Removal of Micrometer-sized Particles on a Solid Wall by High-speed Impinging Air Jet

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Abstract: In this study, a cleaning device to remove micron-sized particles on a solid surface by an air jet is developed. This device has a special nozzle containing a triangular cavity to add high intensity turbulence to the air jet, and the air jet impinges on the solid surface removing the particles. Assuming the removal of a spherical particle by rotational movement, we performed numerical simulation of the flow field in the cleaning device and estimated the rotational moment induced by the drag force from the numerical results. As the result of the numerical analysis for modified nozzle shapes, it was clarified that the minimization of slit length reduced pressure loss in the slit and increased the velocity of near-wall flow. This effect enhanced the removal moment and improved removal performance.

Keywords: Particle removal, Impinging jet, Numerical analysis, Cavity nozzle

1. Introduction

In the production process of precise glass plates for liquid crystal display (LCD) or high-function films, simple and effective cleaning technique for removing fine particles adhering on their surfaces is strongly demanded. Dry cleaning technique which utilizes a high-speed impinging air jet for removing the fine particles has great advantages of being a simple device without rinsing or drying process, in comparison with wet technique which uses cleaning liquid. However, the dry-cleaning technique also has a disadvantage of being difficult to remove micrometer-sized particles. To overcome this disadvantage, we developed a new type dry cleaner system with a special nozzle[1–3]. The system has an original nozzle with triangular cavities inside designed to add fluctuations. We measured wall pressure fluctuations and particle removal rates, and demonstrated high correlation between the pressure fluctuations induced by the cavities and the particle removal rates[1–3]. In addition, we estimated rotational moment acting on a spherical particle in the impingement jet from the result of numerical simulation[4]. In this study, we performed numerical simulations of air flows in the dry-cleaning devices with different nozzle shapes, and investigated the optimal nozzle shape for the particle removing. Furthermore, we measured particle removal rates for the different nozzle shapes to verify the removal performance estimation by the numerical analysis.

2. Numerical Analysis

2.1 Geometry of cleaning device

Figure 1 shows our developing cleaning device[1]. The cleaner head(1) is a rectangular parallelepiped shape with uniform section, and it consists of an air storage chamber(2) and two suction chambers(3). The air is supplied to the air storage chamber by a blower, and is ejected from a two-dimensional nozzle(4) at over 100 m/s. The pressure in the air storage chamber is maintained at a constant value, and is monitored with a pressure gauge(5). The air jet from the nozzle impinges on a surface of a glass plate(6) placed 2 mm away from the exit of the nozzle. After removing the particles(7) on the wall surface, the impinged air flow is...
The cavity (type B) and addition of a square space to the C, D and E, as shown in Figs. 2(a) to 2(e), to optimize the with double-step cavity similar to Fig. 2(e) or no cavity. The estimation revealed that the nozzle with single-step hydrodynamic forces acting on a spherical particle[4,5]. numerically in the cleaning devices with different numbers smaller than the jet speed (0.3 m/s on a conveyer. Since the transfer speed is quite transferred in a horizontal direction with the constant speed . In this study, we considered five types of nozzle, A, B, C, D and E, as shown in Figs. 2(a) to 2(e), to optimize the nozzle shape. Type B, C and D are modified shapes from the previous best shape, type A. Downward relocation of the cavity (type B) and addition of a square space to the end of the triangular cavity (type C and D) enable extremely short slit length of 1.5 mm. It is expected that such short length reduces pressure loss in the slit and decay of turbulence. Although type D is similar to type C, the channel width for type D is smaller than standard size of 1mm for other types. This narrow channel possibly changes the inflow velocity to the cavity and turbulence characteristics in the cavity. Although double-step cavity nozzle like type E was not effective in the previous research[5], we recheck the removal performance of the double-step cavity nozzle in which the square space and short slit are applied.

We performed numerical simulations in the cleaning devices with the above-mentioned five nozzle shapes and compared flow characteristics near wall. To investigate the removal performance, we also estimated removal moments for the five nozzle shapes. Since the removal moment does not necessarily reach maximum near the stagnation point, the nozzle performance is evaluated from the local distribution of the removal moment along the wall surface.

### 2.2 Numerical method

We performed a numerical simulation to estimate the flow field in the domains as shown in Figs 2(a) to 2(e). Three-dimensional simulation of unsteady incompressible flow was executed in a Cartesian reference frame. In the coordinate system, the origin is taken at the stagnation point of the jet flow on the wall, and x, y and z coordinates express horizontal, vertical and depth directions, respectively. Commercial computational fluid dynamics software, Ansys Fluent 19.1, was used for the simulation. Detached eddy simulation (DES) was applied as a turbulence model. Computational domain with the depth length of 1.2 mm was configured and about 2 million grid points were used. The grid nodes were refined near the wall and in the jet shear layers. The smallest size of the grids which are located next to the bottom wall is 10 μm. The mesh size is selected by considering computational load and resolution. Although the grid size is larger than diameters of target particles for removal (1-3μm), the velocity field within y = 0 – 10 μm is predictable since the grids next to the bottom wall are inside a viscous layer. We estimated the velocity at the position of the particle by assuming linear velocity distribution within y = 0 – 10 μm. Inlet pressure was maintained at 11 kPa and outlet was exposed to atmospheric pressure (≈ 0 kPa).

### 2.3 Removal moment

In this section, we briefly describe the estimation method of the removal moment. Figure 3 illustrates the hydrodynamic force acting on a spherical particle with a diameter D. F_D and M_r indicate the drag and moment caused by the viscous stress on the particle surface. Numerous studies have shown that fine spherical particles are removed in a rolling motion rather than lifting or sliding motion[6-8]. In this study, we also assume removal by the rolling motion and considered the moment acting on a spherical fine particle. Assuming air flow around the micro-meter sized particle, Reynolds number becomes less than unity. Since Stokes’ law is applicable to evaluate the drag force, rotational moment M_r caused by F_D and M_r is estimated as follows[4].

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The estimation revealed that the nozzle with single-step cavity and estimated the removal moment from the numerically in the cleaning devices with different numbers of the cavity and estimated the removal moment from the numerical simulation.

In the previous papers, we analyzed the air flows of 0.3 m/s on a conveyer. Since the transfer speed is quite transferred in a horizontal direction with the constant speed short slit are applied.

Double-step cavity nozzle in which the square space and research[5], we recheck the removal performance of the nozzle like type E was not effective in the previous characteristics in the cavity. Although double-step cavity 1mm for other types. This narrow channel possibly such short length reduces pressure loss in the slit and decay extremely short slit length of 1.5 mm. It is expected that the nozzle performance is evaluated from the local distribution of the removal moment along the wall surface.

In this section, we briefly describe the estimation method of the previous best shape, type A. Downward relocation of C, D and E, as shown in Figs. 2(a) to 2(e), to optimize the moment in comparison to the removal moments of nozzles cavity as shown in Fig. 2(a) gave the largest removal. The estimation revealed that the nozzle with single-step cavity and estimated the removal moment from the numerically in the cleaning devices with different numbers of the cavity and estimated the removal moment from the numerical simulation.

In the previous study, we estimated pressure gradient caused by pressure fluctuation approximately and considered rotational moment \( M_r \) by the pressure gradient[4]. To check the validity of the approximation, we calculated the pressure gradient numerically using small grids with high resolution. The recalculated pressure gradient became quite smaller than previous approximated one. As a consequent, the contribution of \( M_r \) was expected to be smaller than those of \( M_D \) and \( m_{D'} \). From this result, we treat \( M_r \) as negligible here.

Since the particle is removed for a moment when \( M_r \) exceeds an adhesive moment, we evaluated \( M_r \) from instantaneous maximum value, that is, \( u' \) in Eq. (1) was defined as 1.96 times standard deviation of x-directional velocity. Instantaneous velocity above \( u' \) appears with a probability of 2.5%.

3. Measurement of Particle Removal Rate

We conducted a verification experiment to confirm the validity of the removal performance evaluation by numerical analysis. The cleaning device shown in Fig. 1 was used for this experiment. We measured particle removal rates for five nozzles, type A to E, and compared them with calculated removal moments. The procedure of the experiment is as follows. Mono-disperse spherical silica particles with a diameter of 1.5μm (Nippon Shokubai, KE-P150) are dispersed on the surface of a 4-inch silicon wafer, and the number of the particles within the test area of 50 mm × 50 mm is counted with a surface inspection device (Hitach High-Technologies, GI-4830). The wafer is fixed on a vacuum suction table, and then the cleaner head passes over the wafer at the constant speed of 150 mm/s. The pressure in the air storage chamber is maintained at 11 kPa. The number of particles adhering to the surface is measured again after the cleaning. The removal rate \( \gamma \) is defined as \( n_s/n_b \), where \( n_b \) and \( n_s \) are the numbers of particles counted before and after cleaning. This procedure is repeated 6 times for each type of nozzle to obtain average of the removal rate.
4. Flow Characteristics in the Nozzle

In this section, we describe flow fields calculated by numerical simulation to realize flow characteristics in the different five nozzles.

4.1 Distribution of vorticity magnitude

The distributions of instantaneous vorticity magnitude for the five nozzle types are shown in Figs. 4(a) to 4(e). When air flow comes in the triangular cavity, shear layers develop into vortices in the cavities regardless of nozzle type. In the square spaces placed within the nozzles of type C, D, and E, the vortices transform to random turbulences. The vortices or turbulences flow into the slit, and they are advected downward through the slit. However, type D shows slightly different behavior. Air flow is deflected leftward in the cavity because of Coanda effect, and small-scale strong vortices are generated.

As can be seen in close-up views near stagnation point, when an air jet is ejected from a slit exit, vortices are formed again in the jet shear layer in addition to the advected vortices from the cavity. Consequently, the combined vortices generated in the cavity and jet shear layer results in fluctuation of the flow along the wall surface.

The close-up views also reveal that vorticity magnitude at the stagnation point (x = y = 0) is enhanced for type C, D and E owing to the turbulence advected from the square space. In contrast, vorticity magnitudes of type A and B are relatively small at x = y = 0 because vortices generated in the cavity move down along the sidewall of the slit. It can be observed that relatively smooth flow directly comes down from the slit exit to the wall surface along the center axes of A and B nozzles.

4.2 Near-wall velocity

Figure 5(a) and 5(b) show mean and fluctuation velocities, U and u', of near-wall horizontal flow at y = 10 μm. Horizontal axis represents the horizontal distance x from the stagnation point.

As indicated in Fig. 5(a), mean velocity U increases up to x = 0.5 mm or 0.6 mm and then it decreases regardless of nozzle shape. Type B and C nozzles with the short slit and standard-width channel show similar large mean velocities. Type A and E nozzles with a long slit or double-step cavity give relatively large mean velocities next to type B and C. In contrast, the velocity U of type D is quite small. The high velocities of type B and C are attributed to the reduction of pressure loss by the short slit. In the case of type D, it is considered that narrow channel and complicated small-scale turbulence in the cavity increase pressure loss remarkably.

As can be seen from Fig. 5(b), fluctuation velocity u' increases up to x = 0.6 mm or 0.7 mm with x and then decrease gradually regardless of nozzle shape. At the stagnation point (x = 0), fluctuation velocities of type C, D and E are similar, and larger than those of type B and D. The large u' corresponds to high vorticity magnitudes observed at stagnation point for type C, D and E (see close-up view of Fig. 4). Focusing on the point of x = 0.6 mm or 0.7 mm where u' reaches maximum, we can see that u' of type D and E are smaller than those of type A and B while type C keeps the largest u' of five types. The quite small u' of type D is probably due to large pressure loss. Since the large pressure loss reduce the velocity of the air jet ejected from the slit exit, vortices in the jet shear layer become weak. On the other hand, type C indicates the largest u' of the five types in the region of x=1mm. Short slit length and square space of type C improves both U and u'.

5. Comparison between Calculated Removal Moment and Measured Removal Rate

Figure 6 shows the horizontal distribution of total removal moment Mr calculated under the condition of D = 1.5μm. For the calculation of Mr, velocities of U and u' at the center of the particle (y = 0.75 μm) were estimated from numerical results obtained at y = 10 μm as mentioned in 2.2. Total removal moment Mr increases with x and has a maximum at x = 0.5 mm or 0.6 mm regardless of nozzle shape. The maximum values of Mr for the five nozzle shapes are summarized in Table 1. Contributions of M_d and m_d' to
$M_r$ are also shown in Table 1. Total removal moments of type B and C become larger than original $M_r$ of type A. Although the values of $M_r$ for type B and C are very similar, type C indicates the largest $M_r$. The $M_r$ of type B is enhanced by quite large $M_D$ despite of relatively small $m_{o}'$. On the other hand, the $M_r$ of type C is improved by both increases of $M_D$ and $m_{o}'$. The differences of $M_D$ and $m_{o}'$ between type B and C originate in flow fields explained in 4.1 and 4.2. In contrast, total moments $M_r$ of type D and E are reduced from that of type A. These reductions are mainly due to decrease of $M_D$. Narrow channel of type D and double-step cavity of type E increase pressure loss and reduce mean velocity. As a consequence, type C has the largest $M_r$, followed by type B, A, E, D.

The measured removal rates $\gamma$ for the five types are also shown in Table 1. In this experimental condition, $\gamma$ ranges from 86.2% to 91.2%. Although the difference is slight, Type C has the largest $\gamma$ followed by B, A, E and D in this order. This order of $\gamma$ agrees with the order of $M_r$.

From this agreement, it can be stated that the removal performance can be predicted by the numerical result of the removal moment estimated from mean and fluctuation velocities.

### 6. Conclusion

To improve the removal performance of the dry-cleaning device equipped with a cavity nozzle, we propose 4 nozzle shapes with minimized slit length and square space, which are modified from the conventional shape of type A and are named type B, C, D and E. The flow velocities for type A to E were calculated numerically, and the removal moments were estimated from the calculated velocity fields. From the numerical analysis, it is clarified that the short slit reduces pressure loss and increases mean velocity. The square space transforms circular vortices in the cavity into random turbulence and enhances fluctuation at the stagnation point. These effects improve removal performance. On the other hand, a narrow channel and double step cavity increase pressure-loss and reduces removal performance. As the consequence, type C has the largest removal moment, followed by type B, A, E, D in this order. We also measured particle removal rates for the five nozzle shapes to verify the numerical estimation of removal performance. As the result of the experiment, type C has the largest removal rates, followed by type B, A, E, D. The order of the measured removal rates agrees well with the calculated removal moment. This agreement demonstrates that the numerical result of the removal moment estimated from mean and fluctuation velocities is effective to predict removal performance. More precise and quantitative prediction is the future task.

### Nomenclature

- $D$: particle diameter [m]
- $M_D$: removal moment by mean velocity [N m]
- $m_{o}'$: removal moment by fluctuation velocity [N m]
- $M_r$: total removal moment [N m]  
- $U$: mean velocity [m/s]

### Table 1 Comparison between calculated maximum removal moment and measured removal rate

<table>
<thead>
<tr>
<th>Nozzle shape</th>
<th>Rank of $M_r$</th>
<th>Calculated moment $[\times 10^{-15}$ N m]</th>
<th>Rank of $\gamma$</th>
<th>Measured removal rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>3</td>
<td>4.41 (at $x=0.5$ mm)</td>
<td>3</td>
<td>91.2</td>
</tr>
<tr>
<td>Type B</td>
<td>2</td>
<td>4.68 (at $x=0.5$ mm)</td>
<td>2</td>
<td>91.6</td>
</tr>
<tr>
<td>Type C</td>
<td>1</td>
<td>4.70 (at $x=0.5$ mm)</td>
<td>1</td>
<td>91.9</td>
</tr>
<tr>
<td>Type D</td>
<td>5</td>
<td>3.71 (at $x=0.6$ mm)</td>
<td>5</td>
<td>86.2</td>
</tr>
<tr>
<td>Type E</td>
<td>4</td>
<td>4.31 (at $x=0.6$ mm)</td>
<td>4</td>
<td>86.8</td>
</tr>
</tbody>
</table>

Fig. 6 Total removal moment ($D = 1.5 \mu$m)
\[ u' \] fluctuation velocity [m/s]
\[ \gamma \] particle removal rate [%]
\[ v \] kinematic viscosity [m²/s]
\[ \rho \] density [kg/m³]

**References**


