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MONITORING OF DUST EMISSION AND DEVELOPMENT OF A CFD MODEL TO PREDICT THE DISPERSION OF FUGITIVE DUST AT A RECLAIMED LAND

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ABSTRACT A study on fugitive dust dispersion was conducted in a 40, 100 ha of reclaimed land located in the west coastal part of Korea. The dusts are composed mainly of minerals with high salinity that is very harmful to human health such causing skin and eye irritations and if frequently inhaled, respiratory diseases can occur. More so, the highly concentrated salty dusts can be very harmful to farms located nearby. A computational fluid dynamics (CFD) model was developed to predict the dispersion of fugitive dust from Saemangeum reclaimed land considering the topography of the area. Field experiments remain the ideal method to understand the aerodynamic phenomenon. Nevertheless, it is very difficult to find a correlation between weather condition and dust dispersion because of limited measuring points, labor and time. Moreover, the weather condition are very unstable and unpredictable as well and cannot be artificially controlled. To overcome these limitations, CFD simulation was used to quantitatively and qualitatively analyze the dust dispersion phenomenon according to various weather conditions. Great effort was needed to improve the CFD accuracy with topographical design, mesh structure, particle generation, and computational process by parallel processing technique. Results from this study in 2006, 2007 and 2008 showed that the changes in dust source are highly connected with the changes of dust concentration. The dust concentration showed a decreasing trend in 2008, and is expected to decrease further as more dust source areas are being covered by plants. The samples analyzed through SEM showed that most dust particles are large in size with irregular dimension. Dust dispersion ranges of CFD result were compared with that of field experiment at the same measuring points for the CFD validity, and the results at stable weather condition were very acceptable with an average error of 6.8%. The vertical dust concentration of the CFD results also became very similar with the general log-profile of fugitive and suspended dust presented by Gillies et al. (2004). The results also showed that the dispersion of the fugitive dust was mainly affected by particle size, wind speed as well as wind direction. Through this study, it was found that the CFD technology can be effectively used to complement the field experiments and more accurate and reliable results can be obtained.

Keywords: CFD, Dust dispersion, Fugitive dust, Reclaimed land, SEM-EDX analysis, Statistical analysis, Topographical modeling

INTRODUCTION. The Saemangeum reclaimed land is a large-scale reclamation project in Korea implemented by the Korean public works. The reclamation started in 1991 and is expected to terminate until 2011. The land is located at the west coastal area of Jeon-buk Province with a total area of 40,100ha (land: 28,300ha, fresh water lake: 11,800ha). To reclaim the land, a 33km long sea dike connecting the cities of Gun-san and Bu-an was constructed. The construction was finished in 2006, and developments are underway to maximize the potential of the land.

A study on fugitive dust dispersion in Saemanguem reclaimed area was conducted since there’s a strong possibility of the generation and dispersion of dust from the land to the neighboring areas. The dust in the reclaimed land is composed mainly of minerals with high salinity, and it could be very harmful to crops as well as on to human health which can cause skin and eye irritation and some respiratory diseases. Especially, when the dust particles are settled on the leaves of the crops, the photosynthesis and respiration of the plants can be under restraint resulting in the decrease of production. More so, the highly concentrated salty particles can directly damage the leaf cells of the plants. Considering the scenario presented, field experiments has been conducted to regularly measure the locally suspended dust particles and analyze their dispersion mechanism to the neighboring areas. The collected dust particles were analyzed to examine their size, concentration, and composition. The information is needed to develop a forecasting system for dust dispersion and diffusion in the very near future.

Research studies on fugitive dust have been carried out (RRI, 2005) ever since a community petition was filed against the Hwaung land area (4,482 ha) which was reclaimed in 2002. However, no in-depth analyses were conducted in those studies because they were limited to field experiments. Numerical models are important tools for assessing dispersion and deposition of dust-sized particles in boundary layer flows and in the design of dust mitigation strategies for various weather conditions, diverse topographies and different dust generation mechanisms. Aerodynamic analyses on fugitive dust diffusion considering complicated topography domains like Saemangeum are still rare in the literature. The main objective of this research was to develop a three-dimensional CFD simulation model to analyze diffusion of fugitive dust under various weather conditions. In modeling studies for pollution such as dust diffusion, GIS provides vital topographical data. In this study, CFD, GIS information, and other programs were used to model and predict dust diffusion in the Saemangeum reclaimed land. Topographical work, mesh construction, diffusion modeling and simulation operating techniques were mainly performed to achieve results ensuring accuracy despite limited computer resources. Validation of the CFD model to establish reliability was also carried out comparing to previous studies and field experimental data. Diffusion distances of fugitive dust were investigated using CFD models according to weather conditions, topographical differences, and particle sizes.

MATERIALS AND METHODS. The study is divided into two; first part is the field monitoring of the fugitive dusts and the second part is focused on laboratory experiment for the analysis of the dusts. In the field monitoring aspect, several points for the collection of dust were selected in each area as shown in Fig. 1. To monitor the weather and climatic condition such as temperature, humidity, solar radiation, and wind speed and wind direction in Saemangeum area, two automatic weather stations (AWS) in Gunsan and Gimje were installed. This is aside from the government meteorological station in Gunsan and sub-station in Buan. Saemangeum area is so large and so having more automatic weather stations, the more accurate the data. The AWS were installed approximately at 10m height as shown in Figure 2. Low volume dust sampling pumps with volume rate of 2 and 4 per minute(PCRX8, SKC. Inc., USA) were used to measure continuously the diffusion mechanism of dust at each measuring points. The small volume pump with a rate of approximately 4l/min was used to collect PM_{10} dust and small volume pump with a rate of approximately 2l/min was used to collect the total suspended particles or TSP. The dust collectors were installed approximately at 3m height and collects dust for approximately 16 hrs. Dust collection was done simultaneously at all points in each location. To determine the dust vertical distribution in the reclaimed land, BNSE (Big Spring Number Eight) dust sampler was used. This instrument can capture creeping dust particles from the ground surface and the suspended dust particles at different height and at different wind direction. Results from the data analysis will confirm if the from the reclaimed land or from other sources. SEM (JSM-5410LV, JEOL Inc, Japan) and SEM-EDX analyser was used to determine the size, shape and components of the collected dusts.

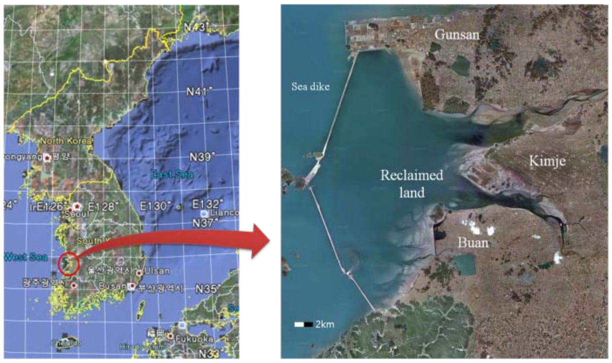

Fig. 1. Satellite picture of Saemangeum reclaimed land at Jeonbuk Province (35° 49’ N, 126° 36’ W).

Fig. 2. Weather station installed in Gim-je

Fig. 3. Universal dust sample collector installed at 3m height.

Simulation Tool GIS is commonly applied in topographical studies by modifying and analyzing geographic information. This data can be effectively used to determine turbulent characteristics which are important in the analysis of fugitive dust diffusion. Commercial software ARCGIS (version 8.3, ESRI, USA), AUTOCAD (version 2006, Autodesk, USA) and RHINOCEROS (version 3.0, McNeel, USA) were used to make a computational domain based on contour maps.

GAMBIT (version 2.3, Fluent Inc. USA), Fluent’s pre-processor, was used for the mesh construction in the computational domain based on the graphical user interface (GUI). This program designs mesh with complicated geometries by automatically controlling the size and shape using tetra-hybrid, pyramid, wedge, and hexahedron shapes of meshes. The quality of the designed mesh structure was evaluated using equiangle skew criterion

(Eq. 1), which calculates the distortion of each mesh. When this value exceeds 0.85 in the hexahedron type and 0.90 in the tetra-hybrid type of mesh, the model's accuracy is considered unreliable (Fluent, 2007). T-GRID (version 4.0, Fluent Inc. USA) software was used to design the vertical mesh structure.

$$\text{Equiangle skew} = \max\left[\frac{\theta_{\max}-\theta_e}{180-\theta_e}, \frac{\theta_e-\theta_{\min}}{\theta_e}\right] \tag{1}$$

This study used the commercially available CFD code FLUENT (version 6.3, Fluent Inc., USA). FLUENT uses a finite volume numerical scheme to solve equations of conservation for different transported quantities in the flow within every cell in the computational domain. Equations (2)-(4) present the mass, momentum, and energy conservation equations (Fluent, 2007).

$$\text{Mass:} \qquad \frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{v})=S_m \tag{2}$$

$$\text{Momentum:} \quad \frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla P+\nabla\cdot(\bar{\tau})+\rho\vec{g}+\vec{F} \tag{3}$$

$$\text{Energy:} \qquad \frac{\partial}{\partial t}(\rho E)+\nabla\cdot(\vec{v}(\rho E+P))=\nabla\cdot(k_{eff}\nabla T-\sum h\vec{J}+(\bar{\tau}_{eff}\vec{v}))+S_h \tag{4}$$

Figure 5 shows the process of designing a three-dimensional aerodynamic model. The numerical contour map on a scale of 1 to 25,000 provided by the National Geographic Information Institute of Korea was transformed into a computational domain of 40 km by 40.5 km using a triangular irregular network (TIN). The CFD simulation for the designed mesh structure with boundary conditions from field experimental data and theoretical data was carried out using the FLUENT main solver with the following assumptions:

- Particle density is 2,650 kg m-3 (Saxton, 1999).
- Conditions for the diffusion of fugitive dust are uniform from the dust sources.
- Dust concentration at the source was assumed to be 200 $\mu m/m^3$(based on field experimental data conducted by Hwang et al. (2008)).
- There is no generation of dust except from the source areas.
- There is no creeping and saltation of dust particles. Buoyancy effects are ignored at wind speeds of 3 m s-1 and 5 m s-1, which were measured by two weather stations installed in Gunsan and Gimje.
- There is no condensation or generation of particles by collision or chemical reactions.

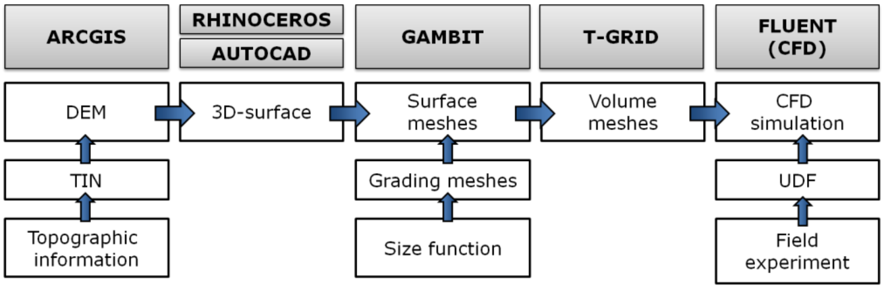

Fig. 5. Flow chart for the design of the aerodynamic simulation model using various software and techniques.

Simulating the continuous distribution of particles was time-consuming due to limited computer resources. Therefore, particle sizes of 2.5, 10, and 30 ㎛, which represent $PM_{2.5}$, PM_{10}, and total suspended particles (TSP), respectively, were used for the CFD model.

Horizontal dust concentration data measured by Hwang et al. (2008) and the vertical dust concentration profile presented by Gillies et al. (2004) were used to validate the CFD model. First, the CFD model was validated with the same environmental conditions used by Hwang et al. (2008) to measure the TSP data in the Saemangeum area.

Vertical dust profiles of the CFD model were analyzed and compared with a logarithmic distribution. After validation, the model was used to investigate the diffusion of fugitive dust at various wind conditions (wind direction and wind speed) which were measured during field experiments.

RESULTS AND DISCUSSION. The weather station was set on a roof of a farmhouse in Gimje to determine the weather changes in the area. The Korea Meteorological Administration (KMA) also provided weather data for Gunsan. The measured weather factors were wind direction, wind speed, solar radiation, temperature, humidity, etc. The following were the results for Gunsan in 2006~2008. The lowest temperature was -5.2℃, and the highest temperature was 27.9℃. January and November had the most temperature range in year. Average wind speed was 2.3 ㎧ and the maximum was 8.5 ㎧. Average humidity range from 71~88%. Windy months were April, July, October, December and dry months from February to May. This explains why maximum dust generation falls during the spring of the country. In 2008, the research area was extended to Saemangeum area. Therefore additional weather data were needed; however, measurement was limited because of the on-going construction works in the area. However, the Korea Rural Community Corporation provided some weather data. After the construction, the prevailing wind direction was changed to north wind and the direction range was expanded. The result of the dust concentration by season is shown in Fig. 6. The maximum dust concentration can be observed during autumn measured at A0 while the absolute minimum dust concentration can be seen in the summer months also measured at A0.

The concentration of PM_{10} was 86.9~114.6 ㎍/㎥, with the absolute minimum concentration and absolute maximum concentration falls during summer measured at A0 and autumn measured at A3, respectively. The concentration distribution of TSP at each measuring point is shown to range from 137~202.4 ㎍/㎥, and the average ratio compared to PM_{10} was computed to be approximately 61%.

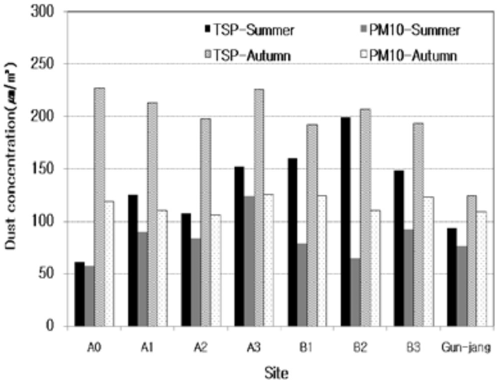

Fig. 6. Seasonal comparison of dust concentrations at the measuring points in 2007.

The occurrence of dust is shown to decreases from the lower layer according to the rate of cover of the halophilous plant as shown in Figures 5 and 6. The occurrence of dust distributed according to the height as well as the density of the plants is expected to show varied results. Shown in Figures 7 and 8 is the amount of dust according to height and according to the density of plants. The dust collected near the ground surface up to 0.35m height has irregular shapes and it was observed that at 0.40m height, the dust particles sizes were relatively smaller compared to dusts collected at 0.35 m height. The result also showed that approximately 79% of the dust was present near the ground which can be moved through saltation and can creep in the ground surface (within 0.4~0.45m).

Fig. 7. Dense area of halophilous plant

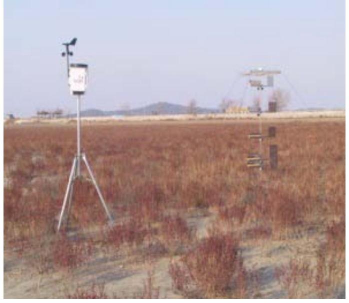

Fig. 8. Thin area of halophilous plant

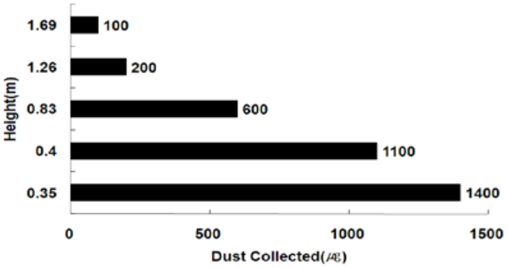

Fig.9. BSNE measurement: when the halophilous plant density in the Gimje area is high.

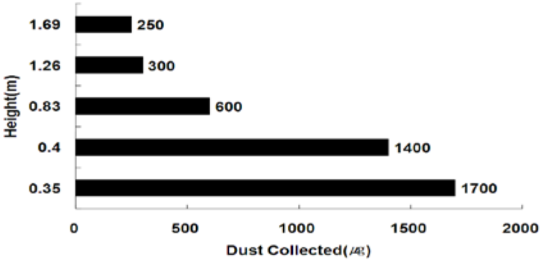

Fig. 10. BSNE measurement: the halophilous plant density in the Gimje area is low.

The Na^+ and Cl^- relationship ingredient were detected in SEM-EDX analysis in occasion of free medical care picking at A0 agency that is the nearest measuring point in the reclaimed land to grasp scattering and particle special quality of airborne particle that is piled up at reclaimed land neighbourhood (Tables 1 and 2). More so, sea salt factor was shown that ingredient of NaCl and MgCl can exist where Mg^{2+} is detected. Therefore, Cl^- course Na^+ were detected, and displayed in the SEM-EDX analysis as shown in Fig. 10. The SEM analysis samples were collected where it is very close to the reclaimed land boundary line.

Table 1. IC & ICP analysis of collected dust components of Gunsan area Oct.30, 2007 (Unit: mmol/kg)

Point	Cl^-	SO_4^{2-}	Na^+
A0	3.96	0.87	15.84
A1	2.33	0.85	14.78
A2	5.18	0.81	14.77
A3	0.34	0.44	17.15
B1	2.79	0.34	16.34
B2	1.97	1.26	1.52
B3	0.46	0.35	0.79
Gun-jang	1.49	0.81	6.41

The relationship between soil similarities piled up in other areas and reclaimed land. Executed analysis through comparison of A0 point situated on junction since correlation analysis with topsoil of each flying and arthromeres. This was thought by topsoil not as it was suspended. Dust that is piled up at A0 measurement agency could judge dust that most happen in reclaimed land, and compared with dust that is piled up at A0 measurement agency. Comparing dust that do collection at each measurement agency with dust that is piled up at A0 measurement agency, could judge whether is that dust of each measurement point is caused in A0. Because continuous halophilous plant seeding was achieved since 2006, Origination of 2007 is state that decrease as is different than hazardous area of 2006 and, distance receded better to seaward to junction (tide embankment).

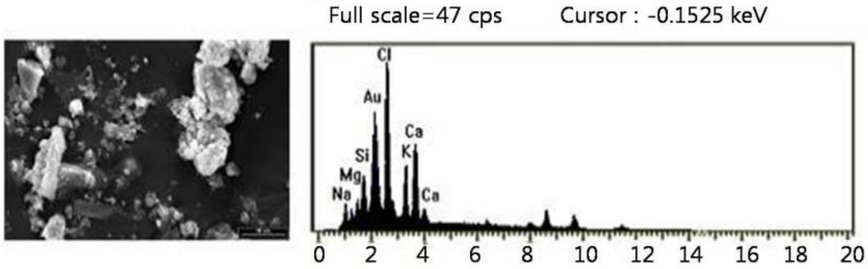

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Fig. 10. SEM-EDX analysis of dusts collected at A0 measurement point (OCT, 30. 2007)

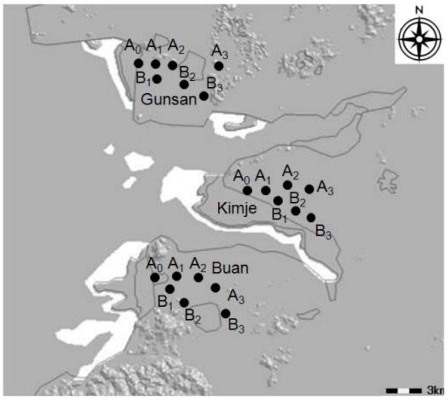

Fig. 11. Measurement point of CFD simulation model

○ : Source ● Field measurement point

In case of Gunsan, the distance of the dispersion of the fugitive dust was about 4.5km in 2006, 3.2km in 2007 and more decreased in 2009. The reason of this is because the generation source was moved farther from the dike. In case of Gimje, the distance was steadily decreasing since 2006 and in Buan, the distance was increased in 2007 but decreased since 2008.

Based on the simulation results of the same designated point with the simulation model of 2007, it has been investigated that the tendency of fugitive dust was very similar with the simulation model of 2008 and 2009.

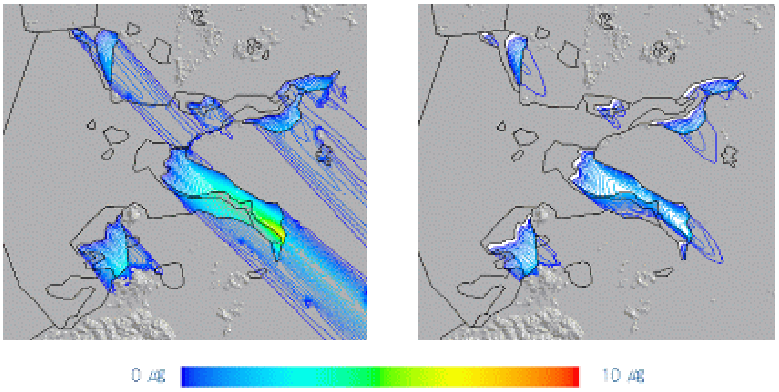

Fig. 12. Result of CFD : 5 ㎧ NW, 2.5 ㎛ and 10 ㎛ ; Height 3m

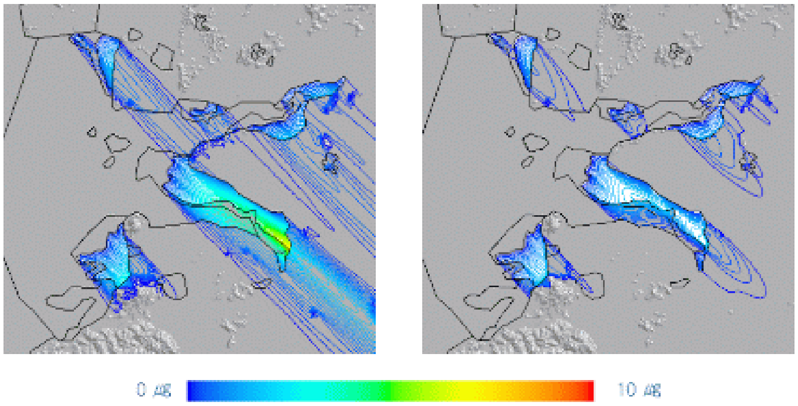

Fig. 13. Result of CFD :10 ㎧ NW, 2.5 ㎛ and 10 ㎛ ; Height 3m

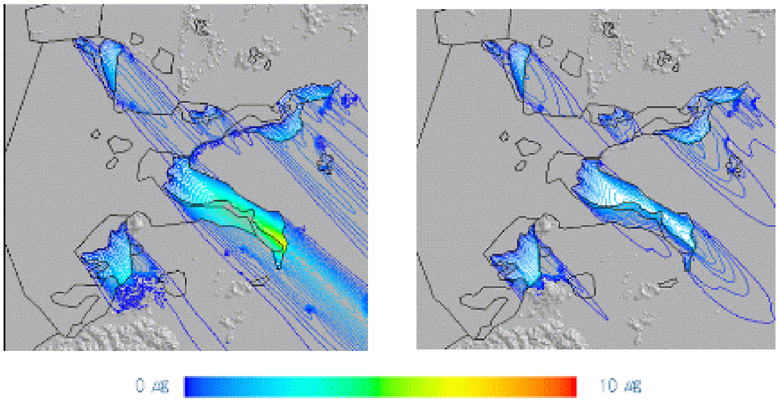

Fig. 14. Result of CFD :15 ㎧ NW, 2.5 ㎛ and 10 ㎛ ; Height 3m

Results, which were calculated by applying size distributions and measurements in field experiments, showed a -6.8% error compared to field experimental results which were conducted under relatively stable weather conditions by Hwang et al. (2008). The vertical concentration profile of the CFD results showed a 5.3% error compared to the field experiment conducted by Gillies et al. (2004). Using the validated CFD model, the effect on fugitive dust was analyzed according to various weather conditions. CFD results revealed that 2.5 ㎛ particles dispersed far from the dust source for all wind directions. However the effect was not significant because those particles occupied only 5% of the TSP. Most of the 30 ㎛ particles, which occupied 20% of the TSP, diffused within several hundred meters from the source. The 10 ㎛ particles, which occupied 70% of the TSP, represented the characteristic dust diffusion according to wind speeds and wind directions.

CONCLUSION. To compliment field experiment, it is necessary to develop a forecasting system using three dimensional CFD simulations and the results from field experimental studies will be used. The result in this study was as follows:

In the field experiment, the weather data showed that the temperature as well as humidity and solar radiation decreased with time duration by seasonal effects. Air velocity in Buan area was 0.9m/s higher than that in Gimje area and the min currents of wind direction were ENE and NW.

The results of fugitive dust generation showed that the mass concentration in Buan area was 0.9 m/s higher than that in Gimje area by 19.7%, 39.5%, 19.3%, 48.8% and 52.6%. The ratio of PM_{10} accounted for is 77.8% and 77.3%.

The results with SEM displayed that the configuration of particle in Buan area was generally big and irregular due to incoming particle in the construction site around the sampler. The stem of crops was shown at the sample in Gimje area due to the harvest work done in the area. Comparing with study in Hwaung area, the ratio of large particle will be increased and the changed will be more irregular.

The simulation results showed that the dust concentration, scattering height and scattering distance changed with the winding of ground as well as most of the dust moved to the side of gullies while some travelled over the hill. The dust concentration travelled to the side of gullies was 5.8% higher at the ground and 9.0% higher at 10m height than those moved over the hill.

To ensure the reliance of CFD simulation, it is necessary that the results should be compared with that in the field experiment. And basis experiment of weather condition, configuration of ground and turbulence model were required to simulate more accurately. These simulation results with aerodynamic approach in the various weather and ground condition were used to basis data for forecasting dust generation and diffusion.

REFERENCES. Gillies, J. A. and L. Berkofsky. 2004. Eolian suspension above the saltation layer, the concentration profile. Journal of sedimentary research 74(2): 176-183

Hwang, H.-S., I.-B. Lee, S.-W. Hong, I.-H. Seo. 2006. Monitoring of dust emission at a reclaimed land and its 3-D aerodynamic modeling. ASABE Paper No. 062055. St. Joseph, Mich.: ASABE.

Hwang, H.-S., I.-B. Lee, M.-H., Shin, S.-W. Hong, I.-H. Seo, J.-I. Yoo, and S.-K. Lee. 2008. Monitoring of the fugitive and suspended dust diffusion at the reclaimed land and neighboring farms: Monitoring I Gunsan. Journal of the Korean society of agricultural engineers 50 (4): 39-50

Kim, Jae-Jin and Jong-Jin Baik (2004) A numerical study of the effects of ambient wind direction on flow and diffusion in urban street canyons using the RNG k-ε turbulence model. Atmospheric Environmental 38: 3039-3048

Li, Yintang and Yi Guo. 2008 Numerical simulation of aeolian dusty sand transport in a marginal desert region at the early entrainment stage. Geomorphology 100: 335-344

Milliez, Maya and Bertrand Carissimo. 2007. Numerical simulations of pollutant diffusion in an idealized urban area, for different meteorological conditions. Boundary-Layer Meteorology 122: 321-342

Rural Research Institute in Korea (RRI). 2005. Report of the fugitive dust generated from the Hwaung reclaimed land.

Saxton, K., D. Chandler, L. Stetler, B. Lamb, C. Claiborn, B.-H. Lee. 2000. Wind erosion and fugitive dust fluxes on agricultural lands in the Pacific Northwest. Transactions of the ASAE. 43(3): 623 - 630

Seo, I.-H., I.-B. Lee, H.-S. Hwang, S.-W. Hong. 2007. Development of a CFD model to predict dust diffusion from Saemangeum reclaimed land. Proceeding of the 2007 Annual Conference. The Korean Society of Agricultural Engineers.

SPO. 2008. Halophyte-covering Methods & CFD modeling for Decreasing Fugitive Dust. SM-02-13-02-08. Jeonbuk, Gimje: Saemangeum Project Office. Korea Rural Community & Agriculture Corporation.

Xie, Xiaomin, Zhen Huang, Jia-song Wang. 2005. Impact of building configuration on air quality in street canyon. Atmospheric Environment 39: 4519-4530