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CFD MODELING OF LIVESTOCK ODOR DISPERSION ON COMPLEX TOPOGRAPHY

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ABSTRACT In most countries, odor annoyance from livestock production is an increasing problem in the community. In order to reduce the odor inconvenience and establish a good relation between livestock industries and the surrounding communities, many studies on the odor dispersion, such as diffusion simulations and field experiments have been investigated. Computational fluid dynamics (CFD), one of the well-known simulation techniques, has been effectively and widely used to study this kind of research since CFD considers both various wind conditions as well as topographical conditions to study aerodynamic phenomenon. Therefore, the ultimate objective of the study was to develop an aerodynamic model to predict qualitatively and quantitatively odor dispersion from livestock. Mesh models of mountainous study areas with a 1.8 km radius were built with a 5 m resolution. Modules for the atmospheric phenomena were also made by user defined functions and the scheme extension functions of FLUENT, and linked into a main computing module. The dispersion of odor was predicted by the 3D CFD model based on large eddy simulation and practically agreed to the field measured data. Based on several comparisons, the atmospheric stability was the most effective factor on the distance of the odor dispersion. The direction of dispersion was not depending mainly on wind direction, but also on the topography and the atmospheric stability. Later, this model will be used to predict the odor dispersion according to various meteorological and topographical conditions as well as to arrange the odor-related conflicts.

Keywords: CFD (computational fluid dynamics), Livestock odor, Odor dispersion, Topographical modeling

INTRODUCTION Odor is one of the major nuisances in the environment. In most countries including Korea, odor annoyance from livestock production is an increasing problem in the rural communities. A survey of livestock industries in Korea (2005) revealed that 32.2% of the total livestock farmers had encountered popular complaints for the last 2 years, and about 56% of those were from swine houses (Hong et al., 2008b). More so, increasing recognition of healthy and safe resident environment has led to an increase in odor complaints in the rural areas. In UK, livestock farming is also increasingly confronted with public grievance due to odor nuisances (Schauberger, 2001).

In many countries, standard regulations on separation distance between the odor source and residential areas are being established (Piringer and Schauberger, 1999). However, the extent and rate of diffusion are changeable depending on odor release, odor concentration, atmospheric stability, offensiveness of odor sensation and etc. Topographical features as well as unpredictable and unstable wind condition, such as fluctuating wind speed and changeable wind direction, also disturb the analysis of quantitative odor diffusion. It is therefore relevant to conduct various approaches in studying odor diffusion and verified through field experiments. Until now, some field experiments and simulation approaches have been made for dispersion prediction (Li et al., 2006; Holmes and Morawska, 2006). Field experiment gives the most realistic results while it measures very limited number of observations, even under various changing meteorological conditions. Simulation approach, especially CFD, can predict a detailed air movement and odor spreading with many artificial environmental conditions, and become one of the most powerful tools for studying the atmospheric environments.

Many researches on the use of CFD for the atmospheric dispersion have been conducted. Most of them were focused on modelling the dispersion phenomenon through CFD in flat areas or to neighborhood scale (Riddle et al., 2004; Li and Guo, 2006; Diego et al, 2009). However topographical consideration is very important in Korea because approximately 70 % of land is mountainous. Most troublesome problems are occurred in a low atmospheric environment, which is significantly affected by the shape of the terrain. Therefore detailed terrain modelling is fundamental for simulation of atmospheric dispersion. The design of the atmospheric boundary layer is also the important factor in CFD dispersion analysis. Contrary to the Gaussian-based models, CFD-based research has a great advantage of the detailed air flow prediction even though it needs much computing costs. Conversely, it means it has need of the detailed design of the atmosphere. Thus several researchers have studied the distribution of turbulence quantities in the boundary layer (Yang et al., 2009). They emphasized the importance of designing profiles of turbulence quantities, ground roughness and top boundary condition of domain to maintain the initial profiles designed at boundaries up to object under investigation. However, in most researches, the numerical designs of the meteorological properties were introduced from theoretical approaches and thus they were apt to be disconnected from the real field condition. Therefore further researches would be still required to improve the meteorological modelling for the CFD-based dispersion simulation

The ultimate objective of this research was to develop an aerodynamic model for predicting qualitative and quantitative odor diffusion from livestock. In this paper, methodology of designing a complicated topography was suggested and a three-dimensional grid model was developed with respect to the study area. And then user-defined-function (UDF) modules for modelling physical atmospheric phenomenon was developed and linked to a main computational process to predict a dispersion of livestock odor according to various atmospheric conditions. Study areas and various phenomena of odor diffusion from livestock houses were already investigated from field experiment (Hong et al., 2008). Odor values were determined at a limited number of measuring points with olfactometric method which employs some panellists trained to detect the presence of odor and judge the odor intensity. Weather measurements, such as atmospheric stability, were also simultaneously conducted when odor gases were sampled.

MATERIALS AND METHODS Commercial CFD package FLUENT (ver. 6.3, Fluent Inc., New Hampsher, USA) was used in this study. The GAMBIT and T-Grid were mainly used to create the computational grids. The FLUENT solves the basic governing equations to calculate the air flow in a domain. Physical phenomena implemented by the atmospheric stability were referred to the related researches and connected to the FLUENT by means of the UDF. Additional module was also developed to create transient wind environment.

Topography and environmental conditions of study areas The study area with a livestock farm is located in Cheongyang-gun, Chungcheongnam-do, Korea (36°27′01″N, 126°45′20″E). Several field experiments were already conducted to investigate the odor distributions dispersed to the neighboring territories by Hong et al. (2008a). The 4,000-sow, piglet and fattening pig farm has 5 mechanically-ventilated barns and manure stirrers. The foul odors were mainly emitted from the exhaust fans, chimneys and latent odors absorbed in the soil. The materials of the farm also contributed to the odor generation. The study area has many hills and mountains and the farm was located at the half of the east slope of a mountain. The east, downward from the farm, is formed with paddy fields, dry fields and residence areas, and the north and south of the east are surrounded by mountains, like a valley (Fig. 1 (a)). Hong et al. (2008a) selected Cheongyang area because valley-shaped area was expected to form a stable wind direction to acquire a valuable field data.

Figure 1. (a)Satellite image (left) and (b)digital topographic map (right) of the study area. The dotted square indicates the livestock farm.

Fig. 1 (b) showed a digital topographic map, drawn on a scale of 1 to 5,000, of the study area provided by National Geographic Information System (NGIS). It consists of contour lines and contains elevation and land use information. These contour lines can be used in making a three dimensional computational domain directly or can be converted into a digital elevation model (DEM). Yesan area, another study area, has 2,000-sow, piglet and fattening pig farm with 4 naturally-ventilated barns. The east of the farm is formed with a small pond, paddy fields, dry fields and residence areas, and the north and south of the east area is surrounded by mountains at a height of about 60 m, like a valley (Fig. 2). Designing the computational domain of the two areas was introduced below

Figure 2. Satellite image of Yesan area.

Wind tunnel experiment and simulation for dispersion modelling Wind tunnel located in the National Institute of Agricultural Engineering (NIAE) in Korea was used to examine a diffusion process. It was built for multi-purposes with a dimension of the test area of 2m (W) × 1.7m (H) × 15m (L). For the tracer diffusion experiment, heat dispersion was utilized instead of gas dispersion. Gas was generally used for diffusion experiment but it had difficulty in dealing and detecting the gas. Heat is convenient and economical for measurement and can be a substitute for gas dispersion because heat and gas dispersions theoretically have similar transport equations in a passive dispersion (Yoo et al, 2005). Fig. 3 shows the experimental view of wind tunnel test and layout of temperature measuring points. Heat dispersion experiment was conducted for the 1/100 scaled model in June, 2008. Temperature was measured at a height of 5, 10, and 15 cm heights in each of the 12 points. The wind velocity and turbulence were measured by a x-probe type hot-wire anemometer (IHW-100, Kanomax, Inc., Japan) with 100Hz frequency and the temperature was measured by thermocouples every 10 seconds. For the similarity of air velocity in wind tunnel, the Froude number was used (Lee et al., 2005) and the scale for air velocity was determined as 1/10. The scale for time was also computed as 1/10 by dimensional analysis. A CFD model was designed with the same configurations in the real dimensional size scaling up 100 times the dimensions conducted in the wind tunnel test. In CFD modelling, the diffusion of ammonia gas, which is one of the main components of livestock odor, was compared with the results of wind tunnel test as a CFD validity test using the commercial CFD package FLUENT version 6.3. Some methods and modelling procedures, such as turbulent model, size of grid, computational time step, were tried and the appropriate criterions were determined in this study.

Figure 3. Experimental view of wind tunnel test

Methodology of topographical modelling For lower atmospheric problems, it is becoming an important requirement to design a detailed topographical condition into the computational domain. Building and meshing the grids, as a pre-processing job for CFD or other scientific applications, were generally achieved by user-developed tools or commercial softwares. The reason that analysts use their own tools is to use raw geographic information into the desired form, while the commercial softwares require much time and computational cost to convert the raw information into vertexes, edges, faces and sometimes geometrical volumes (Chin et al., 2004). However, the user-developed tools mostly adopted a structured grid which can deteriorate the mesh quality near irregular or distorted boundaries and steep mountains. These are also needed to be modified when applied to the other related research. On the other hand, commercial tools were preferred to create various unstructured grids and analyse various cases despite the inefficiency of regular routines demanded by the software developer. In this study, several methodologies of topographical modelling by commercial tools were tried because of the convenience of unstructured grid creation and practical applications. Topographical map and the raw geographic information were provided with DXF/DWG files by the National Geographic Information Institute (NGII). It contained roads, land uses, administrative divisions, contour lines, etc. with a 1:5,000 scale. Many methods could be possible in making a three dimensional ground face into GAMBIT, a pre-processor of FLUENT package, but in this paper one of them was selected based from several trials conducted.

After completing the terrain modelling, it should split into the desired shape or size to facilitate a grid meshing and boundary condition set-up. Splitting surfaces was conducted in Rhinoceros because GAMBIT was not powerful to split the complicated three dimensional objects. GAMBIT was used to mesh the surfaces including ground surfaces and boundaries, and to set up the boundary conditions. TGRID was also employed to make three dimensional computation grids and to mesh the grids. GAMBIT is used to be applied in making three dimensional grids, but it didn't work or took much time in this complex and huge geometry because it should create three dimensional volumes by joining the closed boundary surfaces. TGRID fortunately could create three dimensional grids and unstructured grids without creating volumes more efficient and faster. The computation of air flow was achieved in Fluent, the main computational processor, and the developed topographical model was examined by convergence history in Fluent. Air flow pattern near the complex terrains was also examined according the reasonability.

Module for the atmospheric modelling The effect of the atmospheric stability was introduced into the CFD dispersion model by controlling the vertical distributions of wind speed, turbulence quantities and air temperature. The vertical wind profile was calculated from the following familiar expression,

$$\frac{k\,z}{u*}\frac{\partial u}{\partial z}=\phi_m \tag{1}$$

Where, k is the von Karman constant, approximately equal to 0.4; z is the altitude above ground in m; u is the wind velocity in ms^{-1}; $u*$ is the friction velocity in ms^{-1}; ϕ_m is the Monin-Obukhov universal function for non-dimensional momentum.

The vertical air temperature profile assumed that the heat flux is constant within the arbitrary height, and thus it is expressed as a log profile as the follows,

$$\frac{k\,z}{\theta*}\frac{\partial \Theta}{\partial z}=\phi_h \tag{2}$$

Where, Θ is the air temperature in °K; $\theta*$ is the friction temperature or scaling temperature in °K; ϕ_h is the Monin-Obukhov universal function for non-dimensional temperature.

The above vertical profiles were first designed into inlet boundaries, but they needed to extend to the whole domain because the profiles were not maintained throughout the domain. The shapes of profiles were changed by the irregular topography. However in a real atmosphere, the momentum downward flux contributes to upkeep the vertical wind shear and the wind profile. Continuous insolation flux also help to maintain the vertical temperature profile. Therefore the fluxes of momentum and insolation were applied to the CFD model as a source term of the conservation equations of momentum and energy, respectively.

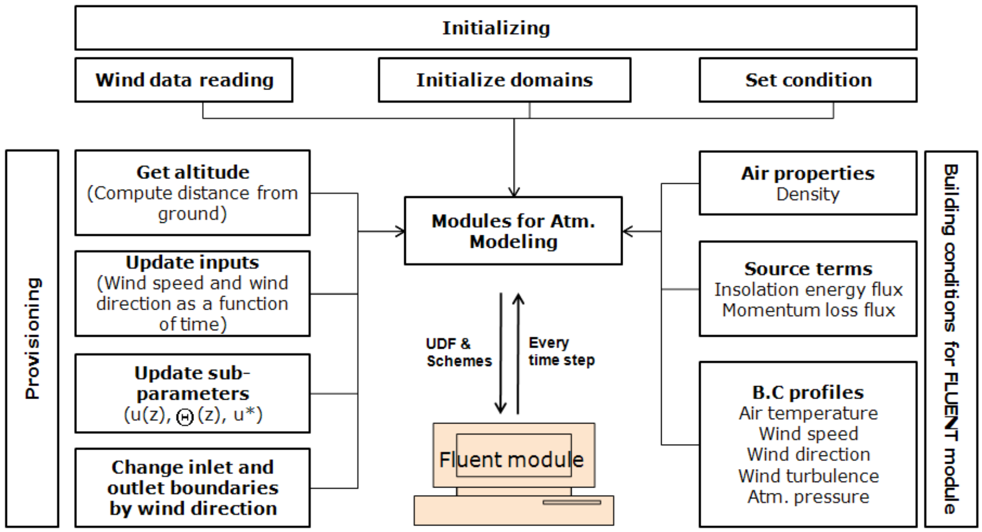

Figure 4. The framework of the module for atmospheric dispersion modelling.

The UDF module was developed for the FLUENT solver to carry out the operation in sync with changing boundary conditions. The module calculates the desired atmospheric environment as well as changes the boundary types from inlet to outlet, or conversely. It consists of three parts - initializing, provisioning and conditions building. In the initializing part, it reads the wind data file composed of wind speed and wind direction in time series. It also initializes the properties inside the domain, set up the necessary initial conditions and synchronizes the computing time with the input data. In the provisioning part, the module calculates the altitudes of all cells and stores them in user defined memory (UDM) of each cell in order to save the troubles of calculating the altitudes repeatedly. It updates the wind speed and wind direction from the input file, and then computes the sub-parameters, like the friction velocity, the friction temperature, etc., which decides the shape of the vertical profiles. It also classifies the boundary type of all the side boundaries, i.e. sorts out the side boundaries by the inlet and outlet, in consideration of the wind direction. The last part of the module is to condition building for the FLUENT computation, e.g. changing physical properties of materials, making vertical profiles to build boundary conditions, making source terms for the conservation equations, taking the required information from FLUENT module, etc. It also issues commands for FLUENT module to change boundary types. The scheme extension functions of FLUENT are especially used to interpret and execute the command of UDF module. The module updates and interact with the FLUENT module every time step.

RESULTS AND DISCUSSIONS

Design criteria from wind tunnel experiment and simulation For the wind tunnel tests, three cases, such as ‘No Block’, ‘Block 1’ and ‘Block 2’, of inlet conditions were made by wooden blocks. Their vertical profiles of mean velocity and turbulent intensity were designed so that ‘Block 2’ case showed to have the most turbulence.

By means of correlation coefficient (R) between the measured temperatures (wind tunnel) and computed gas concentrations (simulation), the appropriate turbulent model, cell size and time step for diffusion modelling were examined. When investigating the widely used turbulent models, such as standard k-ε model, RNG k-ε model, Reynolds stress model (RSM) and large eddy simulation(LES) model, the LES turbulence model was proven to be proper. The others showed low correlation coefficients in strong turbulent case ‘Block 2’ while they showed nearly high correlation coefficients in little turbulent case ‘No Block’ (Figure 5 (a)). Cell size was also an influential factor. The increase of cell size produced low correlations (Figure 5 (b)). Less than 5m size was expected to produce good results. However 10 m size would be possible considering the economical number of cells. Computational time steps of 0.01, 0.1, 1, 10, 30, 60, 600, 3600 s were also tried and small time step led to a more reasonable result. 10 s was also expected to be possible considering the economic feasibility. In this modelling, which had no obstacles, computational time step showed lower influence than the other factors.

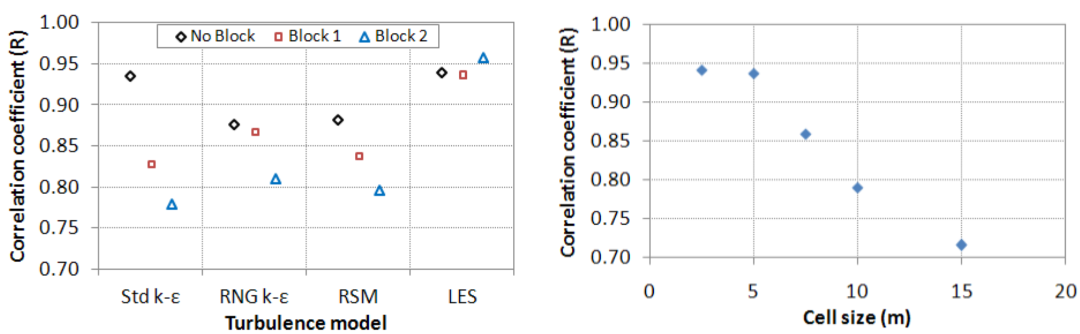

Figure 5. Correlation coefficients between wind tunnel and simulation results with respect to (a)the turbulence models(left) and (b)cell sizes(right).

Topographical modelling and its modification The ground surface was divided into several pieces for convenience of following processes, such as meshing surfaces, setting up boundary conditions, etc., before meshing the surfaces. First it was cut out into a circle to cope with various wind directions. The farm, of course, was located at the center of the map. The circles were constructed with 0.6, 1.2, 1.8 and 2.4 km radiuses in order to make the computational domain into various sizes according to the odor dispersion range and create the different size of mesh by distances from the farm. This also allows the denser meshes in 0.6 km circle which is closer to the farm than 1.2 km circle. All circles except the smallest one were also divided separately into 16 parts, which will be set up with 8 inlets and 8 outlets in accordance with the 16 wind directions. The farm was designed as two 120 m × 60 m rectangles at the center so that they could be selected by the scale of the farm. The complete model with 3.6 km (D) × 2.5 km (H) was created and meshed in TGrid (Fig. 6). The total three dimensional meshes were about 4,371,600 for Cheongyang area and 4,223,735 for Yesan area and consisted of hybrid cells such as hexahedrons and tetrahedrons. The non-conformal interface was adopted to allow relaxing of the requirement for a point-to-point matching at the interface between the different grids - hexahedrons and tetrahedrons. The skewness of meshes was reasonable with an average of 0.2 even though the maximum was about 0.8, which was a little higher.

The convergence was checked with a steady state and the standard k-ε turbulence model as well as with an unsteady state and the LES model. The test results showed a smooth convergence without any divergence.

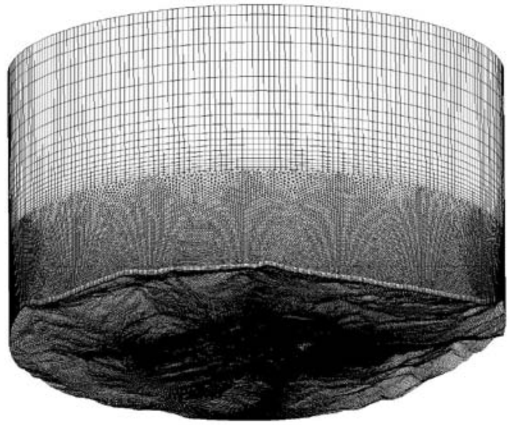

Figure 6. 3D computational domain of Yesan area with 3.6 km (D) × 2.5 km (H) designed in TGrid

Simulation of wind environment and odor dispersion over the study areas For validation of MADM and CFD models, some of the field experimental data conducted by Hong et al. (2008) were applied to the model. The data set consisted of wind speed, wind direction, air temperature and odor values. In Cheongyang area of Fig. 7, the wind speeds and the wind directions predicted in the simulation were well matched to the field experiments while the wind speeds were still slightly high. The variation in wind direction was shown when the wind speed was relatively low or fluctuated steeply. Especially when the wind speed was rapidly decreased, the sudden opposite wind direction was observed occasionally. It was because the sudden decrease in the wind speed at the inlet boundary caused the pressure inversion. As the pressure at the inlet boundary became lower than that at the outlet boundary, the flow was forced to change the direction reversely.

As a whole, the developed module creates well-fitted wind environment compared to the actual input condition while some variations were observed when the wind speed was low or fluctuated rapidly, and when the terrain was complicated.

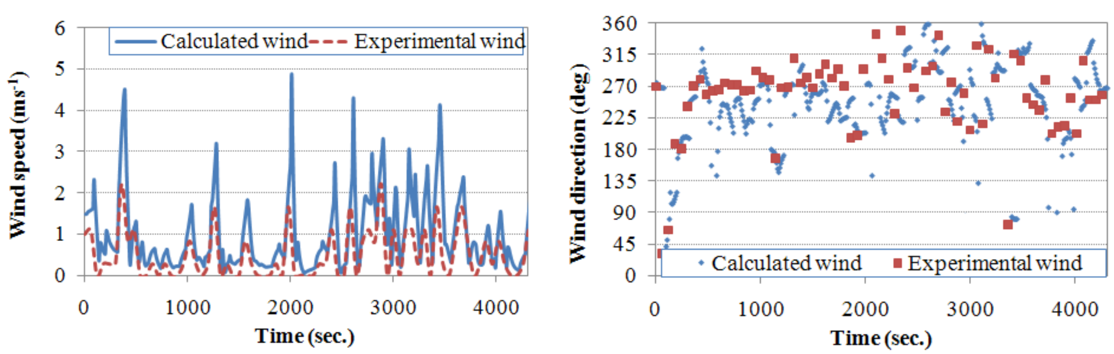

Figure 7. Comparisons of wind speeds (left) and wind direction (right) in Cheongyang area in the daytime on Oct. 12, 2007.

The module linked to the CFD model produced unsteady wind environments, which make the odor spread out farther to the lateral as well as to the leeward. The odor dispersions computed by the CFD model were also compared to the field experiments by Hong et al. (2008) in connection with the unsteady wind environment. The prediction of the odor dispersion by the CFD model was successful when comparing the correlation between the two results. The correlation coefficient was 0.863 as presented in Fig. 8. The points below the trendline 'y=x' or above the trendline indicate that the odor unit by the CFD simulation is lower, or higher than expected due to the resolution problem of the CFD modelling as mentioned above.

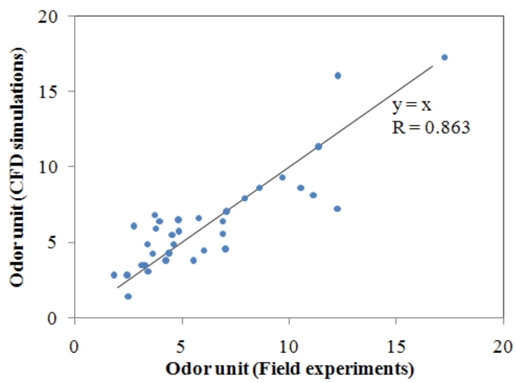

Figure 8. Correlation of the computed and measured odor units

CONCLUSION Unfortunately, many details of the results on the prediction of odor dispersion with various meteorological conditions were not presented in this paper because of the page length restriction. However, the proposed CFD model combined with the developed module was very effective for predicting odor dispersion from a livestock farm with various weather conditions and even an unsteady weather. It is expected to enable evaluation or pre-evaluation of a livestock farm on an environmental impact, and to settle a dispute related to the livestock odor by tracing the odor to its origin and the extent of the dispersion..

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