td>
<td>2.5</td>
<td>3.9</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>-</td>
<td>2.0</td>
</tr>
<tr>
<td>100 %</td>
<td>2.1</td>
<td>-</td>
<td>-</td>
<td>3.8</td>
<td>1.2</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>2.1</td>
</tr>
<tr>
<td>Average</td>
<td>2.5</td>
<td>2.1</td>
<td>2.8</td>
<td>3.7</td>
<td>1.2</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Figure 10. Ammonia concentration maldistribution at the DCS inlet (in ppm)

Although the bench scale prototype showed uniform distribution of outlet ammonia concentrations, it was not so for prototype #2. This might be due to the apparent different sizes between the fans, the different air flow patterns, and the different supplied powers. There was certain ammonia concentration maldistribution at the outlet, but not so obvious as that at inlet.

The simple structure, few spatial requirement, and low cost of the new generation were achieved at the price of lower overall performance of the vertical DCS. On one hand, the long residence
time increased over efficiency, but on the other hand, the air pollutant removal efficiencies were lower than the horizontal one due to the following over-simplified designs.

In the diffusion and coagulation section, turbulent flow is expected, while high turbulence intensity in separation section will reduce the droplet separation efficiency. Since there were only two sets of vanes in the separation section, the gaps of each concentric deduster were wider, which would increase the turbulence intensity and decrease the particle separation efficiency. This might also explain why some droplets were not separated from the air stream but were observed at the exit of the DCS system.

**SUMMARY AND RECOMMENDATIONS**

Up to date, one bench scale and two pilot scale prototypes, #1 and #2, were designed and evaluated. There was one deduster, three concentric annual dedusters, and two concentric annual dedusters in the bench scale prototype, pilot scale prototype #1 (the horizontal prototype), and pilot scale prototype #2 (the vertical prototype), respectively.

The experimental evaluation results provided valuable data for future optimum DCS system design. All the test results indicated that the longer the gas residence time, the higher ammonia removal efficiency. However, dust removal efficiency was not significantly affected by the residence time (i.e., fan power levels), and the amount of concentric dedusters did not influence the dust removal efficiency.

The pilot scale prototype #1 was complex in structure and cost much to manufacture. The advantage of it is that high dust removal efficiency (90%) was achieved due to more concentric annual dedusters with longer separation section. On the other hand, the ammonia removal efficiency was very low (25%) due to short gas residence time, which is limited by its horizontal orientation.

The pilot scale prototype #2 was designed and installed vertically for more gas residence time. At the same time, the structure was much simpler than its predecessor was. The amount of concentric annual dedusters was reduced half, and the separation section time was shorter than that in prototype #1. The overall performance was better than that of prototype #1. The dust removal is dropped slightly from 90% to 80%, but the ammonia removal efficiency increased significantly from 25% to 38%, which could be even higher if more nozzles had been installed.

Based on the field evaluations of these two pilot scale prototypes, a vertical setup is recommended for next generation DCS system in favor of long residence time, little space requirement, and higher stack for faster emission dilution. In addition, more nozzles at the lower stage and longer separation section are recommended. The next generation DCS, prototype #3, is expected to have higher pollutant removal efficiency for both dusty and gaseous pollutants without increasing much cost.

Data in winter with more pigs housed are needed, and the following are recommended for future DCS evaluation.
1. Take samples on days that wind speed is low.
2. Use more accurate ammonia tube for ammonia concentration measurement.
3. Take sample as close to inlet surface as possible.

ACKNOWLEDGEMENT

Funding by the Illinois Council on Food and Agricultural Research (CFAR) is gratefully acknowledged.

REFERENCES

BESS, 2002. (There is a paper describes the fan test chamber by Christianson et al.)