Study on the Particle Removal Efficiency of Multi Inner Stage Cyclone by CFD Simulation

Sang Won Han, Won Joo Lee, Sang Jun Lee

***Abstract*—**A new multi inner stage (MIS) cyclone was designed to remove the acidic gas and fine particles produced from electronic industry. To characterize gas flow in MIS cyclone, pressure and velocity distribution were calculated by means of CFD program. Also, the flow locus of fine particles and particle removal efficiency were analyzed by Lagrangian method. When outlet pressure condition was –100mmAq, the efficiency was the best in this study.

***Keywords*—**Cyclone, SiO_2 particle, Particle removal efficiency, CFD simulation

I. Introduction

AS the air pollution is on the rise with the drastic growth of modern electronic industry recently, many studies have been actively conducted to reduce various hazardous pollutants produced in the processes[1-3]. In particular, semiconductor devices are becoming very large scale integrated, and thus the number of their manufacturing processes is increasing accordingly. In addition, a large amount of residues and pollutants remain on the surfaces after each process, which results in the increasing need for the cleaning process to remove them. As pollutants produced during semiconductor device manufacturing processes cause structural deformation and deterioration of electrical characteristics, such adverse elements must be removed to prevent them from affecting the performance, reliability, and yield rate of the devices.

Currently, the major pollutants produced on silicon boards during the manufacturing processes in electronic industry include particle, organic matter, metal pollutant, natural oxide film, and so forth [4]. Fine particles may be discharged mainly with raw gas, and if the remaining gas is discharged to the atmosphere, the chemical reaction in the air causes fine particles as a result [5]. The size of particles produced in such processes is ranged from 0.1 to 10 ㎛, and they contain a lot of hazardous elements.

$$SiH_4 + 2O_2 \rightarrow SiO_2 + 2H_2O$$

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The major two methods of pollutants removal are the wet cleaning method and dry cleaning method, and the techniques continue to make progress. In general, such methods make use of cyclone, west scrubber, and so forth at the final step of the process to remove exhaust gas, and a large quantity of hazardous gas is produced due to the limitations in terms of efficiency during the process [6]. In addition, as the size of particle pollutants including the diameter of the surface particles is getting smaller while the level of pollutant regulation is getting higher, there is an urgent need to develop a system to remove particles more effectively [7, 8].

This study is to design a new multi inner stage cyclone to remove particles of 0.1~10 ㎛ in size, and to verify the movements and processing efficiency within a cyclone in a three-dimensional form by means of CFD program [9, 10].

II. Mathematical Formulation of the Model

A. Turbulence Model

A turbulent flow means a very irregular, three-dimensionally abnormal flow that occurs at a high speed when Reynolds number (Re) is large.

In utilization of a turbulent flow model, a variety of turbulent flow models may be analyzed based on so-called 'Reynolds-Averaged Navier-Stokes (RANS) equation.' The methods are as follows.

- K-Epsilon Turbulence
- K-Omega Turbulence
- Reynolds Stress Turbulence
- Spalart-Allmaras Turbulence

The two-equation turbulence model must be addressed with the mass and linear momentum, and the two boundary conditions on turbulent flow characteristics need to be set at the inlet and outlet.

This study sets up and calculates K-Epsilon Turbulence, which has k (turbulent kinetic energy) and ε (turbulent flow dissipation rate) to be determined.

B. Lagrangian Method

In analysis of particle motion, such factors as gravity, centrifugal force, air resistance, and drag force are to be taken into consideration, and this study makes use of Lagrangian method in this respect. The particle motion equation is as follows:

$$\frac{dr_p}{dt} = v_p - v_g \quad (1)$$

The expression above is the basic expression of Lagrangian method to trace the object's locus in consideration of the velocity vector $v_p(t)$ and position vector $r_p(t)$ over time. This expression reflects the precondition that the speed is affected by the absolute velocity of the particle while the location of it is determined by the reference value according to CFD program.

When the particle is a material particle of weight, the analysis is implemented generally based on the following equation:

$$m_p \frac{dv_p}{dt} = F_s + F_b \quad (2)$$

In the expression above, F_s indicates the force applied to the particle surface while F_b indicates the force applied to the particle body. The calculations are as follows:

$$F_s = F_d + F_p + F_{vm} \quad (3)$$

$$F_b = F_g + F_u \quad (4)$$

Here,
F_d : Drag force
F_p : Pressure force
F_{vm} : Virtual mass force
F_g : Gravity force
F_u : User-defined body force

The drag force above is divided mainly to the expressions of Schiller-Naumann, Di Felice, Gidaspow, and Haider an Levenspiel, and they are classified as follows:

- Schiller-Naumann : spherical solid Particle, liquid droplet, small (spherical) diameter bubbles
- Di Felice : dense particulate material flow (two-way coupling only)
- Gidaspow : low and high loaded particulate flows (spherical, two-way coupling only), fluidized beds
- Haider and Levenspiel : non-spherical particle (two-way coupling only)

This study analyzes fine particles in a way of Schiller-Naumann since they are small and globe-shaped. The basic equation of drag force is as follows:

$$F_d = \frac{1}{2} c_d \rho A_p |v_s| v_s \quad (5)$$

Here,
C_d = particle of drag coefficient
ρ = density of the continuous phase
v_s = particle slip velocity
A_p = projected area of a particle

Drag force may be expressed in the following manner as well:

$$F_d = \frac{m_p v_s}{\tau_v} \quad (6)$$

In the expression above, τ_s indicates the relaxation time-scale equation, which is as follows:

$$\tau_v = \frac{2 m_p}{C_d \rho A_v |v_s|} \quad (7)$$

The drag coefficient of a particle is as follows:

$$C_p = \begin{cases} \frac{24}{Re_p}(1 + 0.15 Re_p^{0.657}) & : 0 < Re_p \le 1000 \\ 0.44 & : Re_p > 1000 \end{cases} \quad (8)$$

In the expression above, Rep of a particle is expressed as follows:

$$Re_p = \frac{\rho |v_s| D_v}{\mu} \quad (9)$$

This study adopts the turbulent flow model and particle motion model to compare existing cyclones with the inlet aperture relocated, and the changes in outlet pressure are examined.

III. CFD Investigation

The multi inner stage cyclone as shown in Fig. 1 include several stages was designed to differentiate this study from existing ones based on the conditions for improving cyclone flow characteristics and fine particle removal efficiency. The size of the model to be analyzed is 1000L/min. To analyze gas flow types, pressure distribution, and particle locus, the removal efficiency in consideration of the flow characteristics and size of particles was calculated by means of STAR-CCM+, a commonly used CFD program developed by CD-adapco.

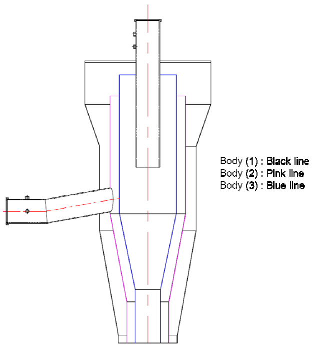


Fig. 1 Scheme of multi inner stage cyclone

The flow characteristics of gas within the multi inner stage cyclone were examined with different pressure conditions respectively. The formation of cyclone meshes was made by means of the polyhedral mesher. The total number of meshes is 447708.

First of all, in order to determine the flow characteristics of gas depending on the cyclone's outlet pressure, the inlet condition of cyclone was set as the pressure outlet while the condition of the outlet was set as that of the stagnation inlet. The outlet pressure was set as -50mmAq and -100mmAq respectively for comparison.

Nitrogen (N_2) gas was chosen for the inflow gas. The density of gas was 1.205kg/m^3, and the viscosity coefficient 1.81×10^{-5}kg/m·s. Gas flow was assumed to be steady state, and K-Epsilon Turbulence was chosen and analyzed for the turbulent flow.

To analyze the flow locus of fine particles, Lagrangian method with the particle motion equation was utilized. The gas flow was assumed to be implicit unsteady state, and such factors as drag force, gravity, and residence time of fine particles were also determined. SiO_2, the object substance of study, was chosen as the fine particles flowing in with gas. The density of fine particles was 2200kg/m^3, the size of fine particles was determined 3 ㎛ and 10 ㎛ respectively.

IV. Results and Discussion

A. Characterization of Gas Flow

Streamlines in MIS cyclone was shown in Fig.2. The gas flow from the inlet aperture forms the swirling flow at body (2) and starts to assume an upward curve. The rising flow went deep into the body, and turned counter-swirling and descending. The flow into the body turned straight back at the suction part and went out through the outlet.

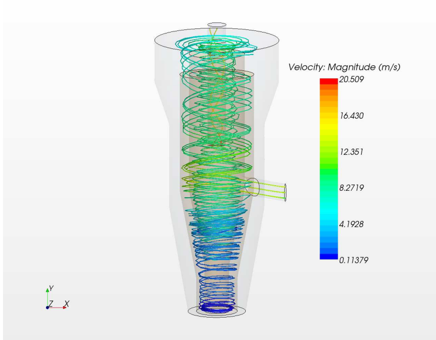
As to the pressure distribution, the effect of the outlet pressure decreases as it advances from the center to the outer wall (Fig. 3). When the outlet pressure condition was -50mmAq, pressure difference was 39.77mmAq from inlet. With -100mmAq as the outlet pressure condition, the pressure difference from the inlet aperture was 67.91mmAq.

The influence on the velocity distribution and vector was also made clear in the figure. The bigger vector was seen on a section that was generally sucked while the vector decreased as it went toward the outer wall (Fig. 4).

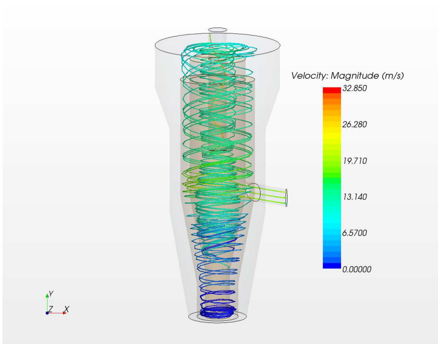
Velocity contour was represented in Fig.5. As to velocity distribution, the turning velocity when the outlet pressure was -100mmAq was faster twice than when the pressure was -50mmAq. However, it did not reach the internal velocity of the existing cyclone, and the flow from the upper part to the outer wall was not observed.

B. Particle Removal Efficiency

As to fine particles, when the outlet pressure was -50mmAq, the time that it took when 3 ㎛ fine particles and 10 ㎛ fine particles at body (2) reached the top was 0.16sec and 0.168sec outlet pressure : (a) -50mmAq, (b) -100mmAq respectively while it took 0.248sec for them to reach the top of body (1). Thereafter, it was observed that some of 3 ㎛ fine particles entered the outer tube while others entered body (3). Meanwhile, 10 ㎛ fine particles that reached the top turned at body (1) and went back to the bottom. It took 0.752sec as 3 ㎛ fine particles went through the outlet, which is faster than existing cyclones. It was also observed that 47.2% of the total inflow of 3 ㎛ fine particles was removed, which is about 4.5% more than the existing removal rates. 10 ㎛ fine particles were removed 100%, which was the same efficiency with existing cyclones.

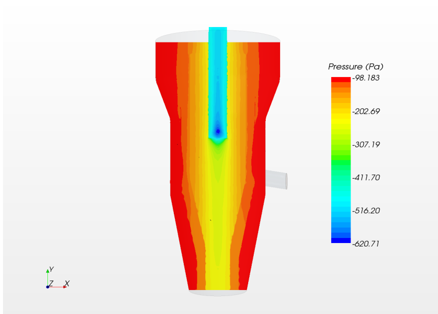


(a)

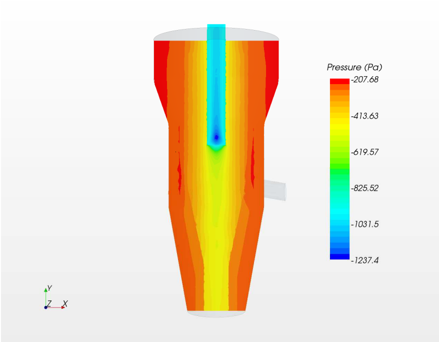


(b)

Fig. 2 Streamlines of MIS cyclone,

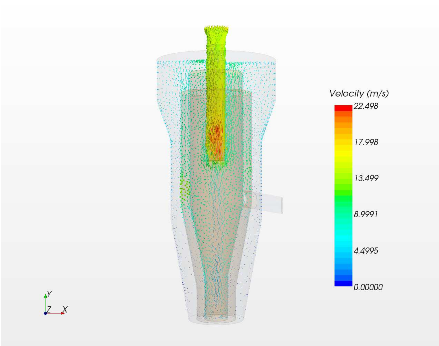


(a)

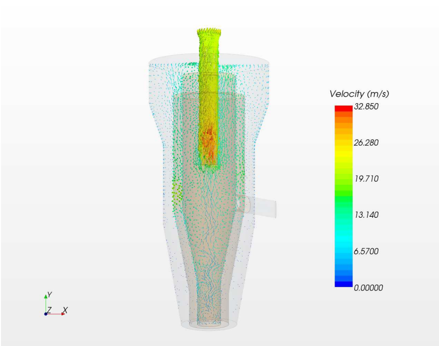


(b)

Fig. 3 Pressure distribution of MIS cyclone, outlet pressure : (a) -50mmAq, (b) -100mmAq

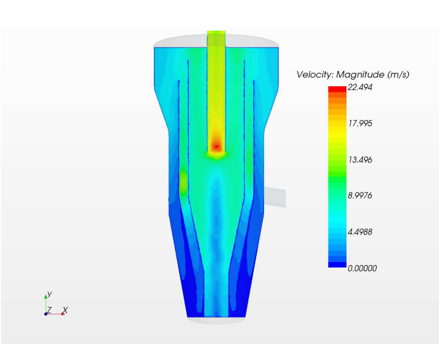


(a)

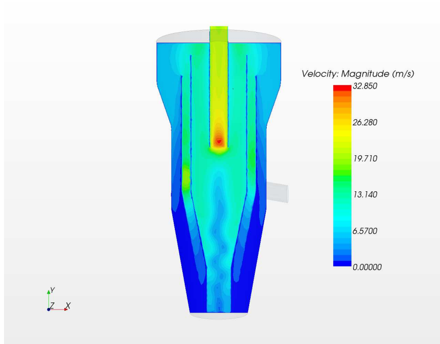


(b)

Fig. 4 Velocity vector of MIS cyclone, outlet pressure : (a) -50mmAq, (b) -100mmAq



(a)



(b)

Fig. 5 Velocity contour of MIS cyclone,outlet pressure : (a) -50mmAq, (b) -100mmAq

When the outlet pressure was -100mmAq, it took 0.16sec and 0.168sec respectively when 3 μm fine particles and 10 μm fine particles at the inlet aperture reached body (2), which is the same with the case of – 50mmAq. Thereafter, it was observed that some of 3 μm fine particles entered body (3) and fine particles were discharged in 0.568sec. In comparison with existing cyclones where 33% of 3 μm fine particles and 48% of 10 μm fine particles respectively were removed, the removal efficiency of 3 μm fine particles at the designed multi inner stage cyclone was 66% while 10 μm fine particles were removed 100%.

V. Conclusion

This study aims to develop a system to remove fine particles and acid gas that remained and were discharged after a semiconductor process. To this end, the study developed the technique to effective reduce the discharge of a variety of hazardous substances produced in processes where various hazardous chemicals based on the simulation.

In particular, the comparison with existing cyclones confirmed that the best efficiency was shown when the outlet pressure condition of the multi inner stage cyclone was set to -100mmAq. These findings are expected to contribute to enhancing the fine particle processing efficiency of the facility in future studies.

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