ABSTRACT: A three-dimensional computational fluid dynamics (CFD) dispersion model was developed to simulate odor dispersion from a 3000-sow farrowing farm. The measured odor emission data were used in the CFD model to predict odor concentrations under 30 different meteorological conditions. Atmospheric stability and wind, and temperature vertical profiles in the atmosphere were configured in the CFD calculation, and their effects on odor dispersion were evaluated. A Lagrangian discrete phase model driven by a large-eddy simulation (LES) turbulent flow field was presented in the CFD model to predict downwind odor concentration. This Eulerian-Lagrangian approach solved for continuous airflow in the Eulerian reference frame and then solved for trajectories of discrete odor gas parcels (OGPs) in a Lagrangian reference frame. The CFD modeling results were compared with results obtained by the CALPUFF model, a Lagrangian puff model recommended by the U.S. Environmental Protection Agency. The results of both models showed that odor traveled farther under stable conditions than under unstable conditions with the same wind speed. Under the same atmospheric stability category, odor concentrations were higher at lower wind speed than that at greater wind speed. Stronger odor concentration and longer travel distance were favored with stable atmospheric conditions and lower wind speed. Odor concentration results predicted by the CFD model were higher than those predicted by the CALPUFF model in short distances (less than 300 m). Beyond that, CFD predictions were higher than CALPUFF predictions under categories A, B, C, and D, and lower than CALPUFF prediction under category F. The gaps in the odor concentration predictions at longer distances remained stable and were influenced by atmospheric stability category and wind speed.

Keywords. Air dispersion modeling, CALPUFF, CFD, Computational fluid dynamics, Fluent, Odor, Swine.

Concentrated animal feeding operations (CAFOs) boomed throughout North America in the last decade. The industry’s growth raised concerns about the environmental and health impacts of odor emissions on neighboring residents. Schiffman et al. (2001) reported that 411 compounds were found in odorous emission from swine facilities. Livestock odors have become a nuisance to neighboring residents and cause physiological and psychological health responses. Many states and provinces in the U.S. and Canada address this odor problem directly or indirectly in local regulations by legislating setback distances, requiring permits, and setting restrictions (Redwine and Lacey, 2000). Either field odor measurement or dispersion modeling can be used to determine downwind odor concentration for the purpose of regulation. It is becoming more common to use air dispersion models to predict livestock odor concentration due to the ability of such models to account for a wide variety of meteorological and topographical conditions (Sheridan et al., 2004).

Most air dispersion models that have been used to predict odor dispersion were originally developed for industrial sources as regulatory tools, e.g., ISCST3, a model designed to support the U.S. Environment Protection Agency’s (U.S. EPA) regulatory modeling programs; AUSPLUME, developed to serve as a regulatory dispersion model in Australia by the Australian Environmental Protection Authority (AEPA); and INPUFF-2, originally developed by the U.S. EPA, but now marketed commercially by Bee-Line Software Co. (Asheville, N.C.). These models are all based on Gaussian plume or puff dispersion models. Sheridan et al. (2004) used ISCST3 to assess the odor impact from a 1000-sow integrated pig unit in Ireland. The ISCST3 model with data from three meteorological stations was used to develop a new odor annoyance criterion and to assess the effects of abatement techniques on odor impact, e.g., exhaust vent modification, feed manipulation, and biofiltration (Sheridan et al., 2004). Zhu et al. (2000) and Guo et al. (2001a) evaluated INPUFF-2 for short distances (<500 m) with odor field plume data collected by trained field assessors on 20 farms in Minnesota, and for long distances with odor measurement data obtained by trained resident odor observers on a 4.8 × 4.8 km rural area. The results showed that the INPUFF-2 model was able to predict the downwind odor levels at distances of 100, 200, and 300 m from odor sources with confidence of 95%, 92%, and 81%, respectively, and the model also estimated odor intensity 1 (faint odor) traveling up to 3.2 km under stable atmospheric conditions with overall agreement of 81.8%. 
between measured and predicted values. However, the model cannot be directly used to predict odor dispersion; scaling factors of 10 for manure storage sources and 35 for building sources are used to amplify the model predictions to the same magnitudes of field odor measurement results.

CALPUFF (Earth Tech, Inc., Concord, Mass.), a Lagrangian puff model with the ability to simulate the effects of temporally and spatially varying meteorological conditions on pollutant transport, was a model recommended by the U.S. EPA (U.S. EPA, 1998a). The CALPUFF model is designed to simulate continuous puffs emitted from a source into the ambient wind flow. As the wind flow changes hourly, the path each puff takes follows the new wind flow direction. Puff diffusion is Gaussian, and concentrations are based on the contributions of each puff as it passes over or near a receptor point (U.S. EPA, 1998b). CALPUFF was used to estimate property-line and nearest-neighbor odor intensities and hydrogen sulfide and ammonia concentrations emitted from three hog-finishing feedlots in Wisconsin. Public health impacts were evaluated by comparing CALPUFF prediction of hydrogen sulfide and ammonia concentrations with the corresponding Wisconsin Ambient Air Quality Standards and with the annual-averaged U.S. EPA reference concentration (Baumgartner Environics, 2004). However, no field measurement was conducted to validate the model predictions made by this study. Xing et al. (2006) evaluated CALPUFF and three other models (ISCST3, AUSPLUME, and INPUFF-2) against field odor dispersion measurements. Considering all the measurements, the agreements between the models' predictions and measured odor intensities ranged from 37% to 50%. However, if the measurements with intensity 0 (no odor) were excluded, the agreements were reduced to between 28% and 35%. CALPUFF performed the best. No scaling factor was used in this study.

Meanwhile, the computational fluid dynamics (CFD) method has proved to be an appropriate numerical method for air dispersion modeling (Baklanov, 2000; König and Mokhtarzadeh-Dehghan, 2002; Baik et al., 2003; Pospisil et al., 2004; Riddle et al., 2004; Pullen et al., 2005; Brown and Fletcher, 2005; Scargiali et al., 2005). The CFD method numerically solves the basic governing equations of mass, momentum, and energy within each cell in a discretized modeling domain. The method employs a Eulerian-Lagrangian approach to simulate atmospheric dispersion. The Eulerian-Lagrangian approach solves turbulent airflow within the Eulerian reference frame, and then calculates trajectories of discrete particles in a continuous flow field within a Lagrangian reference frame (Schiffman et al., 2005). The CFD method has supported many turbulence models to simulate turbulent flow in the atmosphere, e.g., Spalart-Allmaras model, k-ε model and variants, k-ω model and variants, Reynolds stress mode, and large-eddy simulation (LES) model, which is still the best available approach to turbulence and diffusion modeling in the atmosphere boundary layer (ABL) (Ding et al., 2001).

Many commercial CFD packages, including CFX, Fluent, STAR-CD, and CFD2000, are available now and are extensively applied to the study of atmospheric dispersion in rural and urban areas (König and Mokhtarzadeh-Dehghan, 2002; Baik et al., 2003; Pospisil et al., 2004; Riddle et al., 2004; Pullen et al., 2005; Brown and Fletcher, 2005; Scargiali et al., 2005). Bjerg et al. (2004) applied Fluent 5 (Fluent, Inc., Lebanon, N.H.) to predict the dispersion of exhausted air from mechanically ventilated livestock production facilities. Comparison with the full-scale tracer gas measurements (SF6) indicated that the CFD method was a suitable technique to predict the spreading of exhausted air 50 to 150 m from a livestock building. Pullen et al. (2005) assessed the spatial extent of contaminated regions resulting from hypothetical airborne agent releases in Washington, D.C., and Chicago using a Gaussian puff model (SCIPUFF, Titan Group, San Diego, Cal.) and an urban CFD model (FAST3D-CT, Laboratory for Computational Physics and Fluid Dynamics at the Naval Research Laboratory, Washington D.C.). The model grid consisted of a 1 m resolution building database on a flat terrain. The modeling domain was 860 × 580 × 40 levels for Washington, D.C., and 360 × 360 × 55 levels for Chicago. The study found that it was essential for either CFD or Gaussian puff models to receive accurate, high-resolution spatial and temporal information about the winds in order to improve forecasts of contaminant fate. Scargiali et al. (2005) simulated the dispersion of heavy gas clouds over a 30 × 30 km² topographically complex area in Sicily, Italy, with CFX version 4.4 (AEA Technology, Harwell, U.K.) with the k-ε turbulence model. The study found that the effects of atmospheric stability on the dispersion characteristics of the environment resulted in very strong, stable atmospheric conditions giving rise to the highest ground-level concentrations.

The use of the CFD method for air dispersion studies may be found in the literature; however, many research issues in this area need to be clarified and validated. For most of the studies, only the vertical wind profile in the atmosphere was considered in simulation (Bjerg et al., 2004; Riddle et al., 2004; Pullen et al., 2005; Brown and Fletcher, 2005). The methodology is still under investigation to determine whether CFD can consider temperature profiles in terms of atmospheric stability in the planetary boundary layer (PBL), the part of the atmosphere nearest to the ground. Although atmospheric stability plays a key role in air dispersion, current limited CFD applications do not consider the effects of atmospheric stability on air dispersion (Bjerg et al., 2004; Riddle et al., 2004; Pullen et al., 2005) or only simulate dispersion under stable meteorological conditions (Brown and Fletcher, 2005). This is due to the complexities of making use of potential temperature, which is one of the methods used to describe stability in PBL.

There is also the question of how the CFD method performs compared with widely used traditional dispersion models. Very few comparisons have been done to compare CFD modeling results with results predicted by regulatory dispersion models. Brown and Fletcher (2005) used CFX4 and CFX5 to predict odor dispersion and plume visibility up to 4 km downstream of calciner stacks in western Australia. The CFD predictions were compared with results obtained by other dispersion models, e.g., AUSPLUME, TAPM, and CALPUFF. The CFD results were in good qualitative agreement with the results of the other models and demonstrated that the CFD method could be used in a complimentary fashion to develop engineering solutions to reduce the impact of emission from an industrial plant. Ruby and McAlpine (2004) simulated kitchen odor dispersion in urban microenvironments with Fluent 5 and found that the results were comparable with results obtained by IS CST3 and a newer U.S. EPA model, AERMOD. The CFD method demonstrated the most promise for simulation because it provided the
opportunity to examine the results more completely. However, the odor sources for the above comparison studies were industrial sources or urban sources. The odor constituents and emissions from such sources are completely different from the odor emitted from CAFOs, which have ground-level emitting height, low emission rate, and low emitting temperature.

In this study, a three-dimensional CFD dispersion model was developed to simulate odor dispersion from a 3000-sow farrowing farm in Manitoba, Canada. The objectives of this study are to: (1) develop a three-dimensional CFD model to predict odor concentration from CAFOs under different atmospheric stability categories, and (2) compare the prediction results of the CFD model with results from a CALPUFF model.

MATERIALS AND METHODS
FARM DESCRIPTIONS
A 3000-sow farrowing operation located in southern Manitoba, Canada, was selected for this study. The farm has a barn and open single-cell earthen manure storage (EMS) (fig. 1). The barn is mechanically ventilated with 84 wall-mounted exhaust fans. Liquid manure is stored in underfloor shallow gutters and removed to the outdoor EMS once every three weeks. The farm is surrounded by flat cropland. Detailed farm descriptions were given by Zhang et al. (2005). Odor emission rates from the barn and the EMS taken by Zhang et al. (2005) were used in this study; the average odor emission rates were 129,267 OU/s for the barn and 191,923 OU/s for the EMS.

CFD NUMERICAL MODEL
The commercial CFD package Fluent version 6.1 (Fluent, Inc., Lebanon, N.H.) was used in this study. Configurations of odor emission data and meteorological factors were explored in Fluent to consider the effects of atmospheric stability, temperature, and wind vertical profiles in PBL. A Lagrangian discrete phase model driven by an LES turbulent flow field was presented in the CFD model to predict downwind odor concentrations. This Eulerian-Lagrangian approach solves continuous airflow in the Eulerian reference frame and then solves trajectories of discrete particles in the Lagrangian reference frame. Discrete “odor gas parcels” (OGPs) are used in the Eulerian-Lagrangian approach rather than sensations because this approach predicts the dispersion of physical odorants (Schiffman et al., 2005).

Grid Generation
The CFD method numerically solves the basic governing equations in conservation form on a discretized domain. The first step in CFD modeling is the determination of the modeling domain. To study the odor dispersion from CAFOs, the animal facilities and ambient atmosphere were included in the modeling domain. In this study, a full three-dimensional cylinder with a 5000 m radius ground plane and 200 m height was constructed as the CFD modeling domain for odor dispersion. The barn and the EMS were located at the center of the ground plane (fig. 2), and 5000 m downwind from the animal facilities was considered sufficient to cover the typical setback distance recommended by current regulatory guidelines, which is around 400 to 3000 m (Guo, 2001a). Compared with high plume rise from industrial sources (i.e., stacks), the odor emitting level of animal facilities is very low and close to the ground, so the height of the top plane was set at 200 m, which was enough to cover the area for odor dispersion.

The modeling domain was then divided into 16 wedge-shaped parts in accord with the meteorological definition of wind directions (fig. 2). The wedge-shaped divisions were very convenient for wind direction configuration in boundary conditions. For example, if the wind blew from the west, then the circumferential planes of the western divisions were constructed as airflow Velocity-Inlet boundary conditions and the opposite planes on the eastern divisions were set as Pressure-Outlet boundary conditions in Fluent.

The domain was discretized by a non-structural grid strategy. The grid density was not uniform throughout the entire domain. The grid was denser in the vicinity of the animal facilities and in the layer near the ground, and the grid became coarser with increased altitude and distance from the sources. This kind of grid generation approach ensures a high degree of grid precision in the area closer to the odor sources with a lower total cell number. The higher the cell number in the domain, the greater the computation effort would be. There were a total of 200,000 cells in the CFD modeling domain in this study. All the geometrical body constructions

Figure 1. Outline of the swine farm (rooms 1 to 13 = farrowing; rooms 14 to 17 = breeding/gestation).

Figure 2. CFD modeling domain and grid generation.
in the modeling domain and grid generation were completed in GAMBIT (geometry and mesh building intelligent tool-kit), a pre-processor for Fluent.

**Governing Equations**

Assuming that airflow is remains at a steady state and there are no chemical reactions or species diffusion, the governing equations in CFD modeling are known as Navier-Stokes equations, which consist of the following (Fluent, 2003):

- **Mass or continuity equation:**
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
  \] (1)

- **Momentum equation:**
  \[
  \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \mathbf{\tau} + \rho \mathbf{g}
  \] (2)

- **Energy equation:**
  \[
  \frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \mathbf{v} E) = \nabla \cdot (k \mathbf{v} T) + \nabla \cdot \mathbf{\tau} + S_h
  \] (3)

where
- \(\rho\) = air density (kg/m³)
- \(\mathbf{v}\) = wind speed (m/s)
- \(p\) = static pressure (Pa)
- \(\mathbf{\tau}\) = stress tensor (N/m²)
- \(\rho \mathbf{g}\) = gravitational body force (N)
- \(k\) = thermal conductivity (cal/s)
- \(S_h\) = energy source item (J)

and \(E\) is the total (stagnation) energy (J):

\[
E = h - \frac{p}{\rho} + \frac{\mathbf{v}^2}{2}
\] (4)

where \(h\) is sensible enthalpy (J/kg).

The Boussinesq model was activated in Fluent to simulate the thermal-buoyancy effect because the air temperature differences in the modeling domain were not large in this study. The Boussinesq model can get faster convergence for natural convection flow compared to setting air density as a function of temperature. The model treats air density as a constant in all governing equations, excluding the buoyancy term in the momentum equation, in which \(\rho\) is expressed as:

\[
\rho = \rho_0(1 - \beta \Delta T)
\] (5)

where
- \(\rho_0\) = air density at reference temperature (kg/m³)
- \(\beta\) = thermal expansion coefficient (K⁻¹)
- \(\Delta T\) = difference of practical temperature and the reference temperature (K).

Turbulent airflow is characterized by a fluctuating flow field. The small-scale, high-frequency fluctuations in a turbulent flow are very time-consuming to calculate directly using the governing equations. CFD method employs two approaches to solve turbulent flow: Reynolds-averaged process, and LES filtering. LES filtering computes only the large eddies that are responsible for most turbulent transports of momentum, heat, and mass in the flow and filters out eddies smaller than the size of the filter, which is usually taken as the cell size. The LES model was applied in this study to solve turbulent airflow in PBL within the Eulerian reference frame, and a subgrid model (the Smagorinsky-Lilly model) was used to describe subgrid-scale stresses resulting from the filtering operation. The parameters for the LES model were set as the default values in Fluent.

A Lagrangian discrete phase model (LDPM) was used to describe odor parcel emission and dispersion within the Lagrangian reference frame. The uncoupled procedure in Fluent for solving the steady-state Lagrangian discrete phase problem is: (1) solve the continuous phase flow, (2) inject the discrete phase to the flow; and (3) track the discrete phase particles and calculate the trajectories of the particles. Fluent predicts the trajectory of discrete phase particles by integrating the force balance on the particles (Fluent, 2003). In this study, forces considered for the force balance of OGP were drag force, gravity, Brownian force, and thermophoretic force due to air temperature gradient in atmosphere.

**Odor Emission from the Source**

The method used to handle odor sources in Fluent was explored in this study. The surface of the EMS and the areas of the wall-mounted exhaust fans were treated as surface injection types in Fluent. Odor gas parcels (OGPs) were continuously released from the injection surfaces with specific velocity and temperature. The temperature of the parcels was set at 32 °C, which was the same as the temperature inside the barn and at the surface of the EMS. The measured odor emission rates for the barn and the EMS were input in Fluent as injection flow rates with the unit defined as OU/s, corresponding to a mass concentration of g/s. OGP were defined as very tiny particles (10⁻⁶ m diameter). The number of emitted OGP was determined by injection flow rate and particle diameter and was calculated automatically by Fluent.

After release from the injection surfaces, the OGP were neutrally buoyant and moved with the wind. The changes in the speed and direction of the OGP instantly followed the changes in wind speed and direction. The dispersion of parcels due to turbulent airflow was predicted by the stochastic tracking model, which included the effect of instantaneous turbulent velocity fluctuations on the parcel trajectories through the use of stochastic methods. Odor concentrations within the domain were represented by calculations of the trajectories of all parcels in the domain except those that escaped and aborted. The odor concentrations at the receptors were exported in Fluent by a function of discrete phase concentration. The receptors were 1.5 m above the ground (nose height).

**Boundary Conditions**

Boundary conditions specified the flow and thermal parameters on the boundaries of the CFD physical model. The boundaries of the modeling domain in this study included the circumferential planes and the top plane of the domain, the barn walls, the ground, and the surface of the EMS.

The circumferential planes were defined as Velocity-Inlet or Pressure-Outlet boundary conditions according to their positions relative to the wind direction. The LES turbulence model did not specify turbulence characteristics at the velocity inlet. Instead, the stochastic components of the flow at the inlet boundary were accounted for by superposing random perturbations on individual velocity components (Fluent, 2003). In the Velocity-Inlet panel in Fluent, wind
was specified as either three components (x, y, and z components) or wind direction and magnitude. Wind and temperature vertical profiles at the Velocity-Inlet boundaries were configured by a user-defined function in Fluent in terms of the atmospheric stability category. The configuration was the same within the entire domain, as stated in the following section. The pressure at the Pressure-Outlet boundaries was set as normal atmospheric pressure. The top plane of the domain was defined as the symmetry boundary condition.

The barn walls, the ground, and the surface of the EMS were configured as wall boundary conditions in Fluent. Walls are the main source of mean vorticity and turbulence in the domain, and it is in the near-wall region that the solution variables have large gradients. Therefore, accurate modeling of the flow in the near-wall region is crucial to successful predictions of wall-bounded turbulent flows. If the grid is too coarse to resolve the laminar sublayer, then the LES turbulence model assumes that the centroid of the wall-adjacent cell falls within the logarithmic region of the boundary layer, and wall boundary conditions employ a law-of-the-wall approach (Fluent, 2003). The ground of the modeling domain was defined with 0.1 m roughness, the same as the roughness specification of unirrigated agricultural land in the CALPUFF model. The energy of solar radiation is transferred to the ground surface and then heats the surrounding air by conduction, convection, and radiation, so solar radiation was set as a source in terms of energy and added to the whole ground of the domain.

**Solution Initializing and Control**

After being emitted from CAFOs, odor is dispersed in the atmosphere vertically and horizontally. The dispersion in the vertical direction is largely dominated by atmospheric stability, which is driven by the atmospheric temperature gradient. The negative temperature gradient in the atmosphere is called lapse rate and reflects turbulent meteorological conditions classified by atmospheric stability categories. Atmospheric stability is classified into three states according to the lapse rate: unstable, neutral, and stable. A neutral condition is defined as one in which the lapse rate is equal to the dry adiabatic rate (DAR) of 9.8 K/km, while a stable condition has a lapse rate less than DAR, and an unstable condition has a lapse rate higher than DAR. Pasquill stability categories evaluate atmospheric stability with readily available meteorological data, which is the most frequently used classification system in air dispersion models. It is based on the wind speed and either daytime solar radiation or nighttime cloudiness and includes six categories that correspond to different meteorological conditions (Pasquill, 1971): A (strongly unstable), B (moderately unstable), C (slightly unstable), D (neutral), E (slightly stable), and F (moderately stable). In this study, the air temperature vertical profile was configured by the lapse rate according to Pasquill stability categories.

Wind speed increases with altitude in PBL according to the power law relationship. If the observed wind speed at reference height 10 m is \( u_{10} \), then wind speed at height \( z(u_z) \) is defined by equation 6 (Heinsohn and Kable, 1999):

\[
    u_z = u_{10} \left( \frac{z}{10} \right)^p
\]

**Table 1. Power law exponent (\( p \)) for different atmospheric stability categories in a rural area (Heinsohn and Kable, 1999).**

<table>
<thead>
<tr>
<th>Stability Category</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>0.07</td>
<td>0.07</td>
<td>0.10</td>
<td>0.15</td>
<td>0.35</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The power law exponent (\( p \)) depends on the atmospheric stability category. The relationship of \( p \) to the atmospheric stability category is shown in table 1 (Heinsohn and Kable, 1999). The value under category F is the greatest as compared to the other categories. The more unstable the atmosphere, the less the power law exponent of the wind profile will be.

In this study, wind and temperature vertical profiles were configured within the entire CFD modeling domain and the Velocity-Inlet boundary in terms of atmospheric stability. The profiles within the entire modeling domain were configured in the solution initialization procedure in Fluent. The profiles were programmed by C codes in user-defined functions and compiled in Fluent at the beginning of the iteration calculation.

**CALPUFF Model**

The CALPUFF air dispersion modeling system includes three components: CALMET, CALPUFF, and CALPOST. CALMET is a meteorological model that develops hourly wind and temperature fields on a three-dimensional gridded domain. CALPUFF is a dispersion model that simulates the dispersion and transformation process of “puff” materials emitted from the source. CALPOST is a post-processing program for simulation results (U.S. EPA, 1998a). The CALPUFF modeling system defines three-dimensional grid systems for the use of meteorology and computation. The meteorological grid defines land use, winds, and other meteorological variables, while the computational grid defines the extent of the concentration calculations. In this study, the computation grid was constructed identically to the meteorological grid, which covered the domain with 5000 m downwind distance and 2000 m width. The resolution of the horizontal grid size was 200 m. The vertical grid had two layers stretched at 10 m and 200 m heights. A flat terrain and unirrigated agricultural land with 0.1 m ground roughness was defined in the CALPUFF model. The wind profile was defined as ISC rural type in CALPUFF, in which the power law exponent (\( p \)) was defined as the same value as that in table 1.

A Cartesian coordinate system was constructed in both models. The x axis was oriented east, the y axis was oriented north, and the z axis was vertically upward. The zero point was at the center point between the barn and the EMS. The barn and the EMS were treated as area sources in CALPUFF. The height and coordinates of the corners of the barn and the EMS were provided to orient the sources. The measured odor emission rates of the barn and the EMS were divided by their respective areas. Area-averaged odor emission rates, with units of OU m\(^{-2}\) s\(^{-1}\) as required by CALPUFF, were input to the model. Discrete receptors were determined by adding \( x \) and \( y \) coordinates and heights above the ground. The height of all receptors was set at 1.5 m in CALPUFF, the same as in the CFD model.

CALPUFF provides two models to deal with emissions: puff and slug. The puff model considers a continuous plume as a number of discrete parcels of pollutant. Puff diffusion is
a Gaussian distribution, and concentrations are based on the contributions of each puff as it passes over or near a receptor point. The basic equations in the CALPUFF dispersion model for the contribution of a puff at a receptor are given by Scire et al. (2000). As to odor dispersion in the puff model, the odor concentration at a receptor is determined by the following equations:

\[
C = \frac{OE}{2\pi \sigma_x \sigma_y} \cdot g \cdot \exp \left[ -\frac{(x-x_0)^2}{2\sigma_x^2} \right] \cdot \exp \left[ -\frac{(y-y_0)^2}{2\sigma_y^2} \right] \tag{7}
\]

\[
g = \frac{2}{(2\pi)^{1/2}} \sum_{n=-\infty}^{\infty} \exp \left[ -\frac{(H_e + 2nh)^2}{2\sigma_z^2} \right] \tag{8}
\]

where

- \(C\) = ground-level odor concentration (OU/m³)
- \(OE\) = odor emission rate (OU/s)
- \(u\) = wind speed (m/s)
- \(\sigma_x\) = dispersion coefficient along x-axis (wind direction) (m)
- \(\sigma_y\) = dispersion coefficient along y-axis (cross-wind direction) (m)
- \(\sigma_z\) = dispersion coefficient along z-axis (vertical direction) (m)
- \(x_0\) = x-coordinates of puff center (m)
- \(y_0\) = y-coordinates of puff center (m)
- \(g\) = vertical term of the Gaussian equation (m)
- \(H_e\) = effective height above the ground of the puff center (m)
- \(h\) = mixed-layer height (m).

The slug model is designed to handle local-scale dispersion for which the integrated puff approach is not suitable. The slug can be considered as a group of stretched puffs with very small separation distance. The hourly averaged pollutant mass is spread uniformly within the slug. In this study, the slug model was applied in CALPUFF modeling. The concentration for the presence of a slug at a receptor is described by equation 9 (Scire et al. 2000):

\[
C(t) = \frac{F \cdot OE}{(2\pi)^{1/2} \cdot u' \cdot \sigma_y} \cdot g \cdot \exp \left[ -\frac{(y-y_0)^2}{2\sigma_y^2} \cdot \frac{\bar{u}^2}{u'^2} \right] \tag{9}
\]

where

- \(\bar{u}\) = vector mean wind speed (m/s)
- \(u'\) = scalar wind speed (defined as \(u' = (\bar{u}^2 + \sigma_u^2)^{1/2}\) with \(\sigma_u\) = wind speed variance)
- \(F\) = causality function
- \(g\) = vertical term in equation 8.

**Table 2. Meteorological conditions for odor dispersion modeling.**

<table>
<thead>
<tr>
<th>Stability Category</th>
<th>Wind Speed Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A1: 1 m/s; A2: 2 m/s; A3: 3 m/s</td>
</tr>
<tr>
<td>B</td>
<td>B1: 1 m/s; B2: 2 m/s; B3: 3 m/s; B4: 4 m/s; B5: 5 m/s</td>
</tr>
<tr>
<td>C</td>
<td>C1: 1 m/s; C2: 2 m/s; C3: 3 m/s; C4: 4 m/s; C5: 5 m/s</td>
</tr>
<tr>
<td>D</td>
<td>D1: 1 m/s; D2: 2 m/s; D3: 3 m/s; D4: 4 m/s; D5: 5 m/s; D6: 6 m/s; D8: 8 m/s; D10: 10 m/s; D15: 15 m/s</td>
</tr>
<tr>
<td>E</td>
<td>E1: 1 m/s; E2: 2 m/s; E3: 3 m/s; E4: 4 m/s; E5: 5 m/s</td>
</tr>
<tr>
<td>F</td>
<td>F1: 1 m/s; F2: 2 m/s; F3: 3 m/s</td>
</tr>
</tbody>
</table>

C, and E; nine for D; and three for F. The resulting 30 meteorological conditions are listed in table 2. The air temperature at 10 m above the ground was set at 30°C for all meteorological conditions.

**RESULTS AND DISCUSSION**

**EFFECT OF ATMOSPHERIC STABILITY ON ODOR DISPERSION**

Figure 3 presents CFD prediction results of odor concentration at 1.5 m height within 5000 m after 1 h. The meteorological data in the scenarios were all same except for the atmospheric stability categories. The wind blew from west to east at a speed of 3 m/s, and air temperature was 30°C at 10 m height. For the same wind speed, odor traveled farther under stable conditions than under unstable conditions. The longest traveled distance was found under moderately stable condition A3. Odor travel distance under strongly unstable condition F3 was the shortest as compared with the other conditions. According to regression analysis of odor concentration, odor travel distance for achieving 2 OU/m³ was 860 m under A3 and 5610 m under F3.

Figure 4 shows the odor concentrations at 1.5 m height within 1000 m as predicted by the CFD and CALPUFF models. CFD predictions agreed in principle with CALPUFF predictions (fig. 4). For the same wind speed, downwind odor concentrations were higher under stable conditions than under unstable conditions. According to the CALPUFF prediction, odor travel distance for achieving 2 OU/m³ under A3 was 510 m, which was lower than that predicted by the CFD model, and the odor travel distance under F3 was 7360 m, which was higher than that predicted by the CFD model. However, the odor concentration differences among atmospheric stability categories predicted by CALPUFF were greater than those predicted CFD (fig. 4). CALPUFF was more sensitive to atmospheric stability than the CFD model in odor dispersion prediction. For example, at 200 m downwind, the CFD prediction of odor concentration under F3 was 201 OU/m³, 2.3 times the odor concentration under A3, which was 89 OU/m³. Meanwhile, the CALPUFF prediction of odor concentration under F3 was 188 OU/m³, 7.0 times the odor concentration under F3, which was 27 OU/m³. The comparisons of odor concentration results will be discussed further later.

Unstable meteorological conditions correspond to greater vertical turbulent mixing than stable meteorological conditions. Hence, shorter odor travel distance and lower odor concentration would be expected under unstable meteorological conditions as compared to stable conditions. In contrast, stable meteorological conditions limit the vertical turbulent mixing and odor dispersion in the atmosphere, leading to longer odor travel distance and higher odor concentration.
Figure 3. Odor concentration contours as predicted by the CFD model.
These prediction results by the CFD and CALPUFF models were consistent with the conclusions of Jacobson et al. (2001) and Guo et al. (2001b). Jacobson et al. (2001) found that a large majority of odor nuisance events (71%) were reported during stable weather conditions (categories E and F) at low wind speed. For unstable atmospheric category A (strongly unstable) and B (moderately unstable), odor events were seldom reported. Guo et al. (2001b) predicted odor dispersion using the INPUFF-2 model under different atmospheric conditions and concluded that the more stable the weather was, the farther the odor would travel and the stronger the odor would be. Atmospheric stability plays a substantial role on odor dispersion.
EFFECT OF WIND SPEED ON ODOR DISPERSION

Odor horizontal dispersion is largely driven by wind speed and direction. High wind speed and direction variations help to disperse odor quickly. Therefore, a lower downwind odor concentration would be expected at high wind speed than at lower wind speed. Odor concentration is inversely proportional to wind speed (Guo et al., 2001b). Odor concentrations within 1000 m under different wind speeds for atmospheric stability categories A to F were predicted by the CFD and CALPUFF models and are shown in Figure 5.

Under the same atmospheric stability category, CFD and CALPUFF predictions both indicated that odor concentrations at lower wind speeds were higher than those at greater wind speeds. Within each stability category, the odor concentration differences at different wind speeds were great at the short distance (<300 m), but beyond that distance the differences were small or almost disappeared because odor had already been diluted to very low concentrations. Therefore, the effect of wind speed on odor concentration was more significant within short distances (<300 m) than at longer distances (>300 m). The CALPUFF model was more sensitive to wind speed than the CFD model. For example, at a downwind distance of 200 m, CFD prediction of odor concentration under D1 was 137 OU/m³, 3.5 times the odor concentration under D15, which was 39 OU/m³. Meanwhile, CALPUFF prediction of odor concentration under D1 was 346 OU/m³, 15.7 times the odor concentration under D15, which was 22 OU/m³.

For most of the meteorological conditions, the CFD and CALPUFF models both indicated that the odor concentration decreased with increasing distance from the source. CFD modeling results of odor concentrations within the short distance (<300 m) were higher than CALPUFF modeling results, except under stability category F. In the vicinity of the odor sources (<300 m), odor concentration diminished very rapidly, whereas odor concentration decreased at a much slower rate at longer distances. There are exceptions in the CALPUFF modeling results under atmospheric stability category E and F; odor concentrations peaked at a distance of 200 m instead of 100 m. The odor predictions under categories E and F are similar to the predictions for an industrial source with a high stack, i.e., the highest downwind concentration may occur at a place within a certain distance of the source due to source emission plume rise.

Considering the effects of both wind speed and atmospheric stability, the results of both models suggested that
stronger odor concentration and longer travel distance were favored with stable atmospheric conditions and lower wind speed.

**Comparison CFD and CALPUFF Models Using FB Test**

In addition to the comparison of the two models presented previously, the odor concentration predictions of the CFD and CALPUFF models were compared using the fractional bias method (ASTM, 2000) under different meteorological conditions. The fractional bias (FB) statistical test was recommended by the U.S. EPA (U.S. EPA, 1992) and is defined as:

\[
FB = \frac{2 (\chi_{\text{CFD}} - \chi_{\text{CALPUFF}})}{\chi_{\text{CFD}} + \chi_{\text{CALPUFF}}} \tag{10}
\]

where

- FB = fractional bias between predictions by the CFD and CALPUFF models
- \(\chi_{\text{CFD}}\) = odor concentration predicted by the CFD model
- \(\chi_{\text{CALPUFF}}\) = odor concentration predicted by the CALPUFF model

The FB test is symmetrical and bounded by the values between 2 and -2. A value of zero indicates no bias between CFD and CALPUFF predictions. An FB value of 0.67 is considered as the criterion for agreement, i.e., FB values of ±0.67 are considered to indicate good agreement between two models. One problem with the FB statistical test is that the FB value will be inflated to a value close to ±2 when the odor concentrations predicted by both models are very close to zero. A filter was applied to this scenario with low odor concentration values, i.e., if the mean odor concentration \((\chi_{\text{CFD}} + \chi_{\text{CALPUFF}})/2\) was lower than 0.1 OU/m³, then the FB value was then set to 0.

Figure 6 shows the FB values between the CFD and CALPUFF models under various meteorological conditions. In the vicinity of the odor source (<300 m), the FB value decreased with distance. At a greater distances from the source (>300 m), the FB value increased and then remained stable. Atmospheric stability categories had different effects on the FB value at longer distances. For category A, odor concentrations predicted by the CFD model were higher than those predicted by the CALPUFF for short distances; however, odor concentrations predicted by both models were close to zero at longer distances, and the FB value remained at zero. For categories B, C, and D, the FB value was positive at longer distances, which means that odor concentrations predicted by the CFD model were higher than those predicted by the CALPUFF model. For category E, the models agreed much more than they did for the other categories. For category F, the FB values were negative at the long distance, indicating that odor concentrations predicted by the CFD model were lower than those predicted by the CALPUFF model. Figure 6 also shows that under the same atmospheric stability condition, the higher the wind speed, the lower the absolute FB value was. The difference between the predictions of odor concentrations by the CFD and CALPUFF models was influenced by atmospheric stability, wind speed, and distance to odor source.

The gaps between the CFD and CALPUFF predictions of downwind odor concentration resulted from the different methodologies for odor dispersion employed by the two models. The accuracies of the two models cannot be determined without comparing the model predictions with field odor plume measurements. Further investigations should be done to evaluate CFD and CALPUFF predictions against field odor plume measurement data.

The CALPUFF modeling system was proposed by the U.S. EPA as a guideline model for regulatory applications involving long-range transport and on a case-by-case basis for near-field application (Scire et al., 2000). The modeling system is well-developed and relatively easy to use. However, application of the CFD model to predict odor concentration is still in its infancy. The configuration of the modeling parameters still needs to be explored, and sufficient background knowledge of fluid dynamics and numerical modeling are needed when using the CFD model.

The CALPUFF model was designed to use hourly meteorological data and was intended to calculate the average concentration over a period of hours, days, and years. Odor is a human olfactory response to odorants, and the nuisance of odor is quantified by the following characteristics: concentration, intensity, frequency, duration, and hedonic tone (Sweeten et al., 2002). Zwicke (1998) and Fritz et al. (2005) found that using a 1 h time interval for Gaussian-based dispersion models might result in overestimated downwind concentrations. Using a 1 h computational time interval cannot accurately characterize an instantaneous odor plume (Li and Guo, 2006). The CFD model employed computational time intervals ranging from seconds to hours. Therefore, CFD dispersion modeling has the potential to characterize odor frequency and/or duration at the receptor with a sub-hourly computational time interval.

**Conclusion**

A three-dimensional CFD dispersion model was developed to simulate odor dispersion from a 3000-sow farrowing farm. Thirty meteorological conditions were evaluated, ranging from strongly unstable conditions to moderately stable conditions. Wind and temperature vertical profiles in PBL were configured in the CFD calculation, and their effects on odor dispersion were evaluated. A Lagrangian discrete phase model driven by a LES turbulent flow field was used in the CFD model to predict downwind odor concentration. This Eulerian-Lagrangian approach solved for continuous airflow in an Eulerian reference frame and then calculated trajectories of discrete particles in a Lagrangian reference frame. Odor concentrations predicted by the CFD model were compared with the results obtained by the CALPUFF model, a Lagrangian puff model recommended by the U.S. EPA.

Both the CFD and CALPUFF modeling results indicated that atmospheric stability played a substantial role in odor dispersion from CAFOs. For the same wind speed, odor traveled farther under stable conditions than under unstable conditions. Meanwhile, odor concentration was higher under stable conditions than under unstable conditions.
Under the same atmospheric stability category, the predictions made by both models indicated that odor concentrations at lower wind speed were higher than at higher wind speed. The effect of wind speed on odor dispersion was more significant within the short distance than at the long distance. Therefore, stronger odor concentration and longer travel distance were favored with stable atmospheric conditions and lower wind speed.

Odor concentration predictions by the CFD model were higher than those by the CALPUFF model at short distances (<300 m). Beyond that, CFD predictions were higher than CALPUFF predictions under categories A, B, C, and D, and lower under category F. The gaps in odor concentration predictions at the long distance remained stable and were influenced by atmospheric stability category and wind speed.

The accuracies of the two models are unknown. Further investigation should be done to evaluate CFD and CALPUFF predictions against field odor plume measurement data.

The CALPUFF modeling system is well-developed and relatively easy to use. The application of the CFD model for odor dispersion is still in its infancy; the configuration of modeling parameters still needs to be explored, and sufficient background knowledge of fluid dynamics and numerical modeling are required when using the CFD model. However, the CFD model employed computational time intervals ranging from seconds to hours; thus, it has the potential to characterize instantaneous odor concentrations downwind.

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