A Wind Tunnel Study of Airflow Near Model Swine Confinement Buildings

T. J. Sauer, J. L. Hatfield, F. L. Haan, Jr.

Abstract. *One of the most significant and persistent environmental concerns regarding swine production is the transport of odor constituents, trace gases, and particulates from animal production and manure storage facilities. The objectives of this study were to determine how swine housing unit orientation affects air velocity and turbulence and to assess the opportunities for reducing off-site transport of air quality constituents from manure storage facilities located downstream from confinement buildings. Measurements were made with 1:300 models of swine finisher buildings in a low-speed wind tunnel capable of producing air velocities up to 12 m s^{-1} (27 mph). Runs were completed with no building models, with one housing unit oriented parallel and perpendicular to airflow, and with four housing units oriented parallel, perpendicular, and at a 30° angle to airflow. Velocity and turbulence measurements were completed in a grid of 83 points within a 215 mm high × 400 mm wide (8.5 × 15.7 in.) vertical plane at separation distances 2H, 5H, and 10H downstream from the building model arrays (H = model height of 17.5 mm) using a constant temperature anemometer system with a 3-D hot-film probe. A large zone of reduced longitudinal velocity (u) and increased turbulence intensity (I_u) in the wake of model buildings oriented perpendicular to flow was observed and was still apparent 10H downstream. The size and strength of this turbulent wake is attributed to the sloping roofs of the building models that, with a frontal vortex under the upwind building eave, create an unexpectedly tall wake zone in the building lee. One or four parallel building model arrays exhibited the least influence on downstream velocities and turbulence intensities. One perpendicular and four 30° models produced intermediate effects. The observed reduction in air velocity up to 10H downstream from multiple buildings oriented perpendicular to the airflow suggests that entrainment and transport of air quality constituents from manure storage structures may be reduced when these structures are located in this zone. However, increased turbulence in the wake zone and field conditions with variable wind speed and direction and atmospheric stability may counter the effects of reduced velocity. Tracer studies, either in wind tunnel experiments or in the field, are needed to verify the potential for building orientation and spacing to reduce transport of air quality constituents from manure storage structures.*

Keywords. *Airflow, Air quality, Confinement buildings, Swine, Wind tunnels.*

One of the most significant and persistent environmental concerns regarding swine production is the transport of odor constituents (e.g., ammonia and hydrogen sulfide), trace gases (e.g., greenhouse gases such as methane and nitrous oxide), and particulates from animal production and manure storage facilities (Reynolds et al., 1997; Zahn et al., 1997; Schiffman, 1998; Le et al., 2005; Guo et al., 2007). Building type, facility management, animal diet, and climate determine the amount of air quality constituents generated at a production facility. Local environmental conditions, especially wind speed and direction, vegetative cover, and topography also influence the amounts of odor and trace gas compounds transported from production facilities. When new swine production facilities are designed, many factors are considered, including vehicle access, utility location, land area available, slope, obstructions, and soil properties. Most of the design criteria are concerned with economic issues, primarily minimizing the cost of site development and building construction. However, where a production facility is located and how the animal housing units and manure storage facilities are arranged may have a significant effect on the amount and distance that air quality constituents are transported.

Due to the variation in building size and orientation and varying land cover and topography, studies on the transport of air quality constituents from and near buildings of various types (i.e., urban, suburban, and industrial) have often been conducted in wind tunnels (e.g., Huber and Snyder, 1982; Huber, 1989). Wind tunnels offer the advantage of being able to make detailed measurements with scale models of actual buildings under controlled environmental conditions. Some studies combine wind tunnel and field measurements (Mavroidis et al., 2003; Aubrun and Leitl, 2004) and have generally shown that wind tunnel experiments provide an accurate and reproducible assessment of field processes. However, even wind tunnel studies are often completed with single or

Submitted for review in July 2010 as manuscript number SE 8679; approved for publication by the Structures & Environment Division of ASABE in January 2011.

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Thomas J. Sauer,** Research Soil Scientist, and **Jerry L. Hatfield,** Laboratory Director, USDA-ARS National Laboratory for Agriculture and the Environment, Ames, Iowa; and **Fred L. Haan, Jr.,** Associate Professor, Department of Mechanical Engineering, Rose-Hulman Institute of Technology, Terre Haute, Indiana. **Corresponding author:** Thomas J. Sauer, USDA-ARS National Laboratory for Agriculture and the Environment, 2110 University Boulevard, Ames, IA 50011-3120; phone: 515-294-3416; fax: 515-294-8125; e-mail: tom.sauer@ars.usda.gov.

simplified models due to the complexity of airflow disturbance by the models. For the same reason, comprehensive measurement of airflow and air quality constituent transport at full-scale swine production facilities requires a large investment in sophisticated sensing equipment. Even when such resources are available, the data collected are only relevant as a case study, i.e., for one location under the conditions occurring during the measurement period.

As wind approaches a solid object, such as a swine housing unit, the air accelerates around the sides and over the top of the object, diverting air and disturbing the airflow downwind. If an above-ground manure storage tank or below-grade earthen storage facility (lagoon) is located downwind from a building complex, then the orientation of the buildings and the distance between the buildings and the manure storage facility may also affect the transport of air quality constituents from the storage facility. It is, therefore, important to know whether the storage facility is exposed to increased wind speed and turbulence or if it is protected by the upwind structures. If modifying the layout of a production facility reduces the downwind air quality impacts and can be accomplished without a large increase in construction costs, then the producer will derive direct air quality benefits for the lifetime of the facility for an initial one-time cost. The objectives of this study were to determine how swine housing unit orientation affects air velocity and turbulence downstream and to assess the opportunities for reducing off-site transport of air quality constituents.

Materials and Methods

The low-speed wind tunnel at the National Laboratory for Agriculture and the Environment (NLAE) in Ames, Iowa, was used for all measurements. The NLAE wind tunnel is an open-circuit design with a centrifugal blower capable of producing air velocities from 0.5 to 12 m s^{-1} (1 to 27 mph) in a control section 0.46 m tall, 1.22 m wide, and 5.49 m long (18 in. tall, 48 in. wide, and 18 ft long). The ceiling of the control section is adjustable to 0.76 m (30 in.) to accommodate scale models of varying dimensions. This wind tunnel was designed to enable accurate simulation of atmospheric surface layer conditions appropriate for environmental applications (Wooding, 1968; Barlow et al., 1999). A trip fence (1.90 cm tall) and an array of five triangular spires (38 cm tall, 3.5 cm wide at base, 20 cm spacing) were used to create a surface boundary layer within the control section with properties similar in scale to the earth's atmospheric surface layer (Armitt and Counihan, 1968; Irwin, 1981). The floor of the control section was covered with a vinyl mat (Readygrass) that was glued to 1.61 mm thick (1/8 in.) sheet metal. The vinyl mat provided a uniform surface with a texture similar to mown grass at the scale of the building models used in this study.

Scale models of 1000-head swine finisher units were made from balsa wood with dimensions and roof pitches typical of commercial production facilities. The models were 40 mm wide (1.6 in.) and 200 mm long (7.9 in.) with 10.2 mm tall side walls (0.4 in.), 2 mm overhang (0.08 in.), roof slope of 4/12, and peak height of 17.5 mm (0.7 in.). Magnets attached to the bottom allowed positioning of the models on the floor of the control section. These models are 1:300-scale versions of swine finisher buildings approximately 12 m (40 ft) wide and 60 m (200 ft) long with 2.4 m (8 ft) side walls, 5.25 m (17 ft) peak height, and foundations 0.6 m (2 ft) above grade. Scaling criteria followed guidelines described by Snyder (1981), Plate (1982), and VDI Guideline 3783/12 (VDI, 2000). The primary scaling criteria was to simulate a full atmospheric surface layer of 400 m thickness to enable measurement of near- and far-field effects of building models (Cook, 1978; Tieleman and Reinhold, 1978; Barnaud and Gandemer, 1979). Models of swine housing units were placed in the control section of the wind tunnel to simulate an array of possible arrangements. Design factors evaluated were: (1) number of housing units, (2) orientation of the housing units with regard to airflow, (3) distance downstream from the housing units, and (4) air velocity. Measurements were made with no building models, with one housing unit oriented parallel and perpendicular to airflow, and with four housing units oriented parallel, perpendicular, and at a 30° angle to airflow (fig. 1). All measurements were completed with the models arranged in symmetry with the centerline of the control section and the upstream edge of the building models 1.74 m downstream from the trip fence. There was no heating or cooling of the control section floor, so all measurements were made under adiabatic, neutral stability conditions.

Airflow and turbulence measurements were completed at separation distances of 2H, 5H, and 10H downstream from the building model arrays, where H is the model building height (17.5 mm) using a constant-temperature anemometer system (IFA 300, TSI, Inc., Shoreview, Minn.) equipped with a 3-D hot-film probe (model 1299, TSI, Inc.). The 3-D probe was mounted on a computer-controlled traversing mechanism that allowed automated, precise (sub-mm) movement within the wind tunnel control section in longitudinal (x), lateral (y), and vertical (z) directions. Airflow measurements were made in a grid of 83 points within a 215 mm high × 400 mm wide (8.5 × 15.7 in.) vertical plane straddling the centerline of the control section (fig. 2). Velocity measurements and turbulence statistics were calculated from 26 s of data collected at a rate of 10 kHz at each measurement point using Thermalpro software (TSI, Inc.). Parameters of interest were mean longitudinal, lateral, and vertical air velocity (u, v, and w, respectively; m s^{-1}) and the corresponding turbulence intensities (I_u, I_v, and I_w, respectively), which are

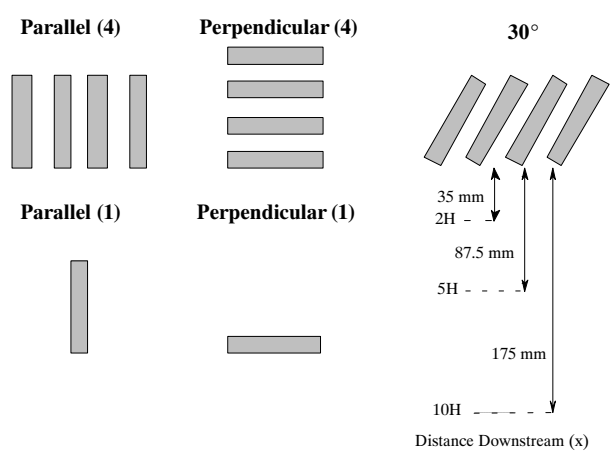

Figure 1. Schematic of five building model orientations and illustration of distance downstream (H = building model height) of air velocity measurements for 30° experiments (not to scale).

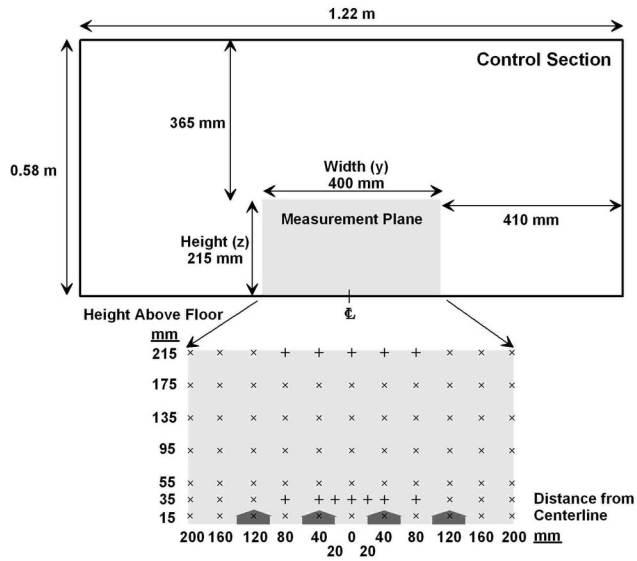

Figure 2. Lateral cross-section of wind tunnel control section showing measurement plane with locations of 83 measurements points (× and +) for hot-film anemometer. Measurement locations for experiments with four building models oriented parallel to airflow are illustrated.

calculated as the ratio of the standard deviation over the mean velocity. The mean vertical Reynolds stress (uw, $m^2\ s^{-2}$) was also monitored as a measure of vertical momentum transport. Measurements were completed for each array at reference air velocities of 0.5, 2, and 5 m s^{-1} measured with a heat transfer anemometer (East 30 Sensors, Pullman, Wash.) at a reference height of 17.5 mm with the sensor located upstream and offset from the building models. Air velocity was controlled by adjusting louvers at the inlet to the centrifugal blower.

For each reference air velocity, vertical profiles of mean and turbulent flow parameters were obtained to characterize the incident airflow. Figure 3 shows a power law fit to the 0.5 m s^{-1} flow according to the following equation:

$$\frac{U}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\frac{1}{\alpha}} \tag{1}$$

where the reference height for these profiles was 100 m full scale, and z is height (m). For the 0.5, 2, and 5 m s^{-1} flows, α values of 5.1, 6.0 and 6.9 were obtained. These values effectively simulate slightly decreasing roughness as the flow velocity increases. The aerodynamic roughness lengths were also found from mean velocity profiles using the following expression:

$$U = \left(\frac{u^*}{\kappa}\right)\ln\left(\frac{z}{z_0}\right) \tag{2}$$

where κ is the von Karman constant (0.4), u^* is the friction velocity, and z_0 is the aerodynamic roughness length (m). Fitting this expression to the logarithmic portion of the profile, full-scale z_0 values of 5.3, 0.9, and 0.1 cm were found. These values were consistent with the trend of decreasing effective roughness for increasing mean velocity. Profiles of turbulence intensity and Reynolds stress are shown in figures 4 and 5. Both of these parameters show decreases with increasing mean velocity. For reference, figure 4 shows a turbulence intensity profile for z_0 of 10 cm, which is described by Cermak and Isyumov (1999) as "low crops, occasional large obstacles."

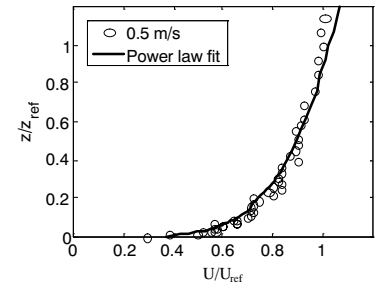

Figure 3. Power law fit to vertical profile of longitudinal velocity normalized to velocity at 100 m full scale.

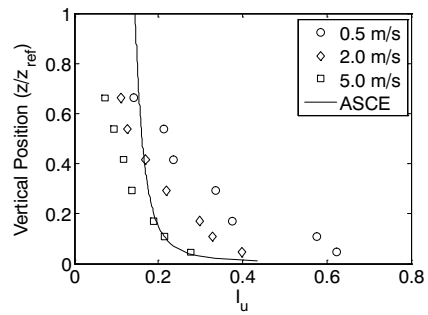

Figure 4. Vertical profile of longitudinal turbulence intensity (I_u) for 0.5, 2, and 5 m s^{-1} reference velocities with a profile from Cermak and Isyumov (1999) for "low crops, occasional large obstacles" (labeled ASCE).

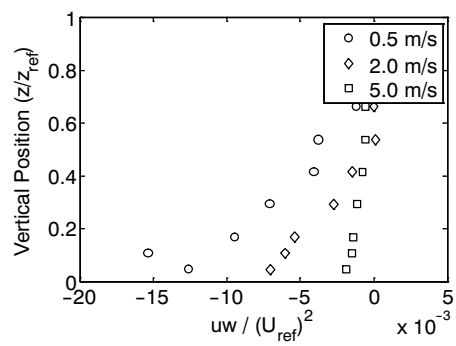

Figure 5. Vertical profile of Reynolds stress (uw) normalized by streamwise air velocity at the top of the building models (U_{ref}^2) for 0.5, 2, and 5 m s^{-1} reference velocities.

Results and Discussion

Centerline Velocity Profiles

Vertical profiles of u measured on the centerline of the control section behind the building model arrays indicate a consistent pattern of building model effects (fig. 6). Velocity measurements were made at 15, 35, 55, 95, 135, 175, and 215 mm above the floor of the control section (fig. 2). Due to small fluctuations in free-stream air velocity between experiments, u values within each profile were normalized for comparison by dividing the observed values by the free-stream velocity at 215 mm. At each reference velocity and

separation distance except 0.5 m s^{-1} at 2H, the greatest reduction in velocity near the surface was always observed with one and four perpendicular building models. Smaller reductions were observed with four models at a 30° angle to airflow or one model parallel to airflow. Indications of possible flow reversal occurred at the 15 and 35 mm measurement heights at the 0.5 m s^{-1} reference velocity and 2H and 5H separation distances for the perpendicular model runs. Potential flow reversal was also observed at the same heights for the 10H separation distance with four perpendicular models. Both four and one perpendicular models at 2H and one perpendicular model at 5H at the 2 m s^{-1} reference velocity appear to have produced flow reversal at the lowest height.

Note that the velocity profile for the one parallel model runs was directly behind the model, but the profiles with four parallel models were measured between the two middle models (figs. 1 and 2). For this reason, velocity profiles for four parallel model runs were always closest to those observed with no building models present. For all profiles but especially those at reference velocities of 2 and 5 m s^{-1}, relative velocity values above 95 mm were in close agreement with those values obtained without any building models present. This indicates that regardless of building orientation, building number, reference velocity, or separation distance, measurable effects of the building models on u directly behind the midpoint of the model array were limited to heights below approximately five times the building model height (i.e., 5H or approximately 25 m at field scale).

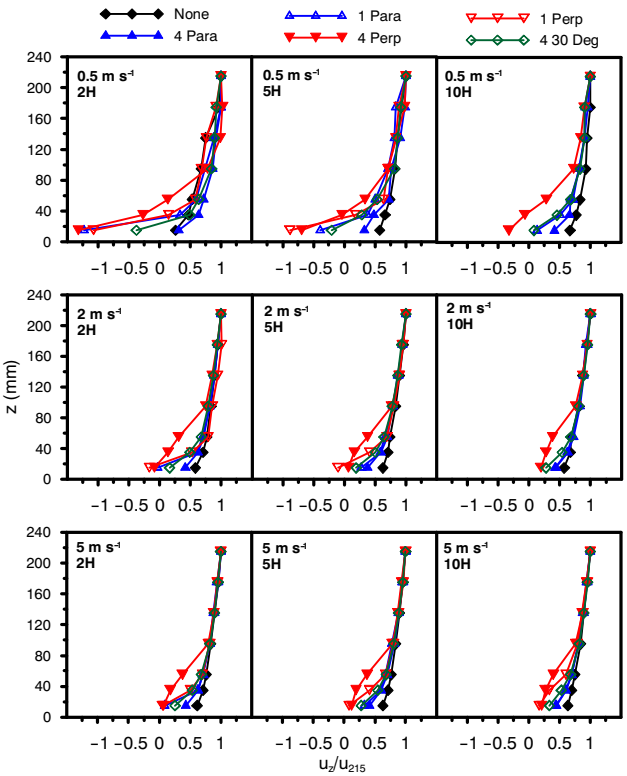

Figure 6. Centerline profiles of u normalized by reference velocity (u_z/u_{215}) with height above the control section floor for no (None), parallel (1 Para and 4 Para), perpendicular (1 Perp and 4 Perp), and 30° (4 30 Deg) building model arrays at reference velocities of 0.5, 2, and 5 m s^{-1} and downstream separation distances of 2H, 5H, and 10H.

Longitudinal Velocity Spatial Patterns

Contour plots of u created from data at each point on the measurement grid were created to display the spatial pattern of downstream longitudinal airflow disturbance by the building models. Figures 7 and 8 illustrate observed patterns of u 2H downstream from four parallel and four perpendicular models, respectively, at each reference velocity. Turbulent wakes behind 3-D objects are particularly complex, as flow separation and reattachment can take different forms, including formation of a cavity and flow reversals. Near-field wakes are also highly obstacle-specific and may have low mean velocities but high turbulence intensities (Taylor, 1988; Mirzai et al., 1994; Simiu and Scanlan, 1996). As expected, for the four parallel models, there was some acceleration around the low-rise models, creating small wake zones of reduced velocity behind the models. The models had relatively little effect on airflow above 3H. The observed patterns persisted but with reduced effect at 5H and 10H downstream (data not shown).

In contrast to these observations, comparable measurements with building models oriented perpendicular to airflow showed quite unexpected results (fig. 8). A large wake zone of reduced velocity centered behind the models was observed at all reference velocities. The characteristic of this flow field had not been observed previously; most wind tunnel studies of airflow around buildings have applications for urban settings and therefore use models of buildings with flat roofs (e.g., Ahmad et al., 2005; Olvera et al., 2008). The sloping roofs of the swine confinement models, when oriented perpendicular to airflow, created a distinct upward jet with a triangular-shaped wake zone beneath it. Also unlike the results for models parallel to airflow, this zone of reduced u persisted with relatively small reduction to 10H downstream and was also observed with just one perpendicular building model (data not shown). Several features of this wake zone have potentially important implications for off-site transport of air quality constituents.

The zone of greatest velocity reduction was only observed for the middle 1/3 of the model length, or approximately 65 mm (19.8 m at field scale). This suggests that flow around the ends of the model reduced the sheltering effect of the sloping roof. Flow visualization was useful in verifying these interpretations. Smoke introduced upstream of the models perpendicular to flow indicated the presence of a recirculation zone or frontal vortex beneath the eave of the first building that likely helped sustain the upward jet and boundary layer detachment from the building model roofs. Frontal vortices have been observed in urban meteorology and are noted for their "pollution trapping" effect as air quality constituents within the vortex are isolated from the bulk flow (Oke, 1987). Flow visualization also indicated airflow in the wake of the first building skimmed across the gaps between adjacent buildings of the four-model array. This is consistent with the observed similarity in airflow patterns when one or four building models were placed perpendicular to flow. Janssen (1979) also found a minimal effect of adjacent model swine buildings on airflow patterns in a wind tunnel study.

At this point, it is clear that building model orientation can have a pronounced effect on near-wake behavior and downstream airflow dynamics. Nonetheless, careful interpretation of these wind tunnel observations is necessary to enable an accurate assessment of the effect on transport of particulates or odor constituents from full-scale buildings or manure stor–

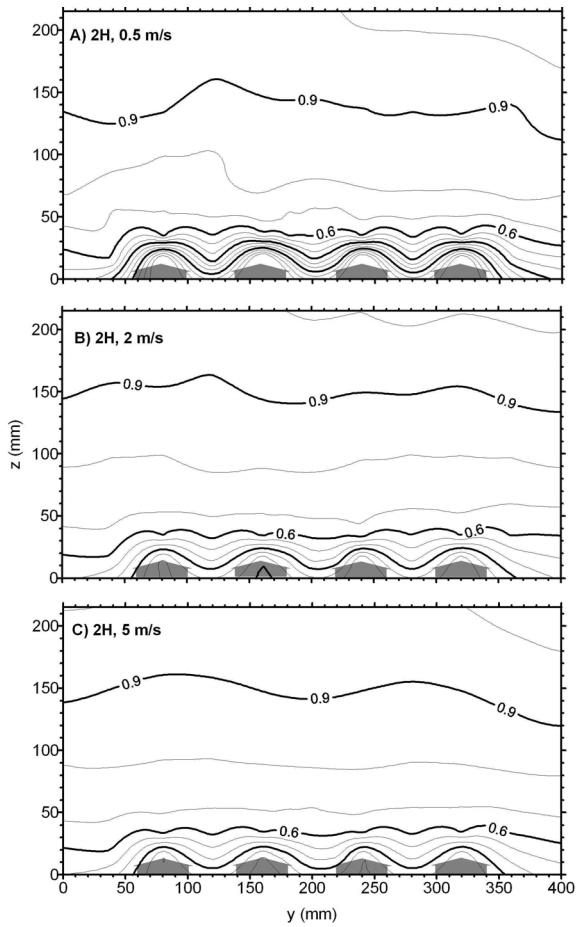

Figure 7. Spatial patterns of longitudinal air velocity (*u*) 2H downstream from four building models oriented parallel to airflow at each reference velocity. The silhouettes indicate model location, and the perspective is facing the airflow. Contours are dimensionless velocity scaled to the free-stream velocity at 215 mm.

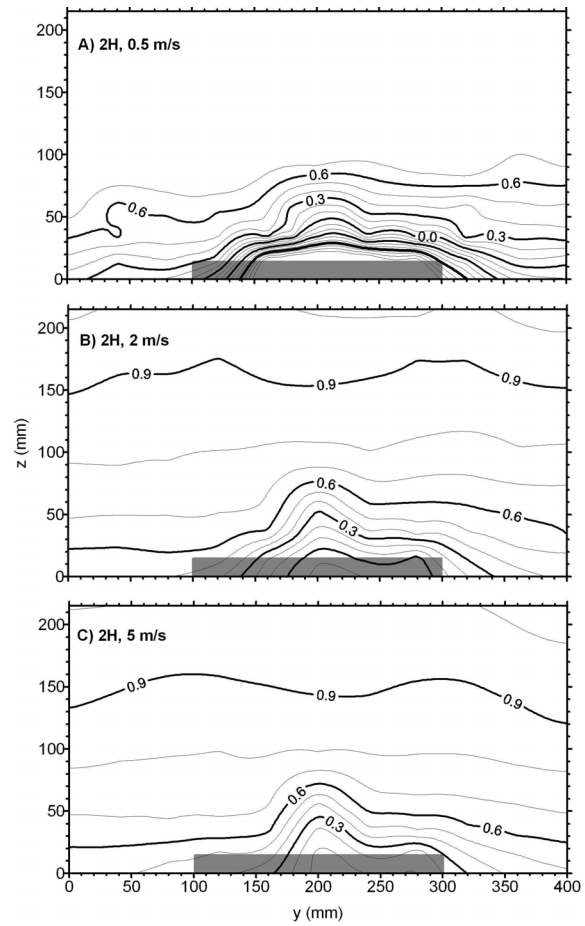

Figure 8. Spatial patterns of longitudinal air velocity (*u*) 2H downstream from four building models oriented perpendicular to airflow at each reference velocity. The silhouette indicates model location, and the perspective is facing the airflow. Contours are dimensionless velocity scaled to the free-stream velocity at 215 mm.

age facilities (below-building pits, in-ground lagoons, or above-ground tanks). Reduction in mean *u* should reduce the potential for downstream transport of particulates and trace gases. However, there are limitations of wind tunnel studies that make direct inference of these results to field situations challenging. All of the simulations in this study were completed under neutral atmospheric stability conditions. Stable (cold air below) atmospheric conditions would suppress vertical transport, and unstable (warm air below) conditions would enhance vertical transport. Depending on time of day and season of year, stable or unstable stratification conditions could exist that would affect airflow patterns and therefore air quality constituent transport. The magnitude of these effects depends on the degree of stability or instability, which is influenced by surface and air temperature gradients and wind speed. A computational fluid dynamics (CFD) modeling study indicated that unstable conditions had an influence on the size and shape of cavity regions behind idealized buildings as compared to neutral conditions (Olvera et al., 2008).

Air velocity and direction in the wind tunnel are constant, which contrasts with field conditions, where wind speed is typically unsteady and wind direction varies. Mavroidis et al. (2003) compared dispersion of a tracer released upstream of models of urban structures in the field and in a wind tunnel and found that the plume was clearly more dispersed under field conditions. They attributed this finding to wind direction meander in the field. The large zone of reduced *u* behind the building models when perpendicular to airflow in this study would likely grow and shrink with varying wind speed and move laterally with varying wind direction under field conditions. These factors would affect the impact of building orientation and location on off-site transport of air quality constituents from downwind manure storage facilities.

Assessment of 3-D Flow Dynamics

To this point, the focus of the discussion has been on the observed impact of building model arrays on longitudinal air velocity. Turbulent wakes behind obstacles, while exhibiting a reduction in longitudinal air velocity, also exhibit an increase in longitudinal turbulence intensity. These effects are also observed, although generally at a reduced level, in the lateral and vertical planes. To enable a more comprehensive assessment of the effects of the different building model arrays on airflow downstream, velocities and turbulence intensities in all three dimensions were considered (figs. 9, 10, and 11). Mean values of u, v, w, I_u, I_v, and I_w were calculated from data collected from seven grid locations at the 35 mm height (+ symbols in fig. 2). The grid locations within ±100 mm of the control section centerline were selected as they represent the height and breadth at which the airflow dynamics are

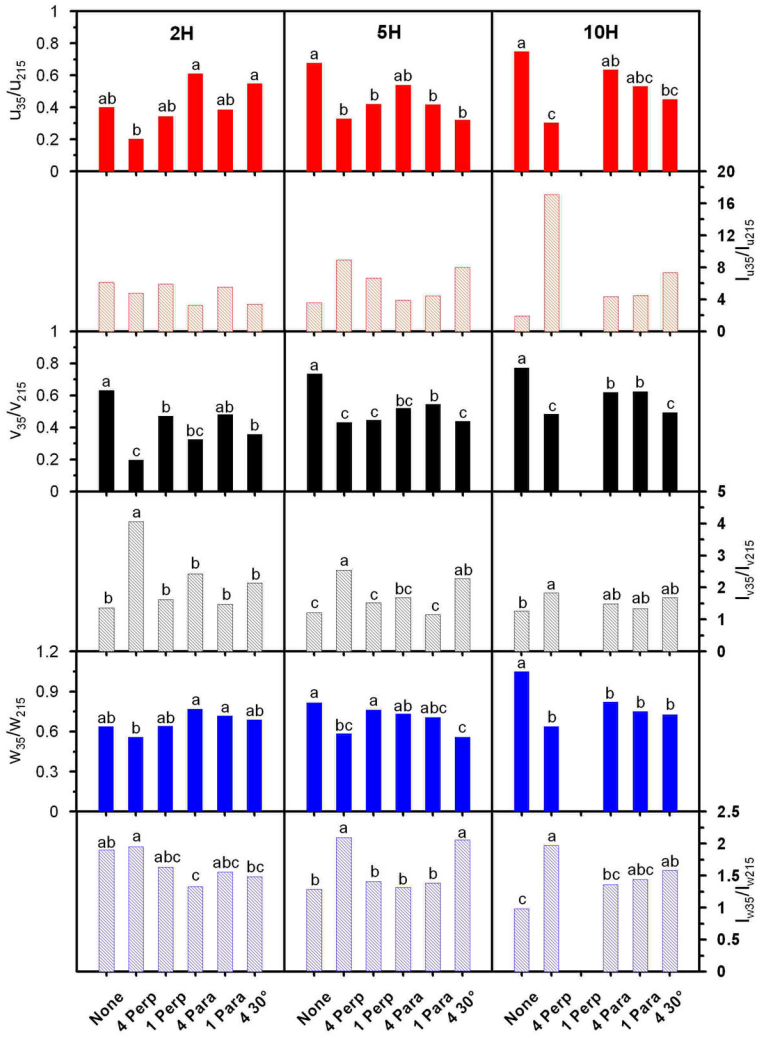

Figure 9. Mean values of *u*, *v*, and *w* and their turbulence intensities (I_u, I_v, and I_w) at 35 mm normalized by their associated values at the reference height (215 mm) for 0.5 m s^{-1} reference velocity for all model arrangements. Bars with the same letter represent no significant difference as determined by the Tukey-Kramer honestly significant difference test (p >0.05). Data were not available for the one perpendicular model (1 Perp) runs at 10H.

most affected by the building arrays. Data from the 35 mm height were selected because they provided both a measure of velocity and turbulence characteristics as influenced by the building models and of airflow properties indicative of the potential for air quality parameter entrainment with the bulk airflow. There was also concern for possible errors or anomalies introduced by operating the hot-film probe when it was positioned too close to the surface. These values were again standardized by dividing by the mean of values collected at the five grid locations at 215 mm (free stream) that were also within ±100 mm of the control section centerline (+ symbols in fig. 2). The resulting ratios of the parameters for all model arrays at the same reference velocities and separation distances were tested for statistically significant differences using the Tukey-Kramer honestly significant difference test (p > 0.05).

For the 0.5 m s^{-1} reference velocity (fig. 9), runs with four perpendicular models had consistently and significantly lower *u*, *v*, and *w* values. In seven of nine cases, the four perpendicular model runs had significantly lower *u*, *v*, or *w* values than the control (no model) runs. The one perpendicular and four 30° model runs generally had values intermediate between the control and four perpendicular model runs. By contrast, runs with one or four parallel models had *u*, *v*, and *w* values closer to those observed for the control, although there were still significant differences in seven of 18 cases. Trends among model arrays for I_u, I_v, and I_w were less clear, with no significant differences for I_u but generally greater I_v and I_w for the four perpendicular and four 30° model runs. The four perpendicular model runs had the greatest I_v and I_w values, although not always significantly greater than the other model arrays. For all model arrays, there was a consistent pattern of arrays with lower mean velocities having greater turbulence intensities.

The significant reductions in *u*, *v*, and *w* with four perpendicular models observed at the 0.5 m s^{-1} reference velocity persisted at the 2 and 5 m s^{-1} reference velocities (figs. 10 and 11). For the 2 m s^{-1} reference velocity, the four perpendicular model runs had *u*, *v*, or *w* values significantly lower than the control runs in eight of nine cases. For the 5 m s^{-1} reference velocity, this was the case in seven of nine cases. Again, smaller and fewer significant reductions in velocities were observed for the one and four parallel model runs, while the one perpendicular and four 30° model runs had intermediate results. There was a less consistent pattern for the turbulence intensities, which were highly variable and without any sig–

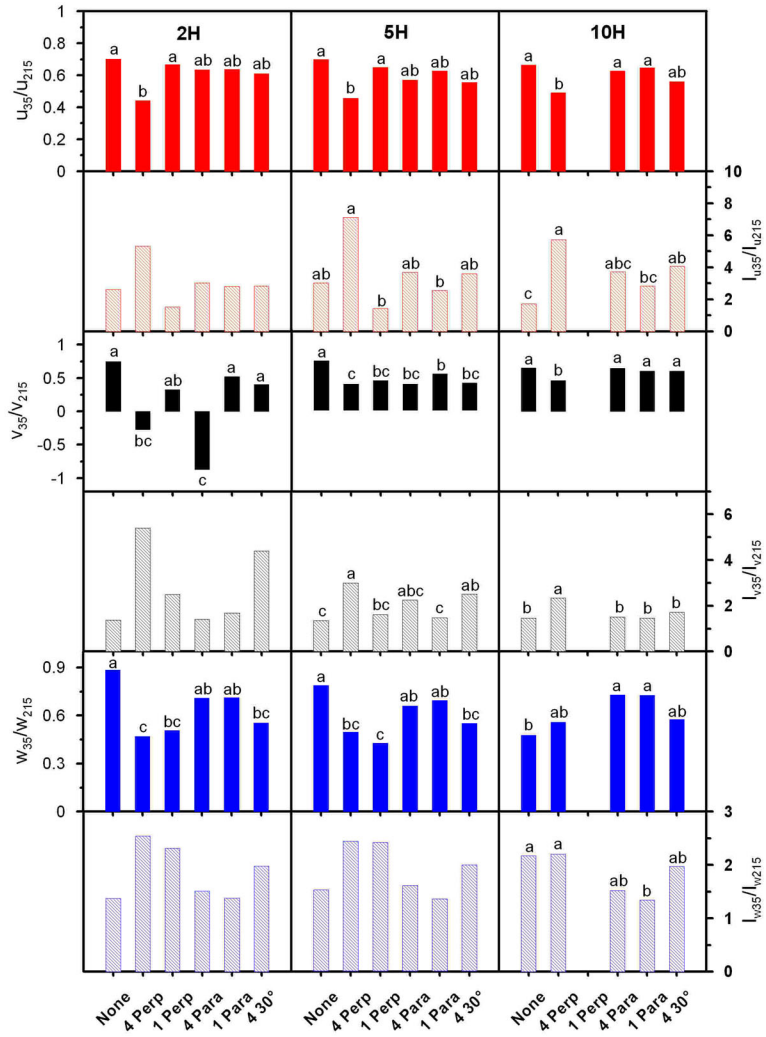

Figure 10. Mean values of *u*, *v*, and *w* and their turbulence intensities (I_u, I_v, and I_w) at 35 mm normalized by their associated values at the reference height (215 mm) for 2 m s^{-1} reference velocity for all model arrangements. Bars with the same letter represent no significant difference as determined by the Tukey-Kramer honestly significant difference test (p > 0.05). Data were not available for the one perpendicular model (1 Perp) runs at 10H.

nificant differences for 10 of 18 sets of wind tunnel runs. Nonetheless, the four perpendicular model runs had the greatest turbulence intensity in 17 of 18 cases, with the one perpendicular and four 30° model runs having the next highest values.

Although there are some consistent and discernable trends exhibited in figures 9, 10, and 11, there are also instances where relationships among model runs do not persist or even reverse with changing velocity and/or separation distance. This pattern of results could simply reflect the already mentioned highly complex nature of turbulent flow in the near-wake of solid obstacles. Examination of the Reynolds stress data helped clarify the inconsistent trends observed for air velocity and turbulence intensity (fig. 12). For each reference velocity and separation distance, the four perpendicular model array had the highest normalized Reynolds stress and was significantly higher for all 2 and 5 m s^{-1} runs. From these data, it is clear that there was consistently significantly greater vertical momentum transport downstream from the four perpendicular model array at all velocities and separation distances.

Perhaps the relevant question is: what are the consequences of any of the observed differences in mean velocities, turbulence intensity, and momentum transport with regard to transport of air quality constituents? Within the region of reduced mean *u*, *v*, and *w*, greater turbulence intensity implies that there is greater variation in velocity and more intense turbulent mixing. Rather than reduce the transport of air quality constituents, greater mixing near the surface may instead enhance surface-atmosphere exchange (Raupach et al., 1991; Prueger et al., 2008). Under field conditions, even when the mean wind speed is reduced, turbulent eddies may sweep across the surface and entrain particulates and trace gases more effectively than by diffusion alone. The proportion of these particulates and gases that are simply mixed and recirculated within the wake zone vs. ejected and transported away by convection or dispersion would depend on a complex set of factors relating to the characteristics of the wake zone and other site factors. These factors include wind speed and direction and their variation, atmospheric stability, surface and air temperatures, source characteristics (type of manure and manure storage structure), and the nature of surrounding obstacles as they affect the approach flow (uniformity of land cover, trees, hills, slopes, and other buildings).

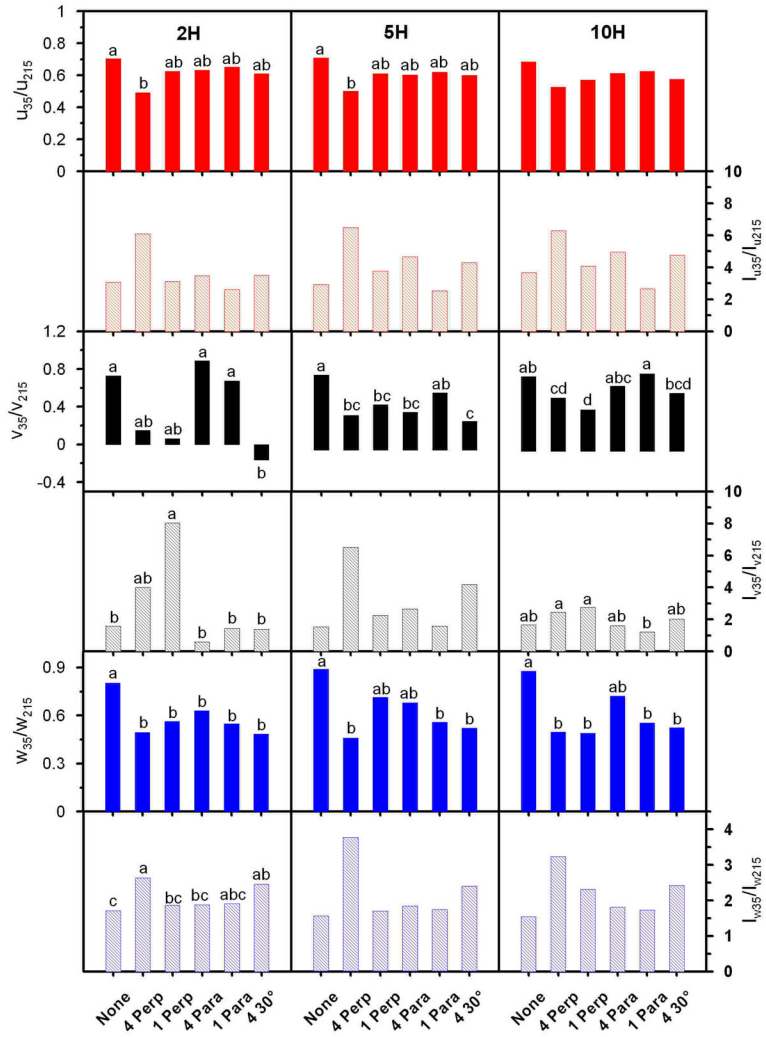

Figure 11. Mean values of *u*, *v*, and *w* and their turbulence intensities (I_u, I_v, and I_w) at 35 mm normalized by their associated values at the reference height (215 mm) for 5 m s^{-1} reference velocity for all model arrangements. Bars with the same letter represent no significant difference as determined by the Tukey-Kramer honestly significant difference test (p > 0.05).

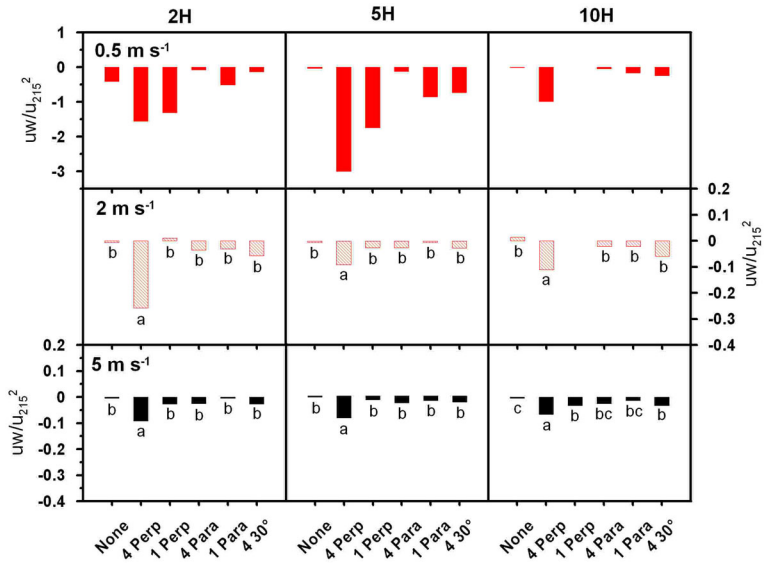

Figure 12. Values of vertical Reynolds stress (*uw*, m^2 s^{-2}) for the seven measurement positions at 35 mm directly downstream from the building models (fig. 2) normalized by streamwise air velocity at 215 mm ($u_{215}{}^2$). Bars with the same letter represent no significant difference as determined by the Fisher's protected least significant difference test (p > 0.05). Data were not available for the one perpendicular model (1 Perp) runs at 10H with 0.5 and 2.0 m s^{-1} reference velocities.

Conclusions

The patterns of airflow dynamics observed under controlled conditions in these wind tunnel experiments serve to reinforce the high degree of complexity of flow near animal production facilities under more variable field conditions. This complexity has important and direct implications for reducing emissions and off-site transport of air quality constituents. Without better knowledge and understanding of the airflow dynamics near production facilities, only limited success in improving air quality can be achieved. One of the primary and certainly unanticipated findings of this extensive series of experiments was the large zone of reduced u in the wake of model buildings oriented perpendicular to airflow and the persistence of this wake zone to a distance 10H downstream. The size and strength of this turbulent wake is attributed to the sloping roofs of the building models that, with a frontal vortex under the upwind eave, initiated and sustained a vertical jet and boundary layer detachment. The observed reduction in air velocity up to a distance 10H downstream from multiple buildings oriented perpendicular to airflow suggests that entrainment and transport of air quality constituents from manure storage structures may be reduced when located in this zone. However, increased turbulence in the wake zone and field conditions with variable wind speed and direction and atmospheric stability may counter the reduced velocity and deserve further study to verify the potential for building orientation and spacing to reduce transport of air quality constituents from manure storage structures. In addition, structural features, including the location and number of tunnel, side, and roof fans and their operation features, need to be included in more comprehensive studies.

The challenges facing further progress in the area of airflow near animal production facilities are multiple and significant. The simplified scenarios represented in this study need to be augmented with inclusion of more realistic atmospheric stability conditions and surface variables, including terrain features (hills and slopes) and other obstacles (trees and other changes in surface roughness with vegetation). A broader suite of approaches, including tracers and flow visualization and integration of complementary wind tunnel, scale-model field, and full-scale field studies, may also need to be employed to address this critical aspect of agricultural interaction with the environment.

Acknowledgements

We wish to thank Jadon Kool, Paul Doi, Tom DeSutter, Aaron Reiter, Tom Trausch, James McNaul, Wade Kent, and Shannon Kulisky for their assistance in this study. This research was supported by the National Pork Board (Grant No. 05-118).

References

Ahmad, K., M. Khare, and K. K. Chaudhry. 2005. Wind tunnel simulation studies on dispersion at urban street canyons and intersections: A review. *J. Wind Eng. Ind. Aerodyn.* 93(9): 697-717.

Armitt, J., and J. Counihan. 1968. The simulation of the atmospheric boundary layer in a wind tunnel. *Atmos. Environ.* 2(1): 49-71.

Aubrun, S., and B. Leitl. 2004. Unsteady characteristics of the dispersion process in the vicinity of a pig barn: Wind tunnel experiments and comparison with field data. *Atmos. Environ.* 38(1): 81-93.

Barlow, J. B., W. H. Rae Jr., and A. Pope. 1999. *Low-Speed Wind Tunnel Testing*. 3rd ed. New York, N.Y.: Wiley Interscience.

Barnaud, G., and J. Gandemer. 1979. Dynamic simulation of the atmospheric boundary layer at model scale of 1/250. *J. Ind. Aerodyn.* 4(1): 35-41.

Cermak, J. E., and N. Isyumov, eds. 1999. *Wind Tunnel Studies of Buildings and Structures*. Reston, Va.: ASCE.

Cook, N. J. 1978. Wind-tunnel simulation of the adiabatic atmospheric boundary layer by roughness, barrier, and mixing device methods. *J. Ind. Aerodyn.* 3(2-3): 157-176.

Guo, H., W. Dehod, J. Agnew, J. R. Feddes, C. Laguë, and S. Pang. 2007. Daytime odor emission variations from various swine barns. *Trans. ASABE* 50(4): 1365-1372.

Huber, A. H. 1989. The influence of building width and orientation on plume dispersion in the wake of a building. *Atmos. Environ.* 23(10): 2109-2116.

Huber, A. H., and W. H. Snyder. 1982. Wind tunnel investigation of the effects of a rectangular-shaped building on dispersion of effluents from short adjacent stacks. *Atmos. Environ.* 16(12): 2837-2848.

Irwin, J. 1981. The design of spires for wind simulation. *J. Wind Eng. Ind. Aerodyn.* 7(3): 361-366.

Janssen, L. A. M. 1979. Wind-tunnel modelling of dispersion of odours in the neighbourhood of pig houses. *J. Ind. Aerodyn.* 4(3-4): 391-398.

Le, P. D., A. J. A. Aarnink, N. W. M. Ogink, and M. W. A. Verstegen. 2005. Effects of environmental factors on odor emission from pig manure. *Trans. ASAE* 48(2): 757-765.

Mavroidis, I., R. F. Griffiths, and D. J. Hall. 2003. Field and wind tunnel investigations of plume dispersion around single surface obstacles. *Atmos. Environ.* 37(21): 2903-2918.

Mirzai, M. H., J. K. Harvey, and C. D. Jones. 1994. Wind tunnel investigation of dispersion of pollutants due to wind flow around a small building. *Atmos. Environ.* 28(11): 1819-1826.

Oke, T. R. 1987. *Boundary Layer Climates*. 2nd ed. New York, N.Y.: Routledge.

Olvera, H. A., A. R. Choudhuri, and W.-W. Li. 2008. Effects of plume buoyancy and momentum on the near-wake flow structure and dispersion behind an idealized building. *J. Wind Eng. Ind. Aerodyn.* 96(2): 209-228.

Plate, E. J. 1982. *Engineering Meteorology*. New York, N.Y.: Elsevier.

Prueger, J. H., W. E. Eichinger, L. E. Hipps, J. L. Hatfield, and D. I. Cooper. 2008. Air-flow distortion and turbulence statistics near an animal facility. *Atmos. Environ.* 42(14): 3301-3314.

Raupach, M. R., R. A. Antonia, and S. Rajagopalan. 1991. Rough-wall turbulent boundary layers. *Appl. Mech. Rev.* 44(1): 1-25.

Reynolds, S. J., K. J. Donham, J. Stookesberry, P. S. Thorne, P. Subramanian, K. Thu, and P. Whitten. 1997. Air quality assessments in the vicinity of swine production facilities. *J. Agromed.* 4(1-2): 37-45.

Schiffman, S. S. 1998. Livestock odors: Implications for human health and well-being. *J. Animal Sci.* 76(5): 1343-1355.

Simiu, E., and R. H. Scanlon. 1996. *Wind Effects on Structures: Fundamentals and Applications to Design*. New York, N.Y.: John Wiley and Sons.

Snyder, W. H. 1981. Guideline for fluid modeling of atmospheric diffusion. EPA-600/8-81-009. Washington, D.C.: U.S. Environmental Protection Agency.

Taylor, P. A. 1988. Turbulent wakes in the atmospheric boundary layer. In *Flow and Transport in the Natural Environment: Advances and Applications*, 270-292. W. L. Steffen and O. T. Denmead, eds. Berlin, Germany: Springer-Verlag.

Tieleman, H. W., and T. A. Reinhold. 1978. On the wind-tunnel simulation of the atmospheric surface layer for the study of wind loads on low-rise buildings. *J. Ind. Aerodyn.* 3(1): 21-38.

VDI. 2000. VDI Guideline 3783/12: Physical modeling of flow and dispersion processes in the atmospheric boundary layer: Application of wind tunnels. Berlin, Germany: Beuth Verlag.

Wooding, R. A. 1968. A low-speed wind tunnel for model studies in micrometeorology. Tech. Paper No. 25. Canberra, ACT, Australia: CSIRO, Plant Industry Division.

Zahn, J. A., J. L. Hatfield, Y. S. Do, A. A. DiSipirito, D. A. Laird, and R. L. Pfeiffer. 1997. Characterization of volatile organic emissions and wastes from a swine production facility. *J. Environ. Qual.* 26(6): 1687-1696.