The Effect of Humidity on the Removal of Fine Particles on a Solid Surface using High-speed Air Jet

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Abstract

The effect of operating conditions on the removal efficiency of deposited particles using high-speed air jet was studied with particular attention to the humidity of surrounding air during particle deposition and air-jet removal. The experimental results showed that the removal efficiency of particles deposited in a low humidity atmosphere, decreased with increasing drying time after the deposition. In the case of a deposition under high humidity, the removal efficiency increased at the beginning of drying and decreased rapidly after reaching the maximum efficiency. For drying over 80 hrs, however, the humidity of the surrounding air during the particle deposition didn’t affect the removal efficiency.

The efficiency also depended on the humidity during the air-jet removal, and reached the maximum value at 67% relative humidity. Such a variation of the removal efficiency has been well explained by the change of Hamaker’s constant with the adsorbed layer-thickness of water molecules and the variation of liquid surface tension with the thickness of liquid bridge.

1. Introduction

Contamination of products by fine particles has been a problem in many fields such as electric, electronic industries etc. Until today, although fine particles deposited on a product have been removed mainly by wet cleaning, the problem associated with wet cleaning is that such method is inapplicable to products sensitive to moisture, requires a drying process, and causes contamination of environments and the like by the cleaning agents. Accordingly, the authors paid attention to a method of removing particles by high-speed air jet which is a dry method using a removing apparatus of a relatively simple structure, and experimentally studied the effects of such flow control conditions as duration time of air jet, jet impinging angle, nozzle-surface distance on the removal efficiency. We also studied the variation of the removal efficiency with jet impingement by continuously applying air jets for short durations. The pulse jets removal was also reported by Otani, et al.

When a high-speed air jet is applied to a surface to remove particles, a separating force due to a resistance to the air jet acts on the particles deposited on the surface. On the other hand, an adhesive force is effective between the particle and the solid surface. Although the main adhesive forces are the van der Waals force, the liquid bridging force and the electrostatic force, they depend on the relative humidity of the air. Therefore, it is expected that the removal efficiency of particles may be affected by the humidity. Thus, in the study, we paid particular attention to the humidity during deposition of particles onto a surface and removal thereof, and studied the effect of the humidity, that is one of the environmental conditions in removing particles.

2. Apparatus and Method of Experiment

Figure 1 shows a schematic view of a particle removing apparatus used in the experiment. In the particle removing experiment, similar to our previous report, compressed air was adjusted to a predetermined pressure by means of a release valve after removal of mist, and supplied to a jet nozzle. For the jet nozzle, a two-dimensional slit-type nozzle having a nozzle area of 0.25 x 10 mm² was employed, as...
Fig. 1 Schematic diagram of experimental apparatus

Fig. 2 Air jet nozzle

shown in Figure 2. The operating conditions of the air jet were constant such that the air pressure at the nozzle (gauge pressure) \( \Delta P_n \) was set at \( 10^5 \) Pa, the jet impinging angle at 45°, and the distance \( d \) between the nozzle tip and the surface at 10 mm. In addition, here, the duration time was constantly set to \( t = 10 \) sec, because the removal efficiency reached the highest value at that time and remained at that value throughout the duration time of air jet, when the air pressure at the nozzle \( \Delta P_n \) was at \( 10^5 \) Pa. During the removal of particles, the room temperature was maintained at constant (approximately 20°C) by means of an air-conditioner, and the relative humidity \( \Psi_r \) at removal was adjusted by varying the water content of the air mainly by means of an ultrasonic humidifier (Matsushita Electric Industry Co., Ltd., FE-05KVE).

In the experiment, the removal efficiency was obtained by microscopically counting the particles after they were deposited on a test piece surface (before removal) and after jet impingement (after removal), respectively, and dividing the difference of the counts by the total number of particles. The removal efficiency was measured at three points (measurement points 1, 2 and 3 in the previous report) in the proximity of the air-jet impingement point, and an average value of the measurements was defined as the removal efficiency \( \eta \). The measurement area for counting the particles was always set to \( 1 \times 1 \) mm².

Other main conditions are shown in Table 1. Standard latex particles (Styrene/Divinylbenzene) of 3.7 \( \mu \)m in size were employed as test particles, and a glass (borosilicate glass) as a test piece. Figure 3 shows an apparatus for depositing particles onto a test piece. Because the standard latex particles are dispersed and stored in a liquid containing surfactant, they were aerosolized by spraying with a nebulizer, and the particles were heated and dried in a buffer container. Water in the aerosol was removed by a diffusion drier filled with silica gel, and the particles were deposited on the wall by inertia impingement using an impactor. The impactor is of a jet diameter of 9 mm, and the mean velocity of aerosol was constant at about 6 m/s. At deposition, the humidity of the air jet was measured downstream of a baffle plate in the impactor by using a digital thermo-hygrometer, and the measurement was taken as the humidity \( \Psi_d \) at particle deposition. The humidity at deposition was changed by varying the heating temperature in the buffer container and the length of the diffusion dryer.

In studying the effect of the humidity \( \Psi_r \) at removal, the conditions at deposition were constant at about

| Table 1 Experimental conditions |
|---------------------------------|
| Surface material | Glass (Borosilicate) |
| Particle | Styrene/divinylbenzene |
| Particle size | \( D_p \) 3.7 \( \mu \)m |
| Nozzle pressure | \( \Delta P_n \) \( 10^5 \) Pa |
| Jet impinging angle | \( \theta \) 45 deg |
| Nozzle-surface distance | \( d \) 10 mm |
| Jet duration time | \( t \) 10 s |
| Relative humidity at deposition | \( \Psi_d \) 52−74 % |
| Relative humidity at removal | \( \Psi_r \) 55−82 % |
| Drying time in desiccator | \( t_d \) 1−180 hr |

Fig. 3 Apparatus for preparing a test piece
KONA place at a humidity not lower than that at removal; efficiency increased at the beginning, and decreased after the maximum efficiency was achieved at a certain drying time, in the case when the deposition took place at a humidity not higher than the humidity as the drying time was increased, in the case when the particles were almost uniformly deposited. The depositing time of particles was adjusted such that about 200 particles were deposited on each measurement area.

After the particles were deposited, they were counted on the measurement surface by using an optical microscope, and dried in a desiccator of about \(7 \times 10^{-3} \text{ m}^3\) in content volume. It takes about 15 min to obtain a constant humidity (approximately 15%) in the desiccator after a test piece is placed in the desiccator, and the cover is closed. Therefore, the test piece was dried for at least 1 hr in order to assume a drying operation at a constant humidity.

3. Result of Experiment and Discussion

Figure 4 shows the result of the removal experiment by varying the drying time in the desiccator, taking the humidity at deposition as a parameter. The humidity \(\psi_r\) at removal was constant at 59%. When the humidity at deposition was lowest at \(\psi_d = 55\%\), the removal efficiency was reduced as the drying time was increased, and reached a constant level of about 10% after 5 hr of drying. At \(\psi_d = 58\%\), reduction of the removal efficiency was minor until about 20 hr of drying, a high removal efficiency of 70 to 80% was obtained, and the efficiency rapidly decreased after the drying time exceeded 20 hr. When it exceeded 60 hr, the efficiency was equal to that at \(\psi_d = 55\%\), and became constant. At \(\psi_d = 64, 72\%\), although the removal efficiency was increased together with the drying time until about 3 and 6 hr of drying, respectively, it dropped rapidly thereafter. In other words: (1) The removal efficiency decreased as the drying time was increased, in the case when the deposition took place at a humidity not higher than the humidity \(\psi_r\) at removal; (2) the removal efficiency increased at the beginning, and decreased after the maximum efficiency was achieved at a certain drying time, in the case when the deposition took place at a humidity not lower than that at removal; and (3) the removal efficiency was not affected by the humidity \(\psi_d\) at deposition after 80 hr of drying. As a result, it is supposed that the removal efficiency is higher immediately after deposition of particles, in the case when the particles are deposited at a relatively low humidity, and after drying them to a certain level, in the case when the particles are deposited at a high humidity.

Figure 5 shows the result of the removal experiment conducted by varying the humidity \(\psi_r\) at removal. Here, in order to avoid any effect of the humidity at deposition, the test piece was dried in a desiccator for 100 hr or longer after deposition of the particles according to the result of Figure 4. After drying, the test piece was transferred to a controlled removal environment, and the removal experiment was conducted after leaving the test piece in the environment for 2 min or longer. The removal efficiency was low at a low humidity, and rapidly increased as the humidity was increased. When the humidity \(\psi_r\) at removal was 67%, the maximum efficiency was achieved, and it decreased at a humidity lower than that. From the figure, it is recognized that the removal efficiency can be increased, regardless of the humidity at deposition of the particles, by adjusting the humidity \(\psi_r\) at removal, which is an environmental condition during the removal of the particles. Such tendency was observed not only on glass pieces used in the

![Fig. 4 Effect of drying time on removal efficiency](image)

![Fig. 5 Effect of relative humidity on removal efficiency](image)
experiment, but also on test pieces made of polymer materials and metals. The result of the experiments using test pieces of different materials shall be discussed in the next report. The experiment was conducted by varying the period during which the test pieces were left after they were set in place in a removal environment after drying, and it was confirmed that the removal efficiency was not affected by the period, if it is set to 1 min or longer. Thus, the results of the experiment shown in Figure 5 are considered to be equilibrium values in the removal environment.

Since the conditions of jet impingement are unchanged in the environment, the particle removing force provided by the air jet is considered to be constant. It is, therefore, supposed that the removal efficiency depends on the humidity, because water molecules on a particle and wall surface may have an effect on the adhesive force between a particle and a solid surface. When the humidity is low, and the effect of water molecules is absent, the van der Waals force can be approximated by a value in vacuum, and represents an adhesive force higher than that in the presence of water molecules. It was reported that the liquid bridging force increases together with the humidity, when a liquid bridge formed between a particle and a surface at a high humidity. Thus, it is considered that the removal efficiency is reduced mainly with an increase of the van der Waals force at a low humidity, and with an increase of the liquid bridging force at high humidity. Now, the variation of the adhesive force due to the humidity is typified.

At low humidity, it is generally considered that water molecules are adsorbed onto a particle and solid surface, and form an adsorbed layer of not more than a few molecules overlaid on each other (Figure 6-a). A variation of the thickness \( \delta \) of the adsorbed water layer on a glass surface was presented by Chikazawa et al., as shown in Figure 7, and the data is now approximated by the Halsey’s formula below.

\[
\ln \psi = -\frac{k}{RT\theta_w^q} \\
\theta_w = \frac{\varphi}{\nu_m} 
\]

At \( \nu = S\delta \),

\[
\ln \psi = -\frac{k_h}{\delta^q} \\
k_h = \frac{k\nu_m^q}{RTS^q} = 1.45 \times 10^{-17} \\
q = 1.81
\]  

An approximate curve obtained by Eq. (2) is sufficiently consistent with plots, as shown in Figure 7. Additionally, it is found from the figure that about 0.5 nm (approximately 1.7 molecules) or more water molecules are adsorbed even at the lowest humidity within the range of the experiment. In such condition, the adsorbed water is different from bulk water, and no liquid bridging force acts as an adhesion force between the particle and the surface. However, the van der Waals force and an electrostatic are considered to be active. Here, taking only the van der Waals force, and neglecting the electrostatic force, an adhesive force \( F_d \) between the particle and the surface is assumed to be obtained by the following formula.

\[
F_d = F_p = \frac{AD_p}{12\varepsilon^2} \left(1 + \frac{A^2k_pD_p}{108\varepsilon^2} \right)
\]

where

\[
k_p = \frac{1 - \nu_p^2}{E_p} + \frac{1 - \nu_w^2}{E_w}
\]

In Eq. (4), Young’s modulus \( E \) and Poisson’s ratio \( \nu \) are independent of the humidity, and can be obtained as follows.

\[
E_w = 7.5 \times 10^{10} \text{ (Glass)} \\
E_p = 0.38 \times 10^{10} \text{ (Polystyrene)} \\
\nu_w = 0.17 \text{ (Glass)} \\
\nu_p = 0.34 \text{ (Polystyrene)}
\]

Accordingly, the modulus of elastic characteristic \( k_p \) in Eq. (3) is considered to be independent of the humidity and constant. Then, dependency of a gap \( z \) between a particle and a solid surface and Hamaker’s constant \( A \) on the humidity is considered.

For this purpose, two models are assumed for the contact between a particle and a solid surface. In
Fig. 7 Thickness of adsorbed water layer as a function of relative humidity

Model I (Figure 8), it is assumed that the medium between a particle and a surface is changed from air through an adsorbed water (air + water molecules) to a liquid (water). In this connection, it is assumed that the conditions of contact between the particle and the surface are unchanged. That is, an adsorbed layer of water is virtually considered as a medium different from air and liquid, and the gap z between the particle and the surface is assumed to be constant, although the Hamaker’s constant of the medium is continuously changed as the humidity is increased. Since the gap z is determined by Born’s repulsion between objects, and generally defined as being about 0.4 nm, it is also defined as $z = 0.4 \text{ nm} = z_0$ here.

The Hamaker’s constant $A$ is varied by the presence of water molecules, and can be approximated for dry air and a liquid by the following formulae, respectively:

\[ A = \sqrt{A_p}A_w \]  \hspace{1cm} (5)

\[ A = (\sqrt{A_p} - \sqrt{A_j}) (\sqrt{A_w} - \sqrt{A_j}) \]  \hspace{1cm} (6)

However, according to the above formulae, the adhesive force created by water molecules should be changed stepwise from that in the air to that in the liquid, and such continuous change of the removal efficiency in relation to the humidity as observed in the experimental result cannot be expressed. On the other hand, the Hamaker’s constant can be obtained by the following formulae, when an adsorption layer of macromolecules is present on a particle surface in a liquid:

\[ A = (\sqrt{A_p} - \sqrt{A_j}) (\sqrt{A_w} - \sqrt{A_j}) \]  \hspace{1cm} (7)

\[ A_j = (K_a\sqrt{A_a} + (1 - K_a)\sqrt{A_m})^2 \]  \hspace{1cm} (8)

In Eq. (9), $K_{a0}$ represents the volume ratio between the adsorbate and the medium between two objects, and $2\delta/z_0$, the ratio of the thickness of the adsorption layer to the distance between the surfaces of the two objects. In the case when water molecules adsorbed are absent, $K_{a0} = 0$, and $A_m = 0$. If it is assumed that water molecules adsorbed are similar to those of bulk water, $K_{a0}$ is constant at $K_{a0} = 1$. If $z$ is assumed to be constant at 0.4 nm, $2\delta/z$ is 1 or more, and $K_a$ is 1 or more within the range ($\delta \geq 0.5 \text{ nm}$) of the experiment. Eq. (9) is, therefore, inapplicable to the experiment conducted in a gaseous phase. Then, by assuming that $K_a$ depends only on the thickness $\delta$ of the adsorbed water, $K_a$ is expressed by a linear function of $\delta$. Because $K_{a0} = 0$
when the thickness of the layer $\delta = 0$, while the thickness of a liquid film is 2.9 to 3.7 nm when adsorbed water film has the properties of a liquid, and capillary condensation is possible $^{10}$, $K_a / 2$ is determined such that $K_a$ becomes equal to 1 when the thickness $2\delta$ of the liquid film between the particle and the surface is 3.5 nm. That is,

$$K_a = \delta / (1.75 \times 10^{-9})$$

$$0 \leq K_a \leq 1$$  \hspace{1cm} (11)

If the thickness of the layer of water molecules adsorbed onto the surface of a test particle is also obtained by Eq. (2), the variation of the adhesive force $F_d$ created by the humidity $\Psi_r$ can be calculated by using Eqs. (3) to (4) and (7) to (11).

On the other hand, in Model II (Figure 8), it is supposed that the number of water molecules between the particle and the surface is increased, and the distance $z$ between the particle and the surface is changed, as the medium between the particle and the surface changes from air to liquid (water) along with the increase of humidity. Thus, Eqs. (7) to (10) are applicable to the variation of the Hamaker’s constant caused by the thickness of the layer of water molecules, similarly to Model I, and the distance between the particle and the surface is given by the following formula as the sum of the initial distance $z_0$ between the particle and the surface and the thickness $2\delta$ of the adsorbed water.

$$z = z_0 + 2\delta$$

$$z_0 = 0.4 \text{ nm}$$ \hspace{1cm} (12)

For Models I and II, the variation of the adhesive force $F_d$ was calculated, respectively, and the result of the calculation is shown in Figure 9. The Hamaker’s constants used in the calculation are shown below.

$$A_w = 1.6 \times 10^{-19} \text{ (Glass: SiO}_2\text{)}$$

$$A_p = 1.2 \times 10^{-19} \text{ (Polystyrene)}$$

$$A_l = 4.8 \times 10^{-20} \text{ (Water)}$$

As shown in the figure, by using either model, a continuous variation of the adhesive force caused by the humidity can be expressed successfully. However, within the range of the experiment ($\Psi_r = 55$ to 82%), the magnitude of the adhesive force is higher for Model I in which the distance $z$ between the particle and the surface is constant.

Since the experimental result is expressed by the removal efficiency, the calculated value $\eta_{cal}$ of the removal efficiency is obtained on the basis of the adhesive force $F_d$ calculated. As shown in Figure 10, by taking the adhesive force $F_d$ as a mean value, the distribution of the adhesive force between the particle and the surface should be given. The distribution of the adhesive force $f_{ad}$ was assumed to be

$$f_{ad} = \frac{1}{\sqrt{2\pi} \sigma_g} \exp \left( -\frac{(\ln F - \ln F_d)^2}{2\ln^2 \sigma_g} \right)$$  \hspace{1cm} (13)

![Figure 9](image1.png)

**Fig. 9** van der Waals force as a function of relative humidity

![Figure 10](image2.png)

**Fig. 10** Schematic diagram showing the distribution of the adhesive force
be a lognormal distribution as expressed by the following formula.

Now, defining the removal force by \( F_r \), and assuming, as shown in Figure 10, that particles having an adhesive force \( F_a \) lower than the removal force \( F_r \) are removed, and those having an adhesive force \( F_a \) higher than the removal force \( F_r \) are not removed, the removal efficiency \( \eta_{\text{cal}} \) can be calculated from the distribution of the adhesive force using the following formula.

\[
\eta_{\text{cal}} = \int_0^1 F_r f_a dF
\]  

(14)

By means of Eqs. (13) and (14), the variation of the removal force can be calculated from the variation of the adhesive force \( F_a \) caused by the humidity.

The variation of the removal force caused by the humidity was calculated using \( \ln \sigma_p \) as a parameter, and the result of the calculation is shown in Figure 11. Here, \( F_r \) was determined for each \( \ln \sigma_p \) such that \( \eta_{\text{cal}} = 12\% \) at the humidity \( \Psi_r = 60\% \) that is obtained from the experimental result, at which no liquid bridge was considered to be formed. In a range of the humidity \( \Psi_r \) not higher than 67\%, at \( \ln \sigma_p = 0.2 \), the result of the calculation is generally consistent with the experimental result for both Models I and II. Accordingly, it is clear that the variation of the removal efficiency at a low humidity can be explained by using either model. However, the result of the calculation provides a curve rising rightward even when the humidity \( \Psi_r \) is 67\% or more, and is inconsistent with the tendency of the experimental result of having a peak. It is considered to be because a liquid bridging force created by a liquid film formed at a high humidity is not taken into consideration.

It is known that a liquid film is formed in the vicinity of a contact point between a particle and a solid surface even at lower pressure than the saturated vapor pressure because water is condensed due to the Kelvin effect. It is considered that a liquid bridging force acts between a particle and a surface because of the liquid film. As impurities (surfactant, etc.) on the surface of a test piece and of a particle and impurities in the atmosphere at deposition and removal of particles are not removed, soluble impurities may be contained in the condensate. Therefore, a formula (Kelvin formula; see Appendix A) presented by Kousaka et al.\(^{11,12}\) for a liquid bridge between two spheres of identical size was employed. Since the formula is derived for two spheres of identical size, it was converted for a sphere and a flat plate \( (d_1 = D_p, d_2 = \infty) \) using an equivalent diameter \( d_e \) that defines \( r_0 \) by the following formula.

\[
d_e = \frac{d_1d_2}{d_1 + d_2} = r_0
\]  

(15)

By using the formula presented by Kousaka et al. and Eq. (15), the radii \( r_1 \) and \( r_2 \) of the liquid bridge when the humidity at removal is at \( \Psi_r \) can be obtained.

The thickness of the liquid film when a liquid bridge is formed, on the other hand, is defined by the distance \( t_b \) between points \( P \) and \( W \) formed by combining the thickness of the adsorption layer and that of the liquid bridge between a particle and a surface. Here, when the angle between the segment \( \overline{CW} \) and the central axis of a deposited particle is at \( \theta_p \), the angle \( \theta_p \) falls within the range expressed by the following formula (see Appendix B).

\[
\theta_p \leq \tan^{-1} \left( \frac{r_2 + r_1}{D_p/2 + z} \right)
\]  

(16)

Because the particle size is 3.7 \( \mu m \), and the radii \( r_1 \) and \( r_2 \) of the liquid bridge are 1.4 nm and 130 nm \( (N_g = 0.0035) \) at the maximum humidity of 82\% within the range of the experiment,
Fig. 12 Approximation of liquid film thickness $t$

$$\theta_p \leq \tan^{-1}(0.036) = 2.03 \text{ [deg]} \quad (17)$$

(Note that $z = z_0 = 0.4$ nm is assumed.)

Thus, within the range of the experiment, the angle is assumed to be at $\theta_p = 0$, and the thickness of the liquid film is approximated by $2 \times (\delta + r_1)$. Although particles are deformed when they are deposited on a surface, since the radius of the deformed part is 71 nm (at the adhesive force $F = 10^{-6}$ [N]; see Appendix B), and is smaller than the radius $r_2$ of the liquid bridge, it is supposed that the calculation of the thickness of the liquid film is not affected.

Because a liquid bridge is formed when a liquid film is 2.9 to 3.7 nm thick, as described above, it was supposed that a liquid bridge was formed at such humidity that the thickness $2 \times (\delta + r_1)$ of the liquid film reached 3.5 nm or more. From the radii $r_1$ and $r_2$ of the liquid film, a liquid bridging force $F_w$ was obtained by using the Laplace-Young's formula expressed as follows.

$$F_w = 2\pi r_2 \gamma + \pi r_2^2 \gamma \{(1/r_1) - (1/r_2)\} \quad (18)$$

The adhesive force $F_d$ between a particle and a surface is given as the sum of the liquid bridging force $F_w$ and the van der Waals force $F_v$ by the following formula.

$$F_d = F_w + F_v \quad (19)$$

The result of the calculation for the models using the adhesive force $F_d$ given by Eq. (19), respectively, is shown in Figure 13, using the molecular number $N_5$ of the impurity. Although the adhesive force continuously decreases as the humidity is increased to the level at which a liquid film is formed, similarly to Figure 9, it is discontinuously increased at a humidity at which a liquid film sufficiently thick to contribute to the liquid bridging force is formed. According to the result of the calculation using Model I for a constant gap $z$ (Figure 13-a), the difference in adhesive force before and after formation of a liquid film is less than that of Model II, in which the gap $z$ depends on the thickness of the adsorbed liquid film.

Similarly, the removal efficiency was calculated using the number of solute molecules divided by single particle volume $N_5$ of the impurities as a parameter, and assuming a distribution of the adhesive force, taking the adhesive force given by Eq. (19) as
mean value, and the result of the calculation is shown in Figure 14. In the calculation, \( \sigma_g \) was set to 0.2 that showed a sufficient consistency with the experimental result at a low humidity shown in Figure 11, and the removal force \( F_r \) was equal to that of Figure 11 (\( 1.1 \times 10^{-6} \) in Figure 14-a, and \( 8.7 \times 10^{-10} \) in b). The result of the calculation based on Eq. (18) is shown by a broken line in the figure. Although the removal efficiency increased with the humidity up to which a liquid film is formed, the removal efficiency dropped to almost 0 in the calculation, and was completely different from the experimental result. The humidity at which the efficiency is inconsistent with the experimental result is estimated by calculating the humidity at which the minimum liquid film \( = 3.5 \text{ nm} \) is formed. The reason why the calculated value of the removal efficiency is inconsistent with the experimental result may be because the fact that the surface tension \( \gamma \) of a liquid bridge is lower than the value \( \gamma_0 \) of water, when the liquid film is thin was not taken into consideration. From the experimental result using a porous glass, the variation of the surface tension with the thickness of the liquid film is approximated by the following formula\((5)\):

\[
\frac{\gamma}{\gamma_0} = 0.17 \times 10^6 (\delta + r_1) + 0.32
\]

\[
\gamma \geq \gamma_0 = 7.3 \times 10^2
\]

The removal efficiency was calculated by substitution of the above formula in Eq. (18), and the result of the calculation is shown by a solid line in Figure 14. Values calculated for a liquid bridging force \( F_w \) in such condition are shown in Figure 13. By assuming \( N_g = 0.0035 \text{ mol m}^{-3} \), the result of the calculation (Figure 14-a) for Model I, in which the gap \( z \) is constant, is substantially consistent with the tendency of variation of the removal efficiency at high humidity. On the other hand, the result of the calculation (Figure 14-b) for Model II that assuming that the gap \( z \) is dependent on the thickness of the adsorbed layer is inconsistent with the experimental result, even if the variation of the surface tension with the thickness of the liquid film is taken into consideration. As shown in Figure 13, it is because the adhesive force \( F_d = F_r \) at a humidity not higher than that at which a liquid film is formed is underestimated in comparison with the liquid bridging force after formation of the liquid film. Thus, it is determined as a result of comparison with the experimental result that Model I assuming a constant gap \( z \) is preferable. In the study, the distance between a particle and a surface is, therefore, considered as being constant at \( z = z_0 = 0.4 \text{ nm} \).

Consequently, it is clear that the increase of the removal efficiency at a low humidity is explained by the variation of the Hamaker's constant due to adsorbed water, as shown in Model I, reduction of the removal efficiency at a high humidity is caused by an increase of the adhesive force due to formation of a liquid bridge, and a variation of the efficiency can be substantially explained by assuming that the surface tension linearly varies with the thickness of the liquid film. Thus, the removal efficiency has a maximum value, because the van der Waals force decreases with an increase of water molecules adsorbed, and a surface tension lower than that of bulk water gradually increases to the same level after a liquid bridge is formed.

From the result of the calculation by varying \( N_g \) of the impurities, a liquid film is formed at lower humidity, and the maximum efficiency is achieved at higher

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**Fig. 14** Calculated removal efficiency considering about the liquid bridging force
humidity, when the quantity of impurities is lower. Accordingly, it is expected that a high removal efficiency as shown in Figure 11 can be achieved by reducing the quantity of impurities deposited on a wall surface, because no liquid film is formed up to a higher humidity, and the van der Waals force is reduced.

A variation of the removal efficiency with the drying time as shown in Figure 4 can also be explained quantitatively by considering that the effect of the variation of the van der Waals force caused by the quantity of water molecules adsorbed and that of the liquid bridging force described above are present during deposition of particles and drying as well. That is, when particles are deposited at high humidity, the liquid bridging force and van der Waals force are considered to be acting as adhesive forces. Because the liquid film is reduced, and the liquid bridging force is lower through the drying process, the adhesive force is reduced, and the removal efficiency is increased. It is considered that the adhesive force increases, and the removal efficiency decreases, as the drying time is increased, because the liquid film reduced to water molecules and disappears. In this process, the van der Waals force approaches the value in air from that in a liquid. When particles are deposited at a low humidity, the adhesion force increases, and the removal efficiency decreases through the drying process, because water molecules form no liquid film, and the van der Waals force is dominant.

Conclusions
We paid particular attention to the humidity at deposition of particles on a surface and that at removal, and studied the effects of humidity on the removal efficiency of particles by using a high-speed air jet. As a result, the following findings were obtained.

1) In the case when particles are deposited at low humidity, the removal efficiency decreases as the drying time is increased. In the case when particles are deposited at high humidity, the removal efficiency decreases once the maximum efficiency is reached after a certain drying time. After 80 hr of drying, no effect of humidity at deposition is observed.

2) Through experiments by varying the humidity at removal, it was found that the removal efficiency is low at low humidity, reaches its maximum value at a certain humidity (about 67% on a glass surface), and decreases at a humidity higher than that.

3) The variation of the removal efficiency at low humidity can be explained by considering the variation of the Hamaker's constant due to adsorption of water molecules. It is found that the variation of the efficiency at a high humidity can be also explained using a formula of the liquid bridging force, when the variation of the surface tension with the thickness of the liquid film is taken into consideration.

Appendices
Appendix A
A formula presented by Kousaka et al.\textsuperscript{11,12} for a liquid bridge between two spheres of identical size was employed for expressing the Kelvin effect, as shown below.

\[ \Psi_r = (1 - \gamma_s) \exp \left( -\frac{M_s \sigma}{RT \rho_w} ds \right) \]  (A-1)

\[ \gamma_s = \frac{3 \rho_w}{4 \pi N S_0^3} - \frac{M_s + iM_w}{\rho_s + \rho_w} \]  (A-2)

\[ 0 \leq \gamma \leq 1 \]

\[ \nu = 2 \pi \rho_0^3 R_1^3 \left[ 1 + H - A_s \left( (1 + R_1)^2 - \frac{1 + H}{2} \right)^2 \right. \]

\[ \left. - \frac{H^2 (H + 6)}{24 R_1^2} \right] \]  (A-3)

\[ \frac{ds}{d\nu} = \frac{2 r_0}{r_0^5} \times \frac{(2 R_1^2 + 3 R_1 - H/2 - H) A_s}{-R_s(3 R_1^2 + 5 R_1 - H/2 - 2 H) A_s} \]

\[ \times \frac{-\sqrt{(1 + R_1)^2 - 1 + H/2}}{\sqrt{(1 + R_1)^2 - 1 + H/2}} \]

\[ \times \frac{R_1(2 R_1 + 3)(1 + H/2)(1 + R_1)^2}{(2 R_1 + 3 R_1)(1 + H/2)(1 + R_1)} \]  (A-4)

\[ A_s = \sin^{-1} \left| \frac{1 + H/2}{1 + R_1} \right| \]  (A-5)

In Eq. (A-2), \( M_s/\rho_s = 0 \), assuming the impurities are at a low concentration. Although \( i \) varies according to the type and concentration of the solutes (impurities), it was taken as 2\textsuperscript{11} in this study. \( R_1 \) is a dimensionless radius of the liquid bridge derived from the following formula.

\[ R_1 = \frac{r_1}{r_0} \]  (A-6)
where $r_1$ is the radius of the condensed liquid bridge shown in Figure 12. By approximating the condensed liquid bridge by an arc in contact with a wall surface, the following formula is obtained for radii $r_1$ and $r_2$.

$$\frac{r_2}{r_0} = \sqrt{(1+r_1)^2 - \left(1+\frac{H}{2}\right)^2 - R_1} \quad \text{(A-7)}$$

From the formulae, the radius $r_1$ of the condensed liquid bridge and the radius $r_2$ of the liquid bridge formed at a humidity $\Psi_f$ at removal were calculated.

### Appendix B

The thickness of the liquid film at formation of a liquid bridge is defined, as shown in Figure 12, by the distance $t_i$ between points $P$ and $W$ formed by combining the thickness of the adsorption layer and that of the liquid bridge between the particle and the surface. Here, when the angle between the segment $CW$ and the central axis of the deposited particle is at $\theta_p$, the following formula is given.

$$t = t_i = \frac{t_1}{\cos \theta_p} \quad \text{(B-1)}$$

$$2 \times (\delta + r_1) = \frac{t_i}{\cos \theta_p} + AB \sin \theta_p$$

Here, the angle $\theta_p$ falls within the range expressed by the following formula.

$$\tan^{-1} \left( \frac{r_2}{D_p/2 + z} \right) \leq \theta_p \leq \tan^{-1} \left( \frac{r_2 + r_1}{D_p/2 + z} \right) \quad \text{(B-2)}$$

Because the particle size $D_p$ is 3.7 $\mu$m, and the radii $r_1$ and $r_2$ of the liquid bridge are 1.4 nm and 130 nm at the maximum humidity of 82% within the range of the experiment, from Eq. (B-2),

$$\tan^{-1}(0.035) = 2.01 [\text{deg}] \leq \theta_p \leq \tan^{-1}(0.036) = 2.03[\text{deg}]$$

(Note that $z = z_0 = 0.4$ nm is assumed.) By substituting this in Eq. (B-1),

$$2 \times (\delta + r_1) = \frac{t_i}{0.999} + 0.035AB$$

$$\theta_p = 2.01, 2.03 \quad [\text{deg}]$$

$$2 \times (\delta + r_1) \equiv t_i$$

Therefore, the thickness of the liquid film is approximated by $2 \times (\delta + r_1)$ within the range of the experiment.

On the other hand, the test particles (standard latex particles: Styrene/Divinylbenzene) are considered to be deformed in the vicinity of the contact point at deposition on a surface, because they are soft. From the theory of elasticity\(^{10}\), the radius $a_c$ of the contact area in the deformed part is given by the following formula.

$$a_c = 3 \sqrt{\frac{3}{4} F_d k_p D_e} \quad \text{(B-3)}$$

Here, by using values below, and assuming that the adhesive force $F_d$ between the particle and the surface is equal to $10^{-5}$[N] (Figure 13-a), a representative value within the range of the experiment, following formula is obtained;

$$D_e = D_p = 3.7 \quad [\mu m]$$

$$k_p = \frac{1 - \nu^2}{E_p} + \frac{1 - \nu_w^2}{E_w} = 2.6 \times 10^{-30}$$

$$a_c = 71 \quad [\text{nm}] \quad \text{(4)}$$

On the contrary, the radius of the liquid bridge within the range of the experiment is equal to 105 nm even when a liquid film having the minimum radius is formed ($\Psi_f = 65\%$, $N_5 = 0.0035$, Model I). It means that the radius $a_c$ in the deformed region is smaller than the radius $r_2$ of the liquid bridge within the range of the experiment, a model shown in Figure 12 is applicable to the formation of a liquid bridge, and the thickness of the liquid film can be approximated by $2 \times (\delta + r_1)$.

### Nomenclature

$A$ : Hamaker constant between particle and solid wall

$A_a$ : Hamaker constant of adsorbate

$A_I$ : Hamaker constant of interface with adsorbed layer

$A_I$ : Hamaker constant of water

$A_m$ : Hamaker constant of media

$A_p$ : Hamaker constant of particle

$A_w$ : Hamaker constant of solid wall

$D_p$ : particle diameter

$d$ : nozzle-surface distance

$d_1, d_2$ : diameter

$d_e$ : equivalent diameter
\( E_p \) : Young's modulus of particle [N\(\cdot\)m\(^{-2}\)]  
\( E_w \) : Young's modulus of solid wall [N\(\cdot\)m\(^{-2}\)]  
\( F \) : adhesive force between particle and solid wall [N]  
\( F_{ad} \) : average adhesive force [N]  
\( F_v \) : van der Waals force [N]  
\( F_w \) : liquid bridging force [N]  
\( f_{sd} \) : frequency of adhesive force [-]  
\( H \) : nondimensional gap (=\( z/r_0 \)) [-]  
\( K_a \) : coefficient in Eq. (8) [-]  
\( K_{ad0} \) : coefficient in Eq. (9) [-]  
\( K_h \) : coefficient in Eq. (2) [m]  
\( k_p \) : coefficient defined by Eq. (4) [m\(^2\)\(\cdot\)N\(^{-1}\)]  
\( k \) : coefficient in Eq. (1) [J\(\cdot\)mol\(^{-1}\)]  
\( M_s \) : molecular weight of solute [kg\(\cdot\)mol\(^{-1}\)]  
\( M_w \) : molecular weight of water [kg\(\cdot\)mol\(^{-1}\)]  
\( N_s \) : number of solute molecules divided by single particle volume [mol\(\cdot\)m\(^{-3}\)]  
\( \Delta P_n \) : air pressure at nozzle [Pa]  
\( q \) : exponent in Eq. (1) [-]  
\( R \) : gas constant [J\(\cdot\)K\(^{-1}\)\(\cdot\)mol\(^{-1}\)]  
\( R_1 \) : nondimensional radius of liquid bridge [-]  
\( r_0 \) : radius of equivalent diameter [m]  
\( r_i \) : radius of liquid bridge [m]  
\( s \) : surface area [m\(^2\)]  
\( s_b \) : surface area of liquid bridge [m\(^2\)]  
\( T \) : temperature [K]  
\( t \) : duration time of air jet [s]  
\( t_d \) : drying time [hr]  
\( v \) : adsorbed molecular volume [m\(^3\)]  
\( v_w \) : volume of liquid bridge [m\(^3\)]  
\( r_m \) : monolayer adsorption capacity [m\(^3\)]  
\( z \) : gap between particle and solid wall [m]  
\( z_0 \) : initial gap between particle and solid wall [m]  
\( \gamma \) : surface tension of liquid bridge [N\(\cdot\)m\(^{-1}\)]  
\( \gamma_0 \) : surface tension of water [N\(\cdot\)m\(^{-1}\)]  
\( \delta \) : thickness of adsorption layer [m]  
\( \eta \) : removal efficiency [-]  
\( \eta_{cal} \) : calculated removal efficiency [-]  
\( \theta \) : jet impinging angle [deg]  
\( \theta_p \) : angle defined in Fig. 12 [deg]  
\( \rho_p \) : Poisson's ratio of particle [-]  
\( \rho_w \) : density of liquid bridge [kg\(\cdot\)m\(^{-3}\)]  
\( \rho_w \) : density of water [kg\(\cdot\)m\(^{-3}\)]  
\( \sigma_g \) : geometric standard deviation [-]  
\( \psi \) : relative humidity [-]  
\( \psi_d \) : relative humidity at deposition [-]  
\( \psi_r \) : relative humidity at removal [-]  

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