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A Study on the Dust Control Characteristics inside a Test Dome in the Port of Inchon

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Abstract

This study focuses on the investigation of the effects of windspeed and particle size on the dust control characteristics inside a test dome built in the Port of Inchon to reduce the fugitive dust originating from the handling of animal feed stuff in the open pile area. The flow field inside the test dome and the trajectories of the particles were calculated using a commercial CFD code, FLUENT, assuming that the animal feed stuff handling activity took place inside the test dome. It was found from the simulation results that high windspeed and small particle size give rise to the increase in both the escaped fraction and the suspended fraction of the particles emitted from the animal feed stuff handling activity. Here, high escaped fraction represents the high possibility of fugitive dust problem outside the test dome, whereas high suspended fraction means the high possibility of severe dust pollution inside the test dome. Our simulation results clearly show that the existing test dome was not designed properly to meet the proposed goal, low escaped fraction and low suspended fraction. Hence, we suggest the need of an efficient ventilation system inside the dome to control the dust.

Key words : fugitive dust, ventilation, particle trajectory, dust control

1. BACKGROUND

The Port of Inchon has served as one of the major ports in Korea handling import cargos including raw materials. Among the raw materials, animal feed stuffs and scrap metals are two major particulate pollution sources in the Port of Inchon. In the case of handling animal feed stuffs such as soy bean shell, alfalfa and many others, dust emissions occur at several point in the storage cycle, such as during material loading onto the pile, disturbance by strong wind currents, and load-out from the pile. The movement of the trucks and loading equipment in the storage pile area is also a substantial source of dust. Storage pile are usually left uncovered, because of the need for frequent material transfer into or out of storage.

There have been frequent complaints from nearby residential area due to the fugitive dust emitting from the handling activities of animal feed stuffs and scrap metal in the Port of Inchon. Therefore, as one of the control measures to reduce the fugitive dust emission from the animal feed stuff handling, the Port of Inchon built a dome-shaped warehouse as a test unit near the pier 1 in 1999, in which a part of animal feed stuff can be handled regardless of weather condition. The dome is made of the fabric of polyester coated with Teflon

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and its dimension is 170 m in length, 35 m in width and 15m in height approximately.

It is expected that the fugitive dust emissions from the test dome will be reduced by handling animal feed stuff inside the dome. However, it is necessary to have a proper ventilation system inside dome in order to protect workers from high dust concentration and to reduce the fugitive dust emission from the test dome to the port area.

The objective of this study is to investigate the effect of wind speed on the particle emission characteristics from the test dome among the many variables affecting the particle dynamic characteristics. At a given wind speed, the flow field inside the test dome was calculated first and then the particle trajectories were calculated to estimate the emission probabilities of each size of particles from the test dome. In particular, simulation method describing the particle emission during loading process inside the test dome was developed in this study for the first time. The results of this study will be a part of the design information for the forthcoming renovation of the Port of Inchon.

2. SIMULATION

2. 1 Theory

When the handling activities inside the dome take place, the doors of the test dome are left open for natural ventilation and frequent material transfer into or out of the dome. As a result, the outside wind enters into the dome through the door and induces the airflow inside the dome. It is clear that the higher the outside wind speed is, the stronger the inside airflow becomes.

In this study, the air flow inside the test dome was assumed to be turbulent flow in view of the fact that the annual average wind speed and maximum wind speed at the Port of Inchon are about 3.3 m/s and 16.8 m/s, respectively. Also, in order to reduce the computational demand to solve the equation of energy conservation, it was assumed that temperature inside the test dome is constant. The airflow field and particle trajectory inside the test dome were obtained by solving the equations of fluid motion and particle motion using commercial CFD(computational fluid dynamics) code, FLUENT V.5.2

For an incompressible fluid, the equations of continuity and balance of momentum for the mean motion are given as

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

and

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} R_{ij} \tag{2}$$

where $\bar{u}_i$ is the mean velocity, X_i is the position, t is the time, P is the pressure, ρ is the constant fluid density, ν is the kinematic viscosity, and $\overline{R_{ij}} = \overline{u_i' u_j'}$ is the Reynolds stress tensor. Here, $u_i' = u_i - \bar{u}_i$ is the i-th fluctuation velocity component.

Here, in this study, Reynolds stress was evaluated by using the standard *k*-ε model (Fluent Inc., 1999; H.K Versteeg and W Malalasekera 1995; Landers and Spalding, 1974), which is a very successful turbulence model in the confined flow like the flow inside the test dome in this study. Here, *k* is turbulent kinetic energy and ε is the rate of dissipation of turbulent kinetic energy, respectively. To simplify the problem, it was assumed in this study that fluid flow is fully developed.

The equation of particle motion can be written as

$$\frac{du_i^p}{dt} = \frac{3\nu C_D Re_p}{4 d_p^2 S\, Cc}(u_i - u_i^p) + g_i \tag{3}$$

and

$$\frac{dx_i}{dt} = u_i^p \tag{4}$$

where u_i^p is the velocity of particle, x_i is its position, d_P is the particle diameter, S is the ratio of particle density to fluid density, and g_i is the gravity. According to Chi Tien (1989) drag coefficient, C_D is given as

$$C_D = \frac{24}{Re_p} \quad \text{for} \quad Re_p < 1 \tag{5}$$

and

$$C_D = \frac{24}{Re_p}\left(1 + \frac{1}{6} Re_p^{\frac{2}{3}}\right) \quad \text{for} \quad 1 < Re_p < 400 \tag{6}$$

where Re_p is the particle Reynolds number defined as

$$Re_p = \frac{d_p(u_i - u_i^p)}{\nu} \tag{7}$$

Here, we only considered gravitational force as the only external force acting on the particle. The instantaneous fluid velocity, u_i can be obtained as

$$u_i = \bar{u}_i + u_i' \tag{8}$$

where u_i' is time average fluid velocity obtained by solving Equation (1) and (2) with boundary conditions. u_i' can be obtained form the following relationship.

$$u_i' = \xi\sqrt{\overline{u_i'^2}} \tag{9}$$

where ξ is a normally distributed random number, and the remainder of the right-hand side is the local rms (root-mean-square) value of the velocity fluctuations. Since the kinematic energy of turbulence is known at each point in the flow, these values of rms fluctuating components can be obtained (assuming isotropy) as

$$\sqrt{\overline{u_i'^2}} = \sqrt{\frac{2k}{3}} \tag{10}$$

The fluctuating velocity components are discrete piecewise constant functions of time. Their random values are kept constant over an interval of time given by the characteristic lifetime of the eddies (Fluent Inc., 1999).

2. 2 Simulation conditions and method

The dimension of the test dome, which is the calculation domain of this study, is 170 × 30 × 15 m, approximately. It has two open doors at each side of it, as shown in Fig. 1. The dimension of each of the four open doors is 5 × 5 m. The test dome also has 32 windows at each side of it for ventilation and particle control purpose. The dimension of each window is 4 × 2 m, which is nearly closed with a panel, allowing only a small fraction of airflow penetrates through, and it has a mesh screen structure and a water spraying system to capture the dust particles emitting from the handling activities inside the test dome. In this study, we assumed that all the airflow enters into the open doors at front side of the test dome and straightly goes out the test dome through the opening door at rear side of it, neglecting the possibility that some of airflow enters through the side windows. The other factors concerning local climate including the prevailing wind direction and the effect of nearby buildings were not considered in this study to reduce the computational demand in the simulation. The cartesian coordinate system was used and total number of grid points used for the simulation were 80,000. The two cases were chosen as the windspeed passing through the open doors: the annual average wind speed of 3.3 m/s and the maximum wind speed of 16.8 m/s in the Port of Inchon. This wind data was taken from the measured data from 1982 to 1992. The temperature inside the dome was assumed to be 20°C.

The particle sizes used for the trajectory calculation were determined by the following procedures. First, soy bean shell, occupying the largest portion in the amount of animal feed stuffs imported, was sampled by using standard sampling method. Next, after classifying the soy bean shell samples in size intervals using a sieve shaker, the fraction penetrated through US sieve #230 (approximately under 50 μm) was taken for the particle size analysis. This fraction was considered as the particle source for the fugitive dust in this study, which may affect the dust concentration near the Port of Inchon. Particle size was analyzed using Aerosizer (TSI Inc.), which uses the principle of the time of flight measurement. The data shown in Fig. 2 was obtained from the measurements using Aerosizer, and the figure shows the particle size distribution expressed as number fraction.

From the results of particle size analysis of the sample, the mode of the particle size in terms of number fraction was found to be about 3.44 μm in aerodynamic diameter. The shape of particle size distribution appeared to be that of bi-modal distribution. This in-

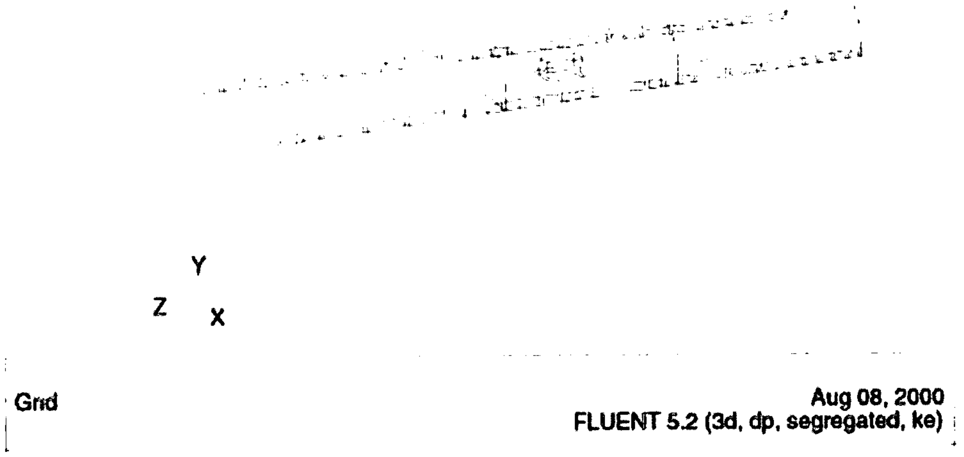

Fig 1. A schematic diagram of the test dome employed in this study.

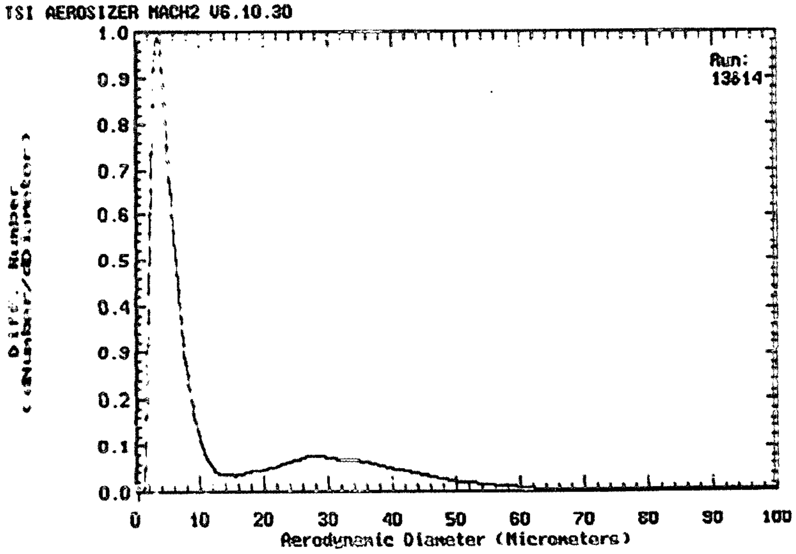

Fig. 2. A plot of particle size distribution of soy bean shell sample.

formation will be used not only for the simulation study, but also for the calculation of emission factor for the future study.

To simulate the handling activity inside the dome, it was assumed that the truck was located at the center of the test dome and the loader vehicle loaded the animal feed stuffs into the truck's loading box at the height of the top of the truck's loading box. The loading of animal feed stuffs by pouring them into the truck's loading box generates the so called dust cloud. It was observed that this activity emitted fugitive dust the most compared to other handling activities in the test dome. Therefore, this activity was chosen for the representative activity for the simulation in this study. Pouring of powdery materials into the confined space like the truck's loading box makes the air originally present in the loading box pushed out of the space and thus the direction of the emitting particle's velocity tends to be the reverse direction to the falling powdery materials, which is +y direction in this study. This qualitatively expected trend was taken into account at the initial velocity of emitting particles in the simulation.

Since falling powdery material also have large amount of trapped air in the void space inside the falling dense cloud of the powder, one can easily expect that the speed of emitting dust from the truck's loading box may be enhanced large enough to create the dust cloud due to the effect of the additional airflow caused by squeezing of the settled powder. We observed this dust cloud at every occasion. Its emitting speed may be somewhere around 0.3 m/s by visual observation, which should be measured by more accurate method later. As a result, throughout this study, the initial particle emission speed was assumed to be 0.3 m/s and its direction were chosen such that the particle moved to the +y direction initially at the height of the truck's loading box. The effect of airflow caused by loading activities was taken into consideration in the calculation of the flow field inside the test dome, assuming the upward airflow of 0.3 m/s in the direction of −y.

The truck's size is set to be 10 × 3 × 4 m and shown in the Fig. 1. In the simulation, the particles are generated at the computational grid points set to the upper surface of the truck's loading box filled with the soy bean shell and their initial positions in x, y, z component were chosen randomly. The trajectories of the generated particles are calculated by the integration of Equation (3) using FLUENT. The initial speed or velocity magnitude of the generated particles was set to be 0.3 m/s, which is same as the fluid velocity.

3. RESULTS AND DISCUSSION

The velocity fields inside the test dome for the wind speed of 3.3 m/s and 16.8 m/s were calculated and shown in Fig. 3 and 4, respectively. The trajectory of 3.44 μm particle emitted from the truck's loading box, which is the most frequent size, are shown in Fig. 5 and Fig. 6 for each case. These figures are drawn on the x−z cross-section. These figures clearly imply that large circulating flow is induced inside the test dome by the wind passing through the two open doors in the direction of −x. It is clear from the figures that as the wind speed increases, the intensity of velocity magnitude increases.

The trajectories of 3.34 μm and 100 μm particle for the case of the wind speed of 3.3 m/s were shown in Fig. 7 and 8, drawn on the y−z cross-section. They clearly show the effect of gravitational settling on the particle trajectory. In the figures, it is clear that the trajectories of 100 μm particle tend to be located near the ground surface, whereas those of 3.44 μm particles seem not much affected by gravitational settling and tends to follow the fluid motion more or less throughout the inner space of the test dome. It implies that particle concentration inside the dome is not only a function of time, but a function of a spatial position. Namely, the larger the particle is, the faster the particle settles, giving rise to the separation of particles in terms of their size. The trajectories of 100 μm particle for the case of wind speed of 16.8 m/s tend to follow the circulating flow induced by strong wind, as shown in Fig. 9, and thus it is expected that the dust concentration expressed as the mass concentration inside the dome will be expected to be very high.

To estimate the probability of particle emission through the open door of the test dome, 500 particles for each size were generated at the upper surface of the truck's loading box and their trajectories were monitored until the total flight distance of each particle became 200 m. There are three outcomes for the particle in motion during its flight: (1) the particle becomes deposited on the ground surface of the test dome, (2) it escapes the test dome through the open doors, (3) it remains suspended inside the test dome following the circulating flow for the time being. It was assumed that if the particle makes contact with the ground surface, the particle becomes deposited. Here, it was also assumed that the possibilities of resuspension of the depo-

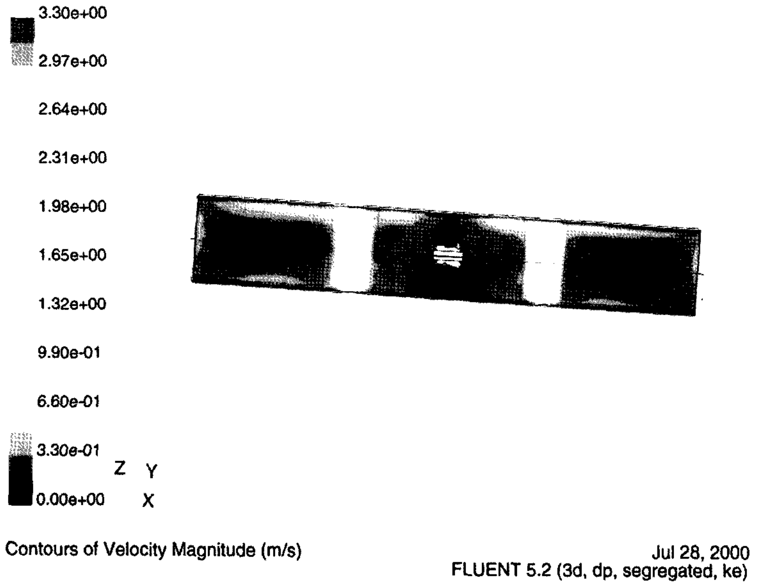

Fig. 3. Velocity profile inside the test dome (at windspeed of 3.3 m/s).

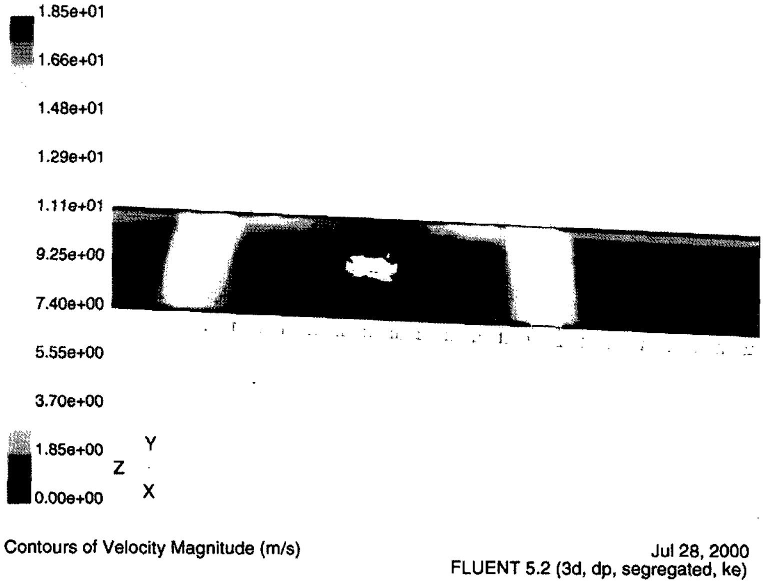

Fig. 4. A plot of velocity profile inside the test dome (at windspeed of 16.8 m/s).

sited particles are absent and deposition of particles onto the dome surface does not occur. In this study, the probability or the fraction of particle emission through the open door was defined as the ratio of the number of the particles escaped from the test dome to the number of particles generated.

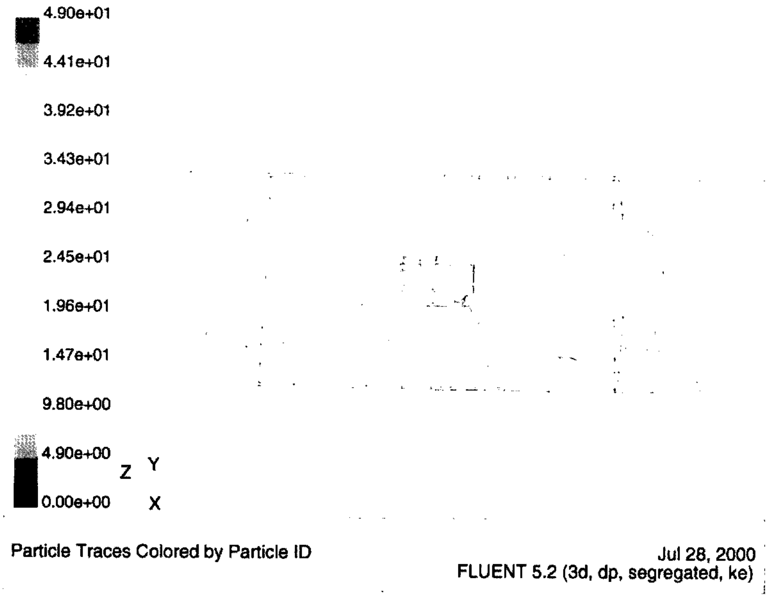

Fig. 5. Trajectories of 3.44 μm particles (at windspeed of 3.3 m/s: a plane figure).

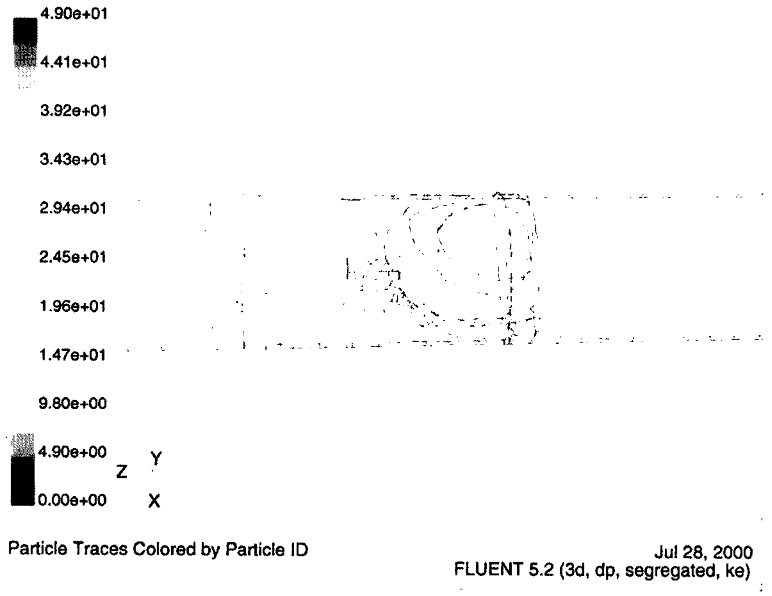

Fig. 6. Trajectories of 3.44 μm particles (at windspeed of 16.8 m/s: a plane figure).

Fig. 10 shows the fraction of the each outcome as a function of aerodynamic diameter when wind speed is 3.4m/s. As shown in Fig. 10, as the particle size increases, the probability of the particle's being suspended decreases while the probability of deposition by settling increases. However, regardless of the particle sizes,

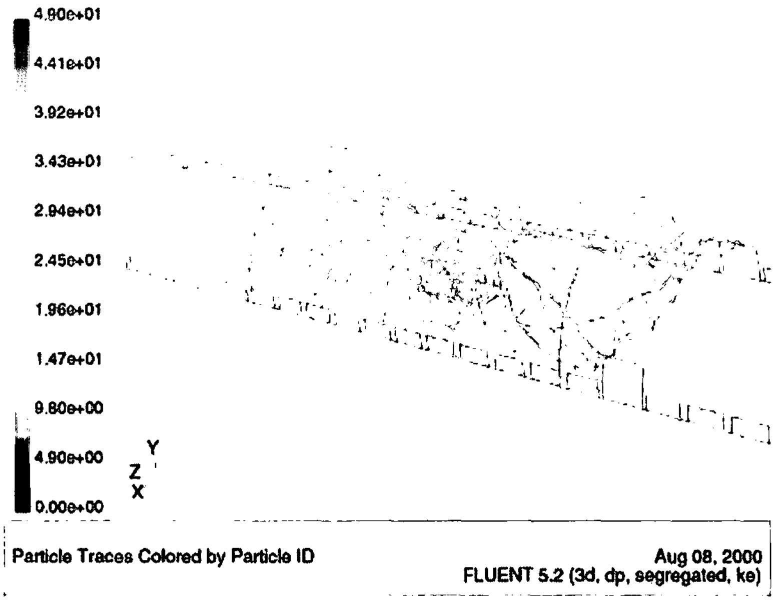

Fig. 7. Trajectories of 3.44 μm particles (at windspeed of 3.3 m/s: a side view).

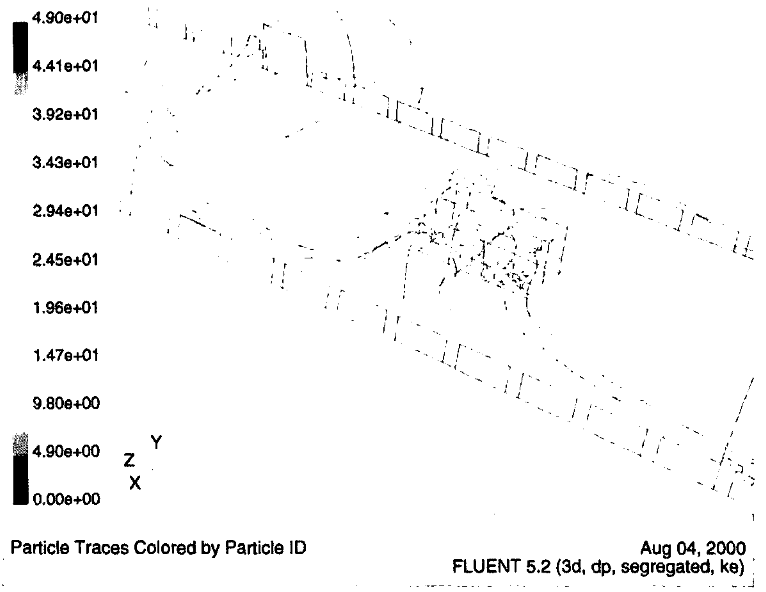

Fig. 8. Trajectories of 100 μm particles (at windspeed of 3.3 m/s: a side view).

the probability of the particle's escape remains almost constant, having the values ranging from 12 to 18%. The reason for the small probability of escape for the case of 1.0 μm particle is that the particle tends to follow the motion of airflow because of the relatively small inertial force acting on the particle compared to

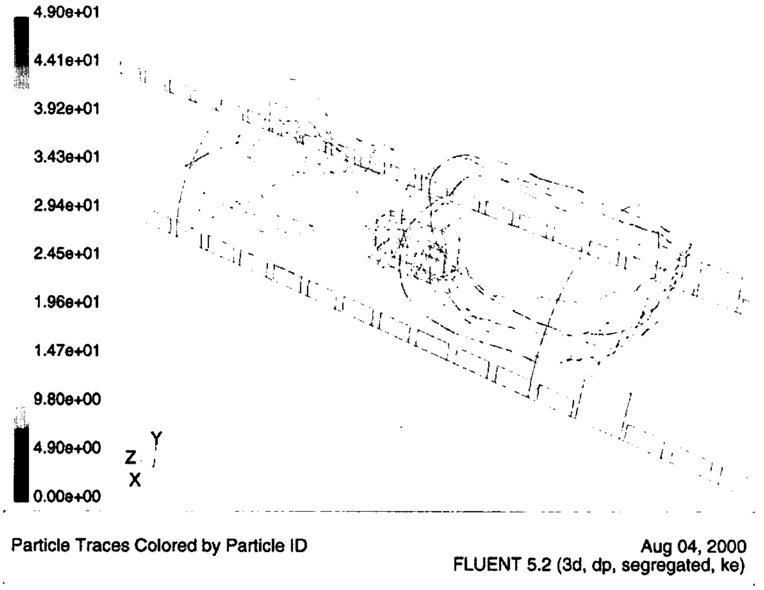

Fig. 9. Trajectories of 100 μm particles (at windspeed of 16.8 m/s: a Side View).

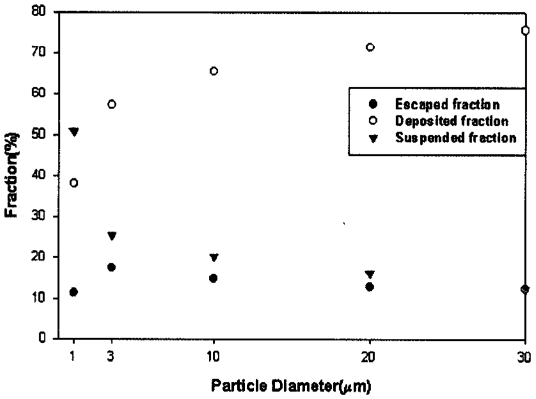

Fig. 10. Fraction of the outcome of emitting particles.vs. particle size (at windspeed of 3.3 m/s).

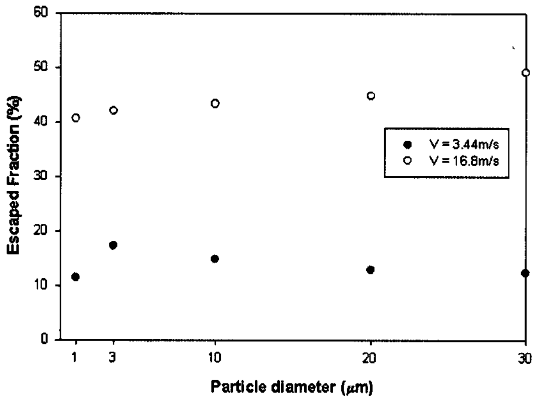

Fig. 11. Fraction of the outcome of emitting particles. vs. particle size (at windspeed of 16.8 m/s).

larger particle. Namely, circulating flow inside the test dome may be responsible for the low probability of the 1.0 μm particle's escape.

When the wind velocity increases up to 16.8 m/s from 3.3 m/s, the fraction of the particles' escape increases up to over 40% to 50% and that of suspended particle increases as well up to 50∼60%, as shown in Fig. 11. Here, the fraction of settled particles were assumed to be negligible in view of high flow velocity near the ground surface, as shown in Fig. 4. Namely, it may not be possible for the particles to be deposited onto the ground surface because of the sweeping action by high wind speed even near the ground surface as well as of the possible bouncing of the particles from the surface, especially when wind speed is very high.

This indicates that at higher wind speed, the emission of fugitive dust is significant, despite handling animal feed stuffs inside the dome. As a result, it is highly advisable not to handle animal feed stuffs at the high wind speed condition. High fraction in the suspend particles means that the particle concentration becomes very high inside the dome and thus it is very hazardous for the workers. High fraction of the particle's escape implies the increase in the amount of fugitive dust emission to the area near the Port of Inchon, which is not desirable either.

The measurements separately undertaken by using portable aerosol monitoring system (Casella MicroDust 880 nm) in this study show that the particle concentration inside the dome with four doors left open ranged from approximately 3.0 mg/m^3 to 5.5 mg/m^3 depending upon the measurement points at the wind speed of about 0.1 m/s. These measured particle concentrations are fairly high. For reference, exposure limit set by NIOSH is 4 mg/m^3 (OSHA, 1988) for grain dusts which may be similar to animal feed stuff in property. Therefore, this suggests that proper ventilation method with efficient particle collection devices should be required in the test dome not only for the health of workers, but for the reduction of particle emission to the ambient air. Furthermore, we are not absolutely sure whether there is a possibility of dust explosion inside the dome at this point. The minimum particle concentration for the explosion of grain dust is known to be about 20 g/m^3 (William C. Hinds, 1999) and thus it is three or four orders of magnitude higher than the measured particle concentration inside the test dome in this study. Nonetheless, it may be premature to conclude that the test dome is absolutely safe for the dust explosion, since the particle concentration very close to the loading zone can easily reach the minimum particle concentration for the dust explosion at any time.

From the viewpoint of fugitive dust, high wind speed causes the spread of the impacted area because of its increase in flight distance due to strong wind. For this reason, the handling activity should be reduced or stopped even inside the test dome when the wind speed is very high. Simulation results clearly show that even in the case of 100 μm particles, dust emission is significant at the strong wind condition.

The ultimate objective of this study is, therefore, to develop the proper control method to minimize the fractions of the particles' escape from or being suspended inside the test dome. This study is being done and will be continued as an extension of this study.

4. CONCLUSIONS

In this study, the dust control characteristic of the test dome was investigated using the computer simulation method, which was developed to describe the dust pollution inside the test dome where handling of animal feed stuff took place. The simulation results show that the dust control characteristics inside the test dome depends clearly on the wind speed and particle size. Namely, at the condition of higher wind speed and larger particle size, both suspended fraction and escaping fraction of particles emitted from the loading activities for animal feed stuff are higher. As a result, it is clear that the test dome should have a proper ventilation system not only for the health of workers, but for the protection of fugitive dust pollution near the Port of Inchon. The result of this study can give us a good information to design the handling facilities for animal feed stuff to be built in the forthcoming future.

ACKNOWLEDGEMENTS

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인천항 시험돔 내부의 먼지제어특성에 대한 연구

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초록

인천항 야적장에서 사료원료를 취급 시에 발생되는 비산먼지를 저감시킬 목적으로 만든 시험돔 내부에서의 먼지제어특성이 바람의 속력과 입자크기에 따라 어떻게 변화하는지 조사하고자 하는 취지로 본 연구를 수행하였다. 시험돔 내부에서 사료원료의 취급 시에 시험돔 내부의 유동장 및 입자궤적을 상용전산유체역학 코드인 FLUENT를 사용하여 계산하였다. 전산모사 결과, 바람의 속력이 빠를수록 입자의 크기가 작을수록 사료원료 취급 시에 발생된 먼지 중에 돔 외부로 유출된 입자분율과 돔 내부에 부유하는 입자의 분율이 큰 것으로 나타났다. 여기에서 유출 입자분율이 크다는 것은 시험돔 외부에서 비산먼지로 인한 문제의 발생 가능성이 큰 것을 나타내고, 부유 입자분율이 크다는 것은 시험돔 내부의 입자오염이 심각할 가능성을 의미한다. 본 전산모사 결과, 현재 사용 중인 시험돔이 설치 목적인 낮은 유출 입자분율과 부유 입자분율을 충족시키지 못하고 있고, 따라서 돔 내부에 효과적인 환기설비를 갖추어야 하는 것으로 판명되었다.