Evaluation of airflow through a horizontal-airflow biofilter with a pressurized headspace

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Garlinski, E.M. and Mann, D.D. 2005. **Evaluation of airflow through a horizontal-airflow biofilter with a pressurized headspace**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 6.29 - 6.34. Emissions from livestock barns contribute odour to the outdoor environment. A process termed biofiltration can be used to treat livestock odour, however, an optimum biofilter design has not yet been determined. Based on knowledge gained from the study of grain bulks, the concept of a horizontal-airflow biofilter has been considered. It was hypothesized that a pressurized headspace created by an inflatable bladder would prevent channeling of air over the top surface of a horizontal-airflow biofilter, even after substantial settling of the biofilter medium. An experimental horizontal-airflow biofilter, with a headspace pressurized using an inflatable bladder, was constructed adjacent to a hog barn. Air velocity at the exit face of the biofilter and medium settling were both measured periodically over two summers of operation. The analysis procedures were able to detect regions of non-uniform exit velocity, but there was no evidence of channeling over the top surface of the biofilter despite medium settling of approximately 10%. The pressurized-headspace design was effective for research purposes, but problems associated with installation and durability of the inflatable bladder render the design inappropriate for a commercial-scale environment. **Keywords**: biofilter, biofiltration, airflow uniformity, horizontal airflow, pressurized headspace.

Les émissions gazeuses provenant des bâtiments d'élevage et rejetées à l'extérieur contribuent à la charge odorante globale de l'air ambiant. Il est possible de faire appel à des procédés de biofiltration pour traiter les odeurs d'élevage, cependant le design optimal de tels biofiltres reste à faire. À partir des résultats obtenus pour les grains en vrac, un concept de biofiltre à écoulement d'air horizontal a été retenu. L'hypothèse à l'origine de cette recherche était qu'une colonne pressurisée créée par un réservoir gonflable pourrait prévenir l'écoulement préférentiel de l'air au-dessus de la surface d'un biofiltre à écoulement d'air horizontal, même après que le substrat du biofiltre se soit considérablement tassé. Un prototype de biofiltre à écoulement d'air horizontal, muni d'une colonne pressurisée utilisant un réservoir gonflable, a ainsi été construit adjacent à une porcherie. Les vitesses d'air à la surface de sortie du biofiltre et du substrat tassé ont été mesurées périodiquement durant deux saisons estivales d'opération. Les procédures d'analyse ont pu démontrer des zones de vitesse de sortie non uniforme, mais il n'y avait pas d'indication d'écoulement préférentiel à la surface du substrat même si celui-ci avait subi un tassement d'environ 10%. Le design d'une colonne pressurisée a été efficace pour des fins de recherche, toutefois des problèmes associés à l'installation et à la durabilité du réservoir gonflable rendent le design non souhaitable pour des applications commerciales. **Mots clés**: biofiltre, biofiltration, uniformité d'écoulement d'air, écoulement d'air horizontal, colonne pressurisée.

INTRODUCTION

Odour control for livestock farms is rapidly becoming both a reality and a priority. Neighbouring communities often complain about odour emissions from hog barns, manure storage facilities, and manure application practices. Manure storage facilities can be covered and manure can be injected into the soil, however, odour emissions from the barns are difficult to contain and treat.

Odour emissions from hog barns tend to be inconsistent. They have been shown to vary with time of day and season of the year (Zhu et al. 2000). Such inconsistencies in exhaust gas streams cause problems for many industrial odour control technologies. Biofiltration, because it relies on a biological process for treating odourous compounds, is able to react to varying input conditions.

Although the process of biofiltration is known to be effective for treating odour from livestock facilities, there are opportunities for improved biofilter design. Currently, the most prominent design features vertical air movement through a shallow bed of porous medium (often wood chips) (Nicolai and Janni 1997; Sweeten et al. 1991; Noren 1985; Mann et al. 2002; Li et al. 1996; Philips et al. 1995). This particular design requires a large surface area to avoid excessive resistance to airflow.

Research, inspired by observations from grain bulks (Jayas et al. 1987; Kumar and Muir 1986; Sokhansanj et al. 1988; Kay et al. 1989), has shown that horizontal airflow through biofilter media produces a smaller pressure drop per unit flow rate per unit thickness than does vertical airflow (Sadaka et al. 2002). This fact inspired the consideration of a horizontal-airflow biofilter.

Little information can be found related to horizontal-airflow biofilters. Two papers described a lab-scale unit that consisted of a series of baffles located perpendicular to the flow of air to prevent channeling of the air over the top surface (Lee et al. 2001; Choi et al. 2003). It was anticipated that settling of the medium would cause channeling over the top surface, but Choi et al. (2003) did not observe problems during the 70-day duration of their experiments. They suggested that channeling would likely become a problem for long-term operation of the biofilter. Sadaka et al. (2002) used a pressurized headspace to prevent the channeling of air over the top surface of the medium. No problems were observed, although the duration of the experiments was insufficient to promote settling. Settling is also expected to increase bulk density, especially in the lower

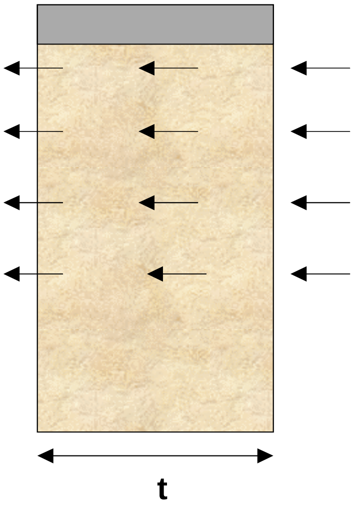

Fig. 1. **Side view of a horizontal-airflow biofilter illustrating the flow of air through media of thickness, t. An inflatable bladder (top layer) fills the space between the top surface of the biofilter media and the bottom surface of the biofilter ceiling, preventing the air from channeling over top of the media.**

layers of the medium. Differential bulk density from top to bottom is expected to cause differential airflow from top to bottom. Of the two problems (i.e., channeling over the top surface or differential bulk density from top to bottom), channeling is the most significant concern because it causes immediate failure of the biofilter.

It was hypothesized that a pressurized headspace created by an inflatable bladder would prevent channeling of air over the top surface of a horizontal-airflow biofilter, even after substantial settling of the biofilter medium. To test this hypothesis, a biofilter was constructed at the University of Manitoba Glenlea Research Station adjacent to a hog barn. The biofilter operated for two summers. Air velocity at the exit face of the biofilter and medium settling were measured periodically. Despite settling of 10% of the original height of the medium, there was no evidence of channeling over the top surface of the medium. It can be concluded that a horizontal-airflow biofilter can be used effectively if an inflatable bladder is used to pressurize the headspace.

THEORY OF A HORIZONTAL-AIRFLOW BIOFILTER WITH A PRESSURIZED HEADSPACE

Without engineering input, channeling of air over the top surface of a horizontal-airflow biofilter will occur when the medium settles. To prevent channeling, the volume previously occupied by the medium must be displaced by something else. Because settling is an on-going process, the empty space (or headspace) will continue to grow. The headspace can be filled by an inflatable bladder (Fig. 1); it expands to occupy the entire space between the top surface of the medium and the bottom surface of the biofilter ceiling. For the inflatable bladder to create a tight seal against the top surface of the medium, the pressure inside the bladder must be equal to or greater than the pressure of the air stream entering the medium.

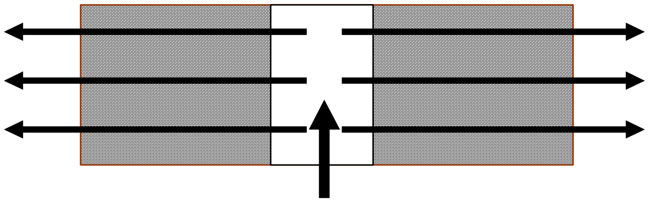

Fig. 2. **Top view of a horizontal-airflow biofilter consisting of a central, internal plenum bounded on both sides by chambers filled with a porous medium. Arrows indicate the movement of air through the biofilter. In this research, the chamber on the left is called Side A and the chamber on the right is called Side B.**

DESIGN OF THE BIOFILTER

To achieve horizontal air movement through a porous bulk, 1) the inlet side of the chamber must be pressurized and 2) a barrier must exist to prevent channeling of the air over the top surface of the porous bulk. As discussed in the previous section, channeling can be prevented with a pressurized headspace. Pressurizing the inlet side of the chamber is not difficult; it could be achieved by the construction of a sealed box on the side of the biofilter chamber. A more efficient design, in terms of construction cost, consists of an internal plenum bounded on both sides by chambers filled with a porous medium (Fig. 2). Arrows indicate the movement of air through the biofilter unit. With this design, a single plenum is used to feed odorous air to two biofilter units.

Figure 3 shows the biofilter structure constructed for this research project. Biofilter dimensions were calculated based on the desired treatment, or residence, time. The “true” residence

Fig. 3. **Exit face of the experimental biofilter (Side A) constructed adjacent to a hog barn at the university research farm. A plywood duct channeled the air from the barn to the biofilter.**

Fig. 4. Flexible aluminum duct attached to exhaust supply (bottom) and inflatable bladder (top). Air from the exhaust supply pressurized the bladder.

time, which accounts for the porosity or void space of the medium, is calculated as:

$$\tau = \frac{V_t \theta}{Q} \qquad (1)$$

where:

τ = true residence time (s),
V_f = biofilter volume (m^3),
θ = porosity (%), and
Q = airflow rate from fans (m^3/s).

As the volume is equal to the product of the three dimensions of the biofilter, Eq. 2 relates biofilter dimensions to retention time as:

$$V_f = lht = \frac{\tau Q}{\theta} \qquad (2)$$

where:

l = length of the biofilter chamber (m),
h = height of the biofilter chamber (m), and
t = thickness of biofilter chamber in direction of airflow (m).

The biofilter dimension in the direction of airflow (i.e., the "thickness") should be chosen based on the airflow resistance characteristics of the biofilter medium. The Hukill and Ives (1955) equation relates the pressure drop required to overcome a given depth of biofilter medium to the rate of surface loading as:

$$\frac{P}{t} = \frac{aSL^2}{\ln\left(1 + bSL\right)} \qquad (3)$$

where:

P = total pressure drop experienced by medium (Pa),
SL = surface loading of the biofilter (m^3 s^{-1} m^{-2}),
a = constant for biofilter medium (Pa s^2 m^{-3}), and
b = constant for biofilter medium (m^{-3} s m^2) (Sadaka et al. 2002).

Surface loading is defined as the airflow rate (Q) divided by the surface area ($l \bullet h$) of the inlet to the biofilter bed.

$$SL = \frac{Q}{lh} \qquad (4)$$

Contaminated air was supplied to the biofilter by a 124 W axial fan (0.48 m in diameter) with a constant flow rate of 1.26 m^3/s. (Note: The biofilter was sized using an assumed flow rate of 1.89 m^3/s based on factory specifications for a fan of similar dimensions. This assumed flow rate was later determined to be too high.) Two booster fans, in series with the barn's ventilation fan, were used to generate the necessary static pressure. A medium mixture consisting of 80% wood chips and 20% compost was used. From previous research, such a mixture would have a porosity of approximately 60% (Sadaka et al. 2002). To achieve a true residence time of 5.4 s (Nicolai and Janni 1998), the biofilter volume was calculated to be 17 m^3. The total volume was divided by a factor of two representing the two chambers on either side of the plenum. With a minimum thickness of 1.5 m chosen to allow the chambers to be emptied using a standard skid-steer loader, the remaining biofilter dimensions were 1.8 m (length) and 3.05 m (height). The pressure drop was predicted to be 140 Pa for a mixture composed of 60% wood chips and 40% compost. A more dense mixture was used for predicting pressure drop because it was assumed that the media mixture would settle during prolonged operation of the biofilter. Using the actual flow rate of 1.26 m^3/s, the surface loading was predicted to be 0.11 m/s.

The inflatable bladder was pressurized by exhaust air from the barn through a circular 152-mm flexible aluminum duct (Fig. 4). With this design, the pressure in the bladder would be approximately equal to the pressure in the internal plenum.

EXPERIMENTAL METHODS

Quantification of medium settling

For a set period of time, settling of the medium can be observed as a change in height. This change in height can be observed either from the top surface or the sides of a rectangular bulk. For this research, change in height was determined from both the top surface and from the exit face of the biofilter.

Because the top surface is accessible only when the inflatable bladder is absent, measurements from the top surface were taken only twice: 1) immediately after filling the biofilter with wood chips and 2) when repairs to the inflatable bladder became necessary during the second summer of operation. Distances from a reference plane to the top surface of the wood chips were measured on a 300-mm grid.

The exit face of the biofilter, on the other hand, is visible and accessible at all times. After filling, orange markers were painted onto the exit face of the biofilter to identify sampling locations. Paint was applied both to the expanded metal of the wall and to the wood chips behind it. As the medium settled, the distance between the centre of the orange mark on the expanded metal and the centre of the orange mark on the wood chips was measured.

Evaluation of exit velocity uniformity

Airflow sampling was conducted with a custom-built amplifying cone. A hotwire anemometer was used to monitor velocity of

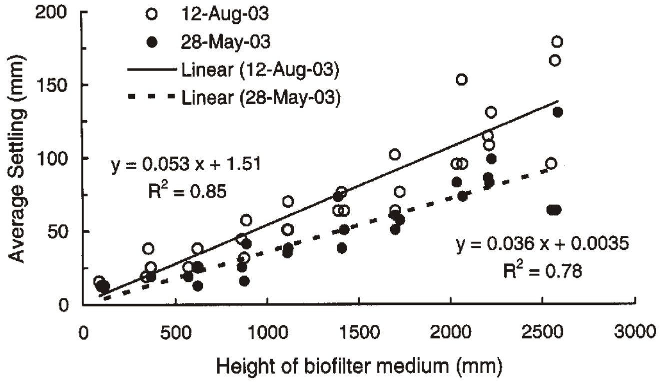

Fig. 5. Medium settling measured from the exit face of the biofilter (Side B) on two dates during the summer of 2003.

the air exiting the centre of the amplifying cone. Actual velocities were calculated using the exit dimensions of the amplifying cone.

Although uniformity is desired, it can be assumed that a properly operating biofilter will have exit velocities that resemble a normal distribution. Thus, locations where the exit velocity is below or above certain values could be considered extreme (i.e., $Z < -1.96$ or $Z > 1.96$) and should be investigated further. A large negative or positive Z value would represent either a dead spot or channeling, respectively. Locations having a measured exit velocity of 0 m/s were identified as dead spots even if the calculated Z value did not identify that point as being extreme.

The information provided from the measured exit velocities provides information about the performance of the biofilter for a specific sampling date. To determine whether stratification is occurring over time, the mean and standard deviation of the Z value over time can be calculated for each sample location. Potential areas of concern can be classified according to consistently high Z values (channeling), consistently low Z values (dead spots), or by unstable, fluctuating Z values (unknown problems).

Table 1. Air velocities observed from both exit faces of the biofilter.

Sampling date	Side	Air velocity (m/s)				Probability >t (%)
		Mean	St. Dev.	Minimum	Maximum	
2003 06 27	A	0.06*	0.02	0.03	0.11	35.0
	B	0.07*	0.02	0.01	0.12	
2003 07 09	A	0.12*	0.03	0.08	0.17	44.7
	B	0.13*	0.04	0.07	0.22	
2003 07 22	A	0.11*	0.03	0.06	0.16	81.2
	B	0.12*	0.05	0.04	0.22	
2003 07 28	A	0.09**	0.03	0.05	0.14	13.2
	B	0.11**	0.03	0.05	0.18	
2003 08 11	A	0.09**	0.03	0.04	0.16	49.6
	B	0.10**	0.03	0.04	0.21	

*number of data points = 25; **number of data points = 50

RESULTS and DISCUSSION

Medium settling

Medium settling from the top surface of the biofilter was measured June 2003. On average, the medium settled 0.30 m from an original height of 2.89 m on Side A. The medium settled an average of 0.25 m from an original height of 2.87 m on Side B. Compared with the original height, this corresponds to settling of approximately 10%. When viewed from the side of the biofilter, settling of the medium was linear from top to bottom (Fig. 5). Settling continued to occur during the summer of 2003.

Settling results in changes to both porosity and bulk density. From assumed initial values of 57% and 387 kg/m^3 for porosity and bulk density, respectively (Sadaka et al. 2002), a 10% reduction in height decreased the porosity to 53% and increased the bulk density to 427 kg/m^3.

Medium settling is definitely an issue that must be considered in the design of a horizontal-airflow biofilter. It is speculated that the constant wetting and drying cycles associated with irrigation of the biofilter medium contribute to settling of the medium. Operationally, some mechanism must be in place to prevent channeling over the top surface of the medium. Structurally, the biofilter must be able to withstand the increased lateral pressures associated with the increased bulk density of the medium. In our experimental biofilter, some bulging of the walls was observed during the second summer of operation. A better understanding of the lateral pressures caused by wood chips during operation of a biofilter is needed.

Exit velocity uniformity

Air velocities from the exit faces of the two halves of the biofilter for five sampling dates are summarized in Table 1. According to statistical analysis (Student's t-test, α=0.05), there were no significant differences between Sides A and B on any sampling date. Mean exit velocity was approximately 0.1 m/s, however, the velocity at specific locations ranged from a low of 0.01 m/s to a high of 0.22 m/s.

Although exit velocity was not constant across the entire exit face of the biofilter, the differences were typically not extreme according to the expectations of a normal population distribution. For example, on 11 August 2003, only a single extreme value was identified near the top along the back wall of Side A (Fig. 6). Some channeling was occurring at this point.

When Z values were averaged for all sampling dates, more variation across the exit face of the biofilter was evident (Fig. 7). The point at which channeling was occurring on 11 August 2003 (Fig. 6) has consistently high Z values. The physical explanation for high airflow in this region relates to the position of the exhaust duct from the barn; air is introduced into the internal plenum at a height of 2 m. The air

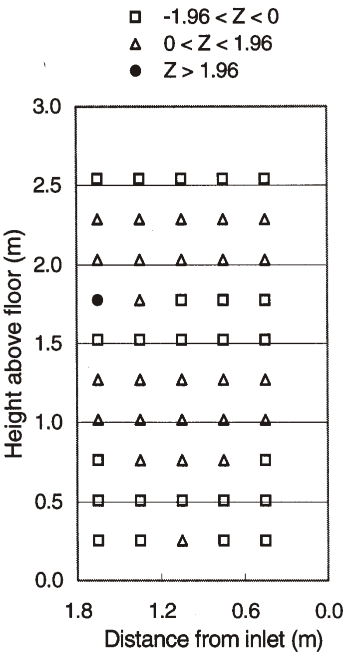

Fig. 6. Exit face of the biofilter (Side A) showing Z values calculated using exit velocities collected on 11 August 2003 from the face of the biofilter. Air was introduced into the central plenum parallel to the x-axis at the point corresponding to 0 m on the x-axis and 2 m on the y-axis, moving from right to left. In the orientation shown, the air is coming out of the page.

hits the back wall of the internal plenum and spreads laterally. Consequently, the high exit velocities at this location can be explained. As an aside, baffles were installed inside the internal plenum to redistribute the air so that this channeling can be prevented, but no data were collected following installation. Other regions of consistently high or consistently low exit velocity cannot be explained with equal certainty. From this research, there is insufficient evidence to suggest that medium settling causes differential airflow from top to bottom.

By looking at the standard deviation of Z values for all sampling dates, we see that Z values tended to be stable throughout the test period as evidenced by low standard deviations (Fig. 8). The relative stability of Z values suggests that the regions of consistently high or consistently low exit velocities may be attributed to issues related to initial porosity of the medium (i.e., there may have been differences in initial porosity due to filling of the biofilter, but there is no evidence of differential rate of porosity change from location to location during operation of the biofilter).

CONCLUSIONS

As stated earlier in the paper, it was hypothesized that a pressurized headspace created by an inflatable bladder would prevent channeling of air over the top surface of a horizontal-airflow biofilter, even after substantial settling of the biofilter medium. The experimental evidence provided in this paper supports this hypothesis. There was no evidence of high exit velocities along the top surface of the biofilter when medium settling caused a 10% reduction in medium height. Thus, the theory of a pressurized-headspace horizontal-airflow biofilter is sound.

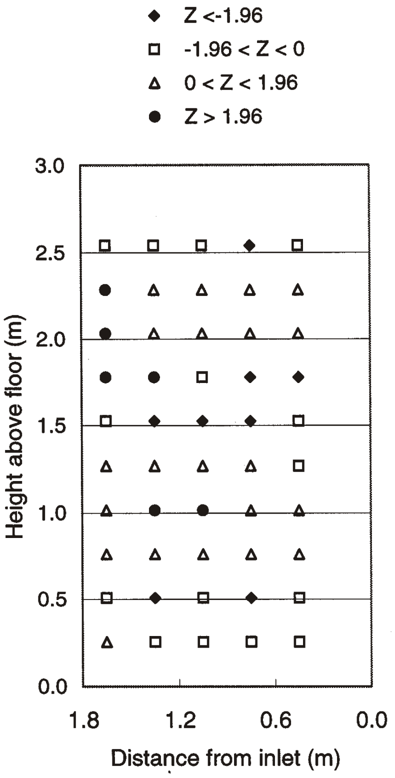

Fig. 7. Exit face of the biofilter (Side A) showing mean Z values calculated for each sampling location using Z values calculated for each of the five sampling dates during the summer of 2003. Air was introduced into the central plenum parallel to the x-axis at the point corresponding to 0 m on the x-axis and 2 m on the y-axis, moving from right to left. In the orientation shown, the air is coming out of the page.

NEXT STEPS

Despite the apparent success of the experiment, there are some practical issues that must be discussed. For laboratory research, the use of an inflatable bladder has been shown to be acceptable, however, it is questionable whether this technology is appropriate in a non-laboratory setting for two reasons. First, it is difficult to install the bladder between the top surface of the biofilter medium and the bottom surface of the biofilter ceiling. Due to the irregular shape into which the bladder must fit, it is difficult to achieve a perfect seal. If a perfect seal cannot be achieved, channeling will occur. The second problem is that the inflatable bladder is subject to rips and tears. This occurred during our research project between the first and second summers of data collection. It was necessary to disassemble the roof to re-seal the bladder. While this may be acceptable for a research project, it is not acceptable for a commercial product. Future work related to horizontal-airflow biofilters should consider alternatives to the pressurized-headspace design.

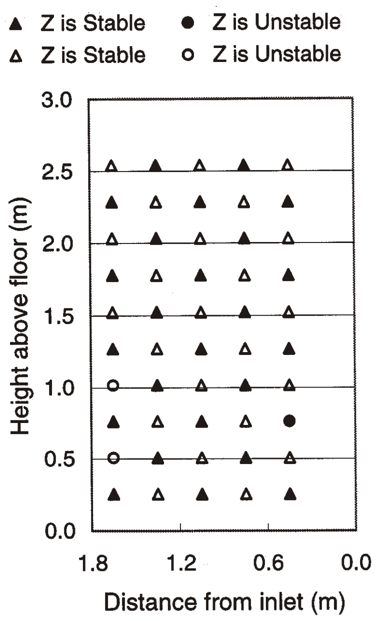

Fig. 8. Exit face of the biofilter (Side A) showing standard deviation of Z values calculated for each sampling location using Z values calculated for each of the five sampling dates during the summer of 2003. Air was introduced into the central plenum parallel to the x-axis at the point corresponding to 0 m on the x-axis and 2 m on the y-axis, moving from right to left. In the orientation shown, the air is coming out of the page. Hollow data points represent standard deviations based on four samples and solid points represent standard deviations based on two samples.

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REFERENCES

Choi, J.K., Y.H. Kim, D.J. Joo, S.J.Choi, T.W. Ha, D.H. Lee, I.H. Park and Y.S. Jeong. 2003. Removal of ammonia by biofilters: A study with flow-modified system and kinetics. *Journal of the Air and Waste Management Association* 53:92–101.

Hukill, W.V. and N.C. Ives. 1955. Radial air flow resistance of grain. *Agricultural Engineering* 36(5):332-335.

Jayas, D.S., S. Sokhansanj, E.B. Moysey and E.M. Barber. 1987. The effect of airflow direction on the resistance of canola (rapeseed) to airflow. *Canadian Agricultural Engineering* 29(2):189-192.

Kay, R.L., C.J. Bern and C.R. Hurburgh, Jr. 1989. Horizontal and vertical airflow resistance of shelled corn at various bulk densities. *Transactions of the ASAE* 32:733-736.

Kumar, A. and W.E. Muir. 1986. Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. *Transactions of the ASAE* 29:1423-1426.

Lee, D.H., A.K. Lau, and K.L. Pinder. 2001. Development and performance of an alternative biofilter system. *Journal of the Air and Waste Management Association* 51:78-85.

Li., X.W., S.J. Hoff, D.S. Bundy, J. Harmon, H. Xin and J. Zhu. 1996. Biofilter- A malodor control technology for livestock industry. *Journal of Environmental Science and Health, Part A: Environmental Science & Engineering and Toxic Hazardous Substance Control* 31(9):2275-2285.

Mann, D.D., J.C. DeBruyn and Q. Zhang. 2002. Design and evaluation of an open biofilter for treatment of odour from swine barns during sub-zero ambient temperatures. *Canadian Biosystems Engineering* 44:6.21-6.26.

Nicolai, R.E. and K.A. Janni. 1997. Development of a low cost biofilter for swine production facilities. ASAE Paper No. 974040. St. Joseph, MI: ASAE.

Nicolai, R.E., and K.A. Janni. 1998. Comparison of biofilter residence time. ASAE Paper No. 984053. St. Joseph, MI: ASAE.

Noren, O. 1985. Design and use of biofilters for livestock buildings. In *Odour Prevention and Control of Organic Sludge and Livestock Farming*, eds. V.C. Nielsen, J.H. Voorburg and P. L'Hermite, 234-237. New York, NY: Elsevier Applied Science Publishers.

Philips, V.R., I.M. Scotford, R.P. White and R.L. Hartshorn. 1995. Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings: Part 1, Basic airflow aspects. *Journal of Agricultural Engineering Research* 62:203-214.

Sadaka, S., C. Magura and D.D. Mann. 2002. Vertical and horizontal airflow characteristics of wood/compost mixtures. *Applied Engineering in Agriculture* 18(6):735-741.

Sokhansanj, S., D.S. Jayas and A.A. Falachinski. 1988. Resistance of bulk lentils to airflow. ASAE Paper No. 88-6535. St. Joseph, MI: ASAE.

Sweeten, J.M., Jr., R.E. Childers, J.S. Cochran and R. Bowler. 1991. Odor control from poultry manure composting plant using a soil filter. *Applied Engineering in Agriculture* 7(4):439-449.

Zhu, J., L.D. Jacobson, D.R. Schmidt and R.E. Nicolai. 2000. Daily variations in odor and gas emissions from animal facilities. *Transactions of the ASAE* 16(2):153-158.