A Study on Removal of Infinitesimal Particles on a Wall by High Speed Air Jet
(Numerical Simulation of Hydrodynamic Removal Force)

Sanghyeon SONG1, Kazuhiko SOEMOTO2, Tatsuro WAKIMOTO1 and Kenji KATOH1

1 Graduate School of Engineering, Osaka City University, Sugimoto, Sumiyoshi-ku, Osaka-shi, Osaka 558-8585, Japan
2 Shinko Co. Ltd, Minamiokajima 5-8-84, Taisho-ku, Osaka-shi, Osaka 551-0021, Japan

(Received 20 January 2014; received in revised form 14 March 2014; accepted 19 April 2014)

Abstract
A cleaning device equipped with a special nozzle containing triangular cavities is developed to add high-frequency turbulence to the impinging jet flow. In order to clarify the removal mechanism of fine particles adhered to a wall by van der Waals force, a numerical simulation is performed to estimate various removal forces acting on the particle. Here we examine the effect of the force due to a pressure gradient fluctuation of the impinging jet on removal performance. The numerical results show that viscous drag has the greatest influence, while the pressure gradient force is enhanced by the cavities and has a remarkable effect on the removal of particles larger than 1.5 μm. The numerical results qualitatively correspond to the tendency of measured removal rates for 1.6 μm particles.

Key words
Impinging Jet, Particle Adhesion, Removal, Van Der Waals Force, Pressure Fluctuation, Numerical Simulation

1. Introduction
Liquid crystal display (LCD) technology is becoming increasingly widespread for televisions, cell phones tablet-type devices and so on. The most important issue for LCD manufacturing is to produce large format glass plates without defects. Therefore, there is an increasing demand for a technology for fine particle removal from glass surfaces. Although cleaning techniques using chemical solutions have been widely used, waste solutions cause environmental problems. For this reason, a dry cleaning process is attracting attention as an alternative. A device that applies an impingement air jet can potentially clean a large surface and minimize the use of complicated technology [1, 2]. The authors previously proposed a new type of dry cleaner system to remove micrometer-sized particles from a surface using a high-speed air jet [3]. The system has an original nozzle containing cavities designed to add fluctuations over 5 kHz to the ejected air jet. The experimental results showed that the removal rate can be improved by adding fluctuation to the jet flow [3].

The aim of this study is to clarify the removal mechanism of micrometer-sized particles in the proposed cleaner system. Here we consider the effect of the removal force due to a pressure gradient fluctuation in the stagnation area [4]. In order to estimate various removal forces, such as drag or lift, and the pressure gradient force, a numerical simulation is performed to analyze the jet flow near the stagnation point. Based on the moment balance on a particle, the contribution of each removal force is compared with the moment due to van der Waals adhesive force measured by the centrifugal method [4]. The effect of the proposed original nozzle is discussed through the estimation of each removal force and the removal rate measured in the previous study [3].

2. Experimental Setup and Numerical Method

2.1 Experimental setup
Figure 1 shows the schematic of the proposed cleaner system [3]. The cleaner head is a rectangular parallelepiped with uniform section, and it consists of an air storage chamber and two suction chambers. The air is supplied to the air storage chamber by a vortex blower (VB-060-E2: Hitachi Industrial Equipment Systems), and is ejected from an exchangeable two-dimensional nozzle at over 100 m/s. The air jet from the nozzle impinges on a test surface placed 1.5 mm away from the exit of the nozzle. After removing the particles on the surface, the impinged air flow is drawn into the suction chambers with the particles. Figure 2 shows the construction of two types of nozzles used in this study. The cavity (C) nozzle has two cavities with a triangular...
geometry (6.0 mm base width and 3.0 mm height) in front of a linear section of 0.4 mm width, as shown in the figure. On the other hand, the straight long (SL) nozzle, which was installed for examining the removal performance of the C nozzle, has only the linear flow section. As shown in Fig. 2, both nozzles have a slit of 0.4 mm width and 7 mm height at the exit.

Using the two types of nozzles, various quantities such as mean velocity, velocity fluctuation, and removal rates were measured in the previous study [3]. In addition, the adhesive force of a particle was measured from the centrifugal force acting on a particle located on a rotating disk [4]. These experimental results will be referred to for comparison with the removal forces estimated from the numerical simulation in this study.

2.2 Numerical method
We performed a numerical simulation to estimate the flow field near the stagnation point as well as inside the two types of nozzles, as shown in Fig. 2. We simulated three-dimensional unsteady incompressible flow in a Cartesian reference frame, as shown in Fig. 2. In the coordinate system, the origin is taken at the stagnation point of the jet flow on the wall. Commercial computational fluid dynamics software, Ansys Fluent 14.5, was used. Detached eddy simulation (DES) was applied as a turbulence model [5]. The number of grid points used in the present calculation was 150, 85, and 30 in the x, y, and z directions, respectively. The grid nodes were refined near the wall and in the jet shear layer. Note that the effect of compressibility may be negligible since the jet velocity was in the order of 100 m/s, corresponding to static pressure of about 6000 Pa, which is much smaller than atmospheric pressure.

Before simulating the flow field as shown in Fig. 2, we calculated the plane impinging jet at Re = 20000 with a uniform velocity (\(V_{CL}\)) distribution at the nozzle exit in order to verify the computational method. Figures 3(a) and 3(b) show the calculated results of time-averaged x-directional velocity \(U\) and turbulence intensity \(u'\) normalized by \(V_{CL}\) at \(x/e = 2\), where \(e\) indicates the nozzle exit width. In the figure, experimental results by Ashforth [6] are plotted as well as the numerical results for the purpose of comparison. As shown in the figures, the calculated distributions in the y direction approximate well the experimental results. We also compared the time-averaged x-directional velocity \(U\) obtained by simulation with that measured in the cleaner system at \(y = 0.15\) mm by a Pitot tube [3]. Figure 4 shows the results of the velocity distribution in the x direction. Although the simulation results are about 10% to 20% lower than the experimental results, both profiles are quite similar and the agreement is fairly good. From the above results, we can say that the flow field in the actual system can be simulated by the numerical method performed in this study.

3. Theoretical Background
Before describing the results of the numerical simulation, it is necessary to understand theoretically the forces acting on a micrometer-sized particle in contact with a surface in the flow field. The relevant forces acting on the particle are schematically shown in Fig. 5. \(F_D\) and \(F_L\) indicate the drag and lift, respectively. \(M_D\) is the moment that results from the viscous stress on the particle surface. \(F_p\) indicates the force that results from the instantaneous pressure gradient fluctuation [4]. \(F_p\) is proposed in this study and will be
stated later. The above forces or moment act on the particle to remove it from the wall, whereas $F_V$ indicates van der Waals adhesive force.

Many authors have suggested that fine particles are removed in a rolling motion rather than lifting or sliding motions [7, 8]. In this study, the moment acting on the particle is considered. The moment balance on the particle as shown in Fig. 5 can be expressed by the following relation [7]:

$$F_D \cdot R + F_L \cdot a + F_V \cdot R + M_D \geq F_V \cdot a$$

(1)

where $R$ is the particle radius and $a$ indicates the contact radius of the particle adhered to the wall as shown in Fig. 5. The contact radius $a$ can be evaluated according to the Johnson–Kendall–Roberts (JKR) theory, which accounts for elastic force balance on a smooth surface [9] as

$$a = \left( \frac{6 \pi \sigma R^2}{4K} \right)^{\frac{1}{3}}$$

(2)

In the above equation, $\sigma$ is the surface energy of adhesion between the particle and the wall, and $K$ is the composite Young’s modulus given by

$$K = \frac{4}{3} \left[ \frac{(1-\eta^2)}{E_1} \cdot \frac{(1-\eta^2)}{E_2} \right]^{-\frac{1}{3}}$$

(3)

where $E$ and $\eta$ indicate Young’s modulus and Poisson’s ratio, respectively. Subscripts 1 and 2 in the above equation correspond to the particle and the wall, respectively. In the experimental system treated here, a silica particle and chrome-coated glass plate are considered [4]. The contact radius $a$ can be estimated if the physical quantities of each material are substituted by Eqs. (2) and (3).

In the moment balance represented by Eq. (1), the adhesive force is considered first. The moment of the adhesive force $F_V$ caused by van der Waals force between the spherical particle and the wall can be estimated by the following relation [10]:

$$F_V \times a = C_V \frac{AD}{12 \, \eta_0^5} \times a$$

(4)

where $D$ is the particle diameter, $\eta_0 = 0.4$ nm is the minimum distance between the particle and the wall, and $A$ is the Hamaker constant [10]. The constant $C_V$ in Eq. (4) represents the coefficient to correct the effect of wall roughness or other factors. Some authors have suggested that the adhesive force is remarkably reduced even by roughness of the nanometer order [11]. Substituting the relation of Eq. (2) into Eq. (4), the following expression can be obtained:

$$F_V \times a = C_V \left( \frac{3 \pi \sigma}{8K} \right)^{\frac{1}{3}} \frac{AD^{5/3}}{12 \, \eta_0^5}$$

(5)

The above equation implies that the adhesive moment increases with $5/3$ power of the particle diameter.

In the preceding study, the adhesive force of micrometer-sized silica particles ($D = 5 \, \mu m$, $6.5 \, \mu m$, $10 \, \mu m$, and $20 \, \mu m$) adhered to a chrome-coated glass plate was measured using a centrifugal force method in a rotating system [4]. Figure 6 shows the measured adhesive moments plotted against particle diameter $D$. The solid curve in the figure indicates Eq. (5), with $C_V = 0.29$. As shown in the figure, the experimental results can be approximated well by Eq. (5). We will refer to Eq. (5) later when the moment balance stated by Eq. (1) is considered.

Now various removal moments that appear in the left hand side of Eq. (1) are discussed. In the case of a very slow flow around a sphere, Stokes’ law is used for the evaluation of the drag force $F_D$. A modified Stokes’ drag is used to describe the drag force in Eq. (1) as

$$F_D = 1.70 \times 3 \pi \eta D U_c$$

(6)

where the constant 1.70 corrects for the effect of wall roughness. $U_c$ is the $x$-directional velocity of the fluid at the center of the sphere [12]. The lift $F_L$ can be described by the Saffman force as [13]
where \( \rho \) and \( \nu \) indicate density and kinematic viscosity, respectively. The moment of viscous surface stresses \( M_D \) in laminar flow is given by the following relation [12]:

\[
M_D = 0.944 \pi \rho D^2 U_c \tag{8}
\]

In addition to the drag, lift, and moment of surface stress, we propose another removal force induced by the gradient of fluctuating pressure [4]. Although the influence of the pressure gradient on particle removal has not been noticed in the past, it can be influential because large pressure fluctuation can be delivered close to the wall while flow velocity quickly decays on approaching the wall. When a particle is located in the instantaneous pressure gradient field with a magnitude \( |\text{grad} \cdot p'| \), as schematically shown in Fig. 5, the resultant force \( F_P \) can be calculated from the integration over the whole surface of the spherical particle as follows:

\[
F_P = \frac{\rho c^v}{\nu u^*} \frac{1}{6} \pi D^3 \tag{9}
\]

A large pressure force could be created instantaneously when a high-speed flow impinges on the wall. We evaluated the pressure gradient in Eq. (9) by the simulated result of \( p' \) and the length scale of the minimum turbulence eddy, which is assumed as \( \nu/u^* \), where \( u^* \) indicates the friction velocity. Then Eq. (9) can be rewritten as

\[
F_P = \frac{\rho c^v}{\nu u^*} \frac{1}{6} \pi D^3 \tag{10}
\]

The subscript C again indicates the value estimated at the particle center.

Each force or moment stated by Eqs. (6), (7), (8), and (10) are estimated by using numerical results, in which mean velocity, velocity fluctuation, friction velocity, and pressure fluctuation are averaged in the \( x \) direction over the stagnation area (i.e., \(-0.2 \text{mm} \leq x \leq 0.2 \text{mm}\)), where the particles may be removed directly by the impinging jet.

### 4. Numerical Results

#### 4.1 Flow fields in the cleaner system

This section describes the simulated results obtained at an air storage chamber pressure \( P_S \) of 8, 11, and 14 kPa, as in the experiment [3]. In this section, only the numerical results for \( P_S = 11 \text{ kPa} \) are shown, since the results obtained for other pressures are almost similar to those for \( P_S = 11 \text{ kPa} \).

Figures 7(a) and (b) show instantaneous velocity vectors and contours of vorticity for the two types of nozzles. The figures demonstrate that velocity fluctuation and vorticity are remarkably enhanced by the C-type nozzle. Comparing Figs. 7(a) and Fig. 7(b), one can see that small-sized vortices are distributed more widely for the C-type nozzle around the stagnation region. It is expected that the C-type nozzle produces high frequency fluctuation in the cavities.

Figures 8 and 9 show the mean \( y \)-directional velocity \( V \) at the nozzle exit and the static pressure distribution on the wall, respectively. The difference between the two nozzles is very small. Figure 10 shows the distribution of the horizontal velocity averaged in the stagnation area (i.e., \(-0.2 \text{mm} \leq x \leq 0.2 \text{mm}\)). The distributions for the two types of nozzles agree with each other in \( y < 10 \mu \text{m} \), where micrometer-sized particles are actually deposited. The agreement of these time-averaged values for the two types of nozzles was also found in the previous experimental study [3].

Figure 11 shows the turbulence intensity (rms) of horizontal velocity \( u' \) averaged in the stagnation area as stated above. The intensity of the C-type nozzle is about three times as high as that of the SL-type nozzle near the stagnation point. Figure 12 shows the pressure fluctuations (rms) at the wall (\( y = 0 \)) for the two types of nozzles. In the case of the C-type nozzle, the pressure fluctuation \( p' \) reaches 900 Pa near the stagnation point. Then the pressure
fluctuation of the C-type nozzle gradually decreases and approaches the value of the SL-type nozzle at $x = 1$ mm, as shown in the figure. It is noted that the local pressure fluctuation as shown in Fig. 12 is much higher than the experimental results shown in [3]. This is because the pressure was averaged over a 0.5 mm diameter sensor, and hence the fluctuation might be suppressed in the measurement.

The above results of the numerical simulation show that the time-averaged quantities are almost similar for both types of nozzles, while the fluctuation is remarkably enhanced by the C-type nozzle containing triangular cavities.

4.2 Hydrodynamic removal forces

The resultant of the removal moment in the left hand side of Eq. (1) was calculated from the numerical results and was compared with the adhesive moment calculated from Eq. (5) in which $C_V = 0.29$ was used. The calculated result for $P_S = 11$ kPa is shown in Fig. 13, in which each moment is drawn against the particle diameter $D$ for the two types of nozzles. As shown in the figure, the removal moment is almost similar for the two types of nozzles, although the moment of the C-type nozzle is slightly larger than that of the SL-type nozzle. The removal moment overtakes and surpasses the adhesive moment at $D \approx 0.5 \mu m$. If we assume that the particle removal rate is equal to 50% when both moments balance each other [11], the cleaner could remove particles larger than 0.5 μm with more than 50% removal.
rate. The diameters at which the removal moment balances the adhesive moment are calculated as \( D \approx 0.6 \) and 0.45 \( \mu \text{m} \) for \( P_s = 8 \) and 14 kPa, respectively. The impinging jet at a higher pressure can remove smaller particles.

In order to discuss the removal mechanism more precisely, the contributions of each removal moment on the left hand side of Eq. (1) are shown in Fig. 14. It is noted that only the sum of drag \( F_D \times R \) and surface stress \( M_D \) is drawn in the figure, since both moments originate from the viscous stress on the particle surface. In addition, the result of the moment of lift \( F_L \times R \) is not shown in the figure because the contribution is less than 1% compared with that of the drag force. As shown in the figure, the moment of drag is almost similar within several percentages for the two types of nozzles and dominates removal, especially for particles smaller than 1 \( \mu \text{m} \). When the particle is upsized over 1.5 \( \mu \text{m} \), however, the contribution of the pressure gradient fluctuation (i.e., \( F_P \times R \)) should not be negligible. The magnitude of \( F_P \times R \) for the C-type nozzle is about twice as large as that for the SL-type nozzle. This is the reason why the total removal moment of the C-type nozzle is about 10% larger than that of the SL-type nozzle for particles larger than 1.5 \( \mu \text{m} \), as shown in Fig. 12. Although the pressure fluctuation generated by the cavities in the C-type nozzle is not as effective for removing small particles, it may improve the removal performance for particles larger than about 1.5 \( \mu \text{m} \).

Figure 15 shows the calculated results of the total removal moment dependent on the pressure in the air storage chamber \( P_s \). It is natural that the removal moment will increase as the pressure increases, since the jet impinging velocity increases with \( P_s \). As shown in the figure, the moment of the C-type nozzle is always larger than that of the SL-type nozzle because of the difference in pressure fluctuation. Figure 16 shows the experimental results of the removal rate \( \gamma \) when the cleaner system shown in Fig. 1 was actually used to remove 1.6 \( \mu \text{m} \)-sized particles. Silica particles were dispersed on the chrome-coated glass plate and then the plate was cleaned using the two types of nozzles [3]. One can see that the tendency of the removal rate is qualitatively similar to that of the removal moment shown in Fig. 15; i.e., the removal rate increases with \( P_s \) and the performance of the C-type nozzle is always superior to that of the SL-type nozzle, even though their jet velocities are almost equal within a few percentages [3]. In addition, it seems reasonable that the removal rates are larger than 50% for all the experimental conditions, since the calculated removal moments always exceed the adhesive moment, as
mentioned before. The numerical simulation performed in this study can qualitatively explain the tendency of the actual removal performance and the effect of turbulence generated by the triangular cavities in the C-type nozzle. The model of instantaneous pressure gradient force can represent the role of high frequency turbulence on the particle removal performance without contradiction.

5. Summary
A numerical simulation was performed to analyze the flow field of an impinging jet generated by the proposed cleaner system in which two types of nozzles (i.e., C and SL-type) were used. Numerical results showed that the time-averaged velocity or pressure was almost similar for both types of nozzles, while the fluctuation was remarkably enhanced by the cavities installed in the C-type nozzle. The hydrodynamic removal moments acting on the particle were estimated on the basis of the numerical results and were compared with van der Waals adhesive moment. The total removal moment of the C-type nozzle was slightly larger than that of the SL-type nozzle, especially for particles larger than 1.5 μm. The force of the instantaneous pressure gradient could have a positive influence on the removal of particles when the particle diameter is larger than a few micrometers. The model based on the pressure fluctuation can explain the tendency of removal rates measured experimentally. Although we assume sphere as particle shape, it is expected that above conclusions are valid for non-spherical particles qualitatively as far as they are removed by not flaking by rolling motion.

Nomenclature
A Hamaker constant
a contact radius of particle [m]
D particle diameter [m]
E Young’s modulus [kg/mm²]
e nozzle exit width [m]
F_D drag force [N]
F_L lift force [N]
F_P pressure fluctuation force [N]
F_V van der Waals force [N]
M_s moment of surface stress [N m]
P static pressure [Pa]
\(P_0\) pressure in air storage chamber [Pa]
\(\rho'\) pressure fluctuation[Pa]
R particle radius [μm]
U time-averaged x-directional velocity [m/s]
\(u'\) fluctuation of x-directional velocity [m/s]
V time-averaged y-directional velocity [m/s]
x coordinate in the tangential direction on the wall [m]
y coordinate in the vertical direction to the wall [m]
z coordinate in the spanwise direction [m]

Greek symbols
\(\rho\) density [kg/m³]
\(\nu\) kinetic viscosity [m²/s]
\(\gamma\) removal rate
\(\eta\) Poisson’s ratio
\(\sigma\) surface energy [J/m]

References