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<th>Instructions for use</th>
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</thead>
<tbody>
<tr>
<td><strong>Title</strong></td>
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<td><strong>Author(s)</strong></td>
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to experimentally and numerically investigate water-droplet impacts with velocities of up to 50 m/s and their subsequent flow fields, especially the gas flow field in the strictly limited area in the vicinity of the contact line. First, we experimentally evaluated the velocity of the splash and numerically calculated the gas velocities. Comparison of these velocities supported our assumption that the maximum gas velocity may be on approximately the same order as the velocity of the splash. Therefore, we concluded that the gas velocity field of the order of 500 m/s indeed develops at the impact of droplet with a velocity of the order of 50 m/s. Moreover, we determined that the gas pressure was of the order of 1.0 MPa by numerical analysis. Such a high pressure leads to shock wave propagation, which can contribute to the cleaning process in semiconductor production.

We, in turn, were inspired by their results, realizing that the gas flow velocities that developed after the droplet impacts in their studies could reach considerably high values when the impact velocity was 50 m/s. Hence, it was evident that compressible fluid flow analysis was urgently required to study the gas flow developed after the droplet impact, since gas compressibility plays a dominant role in the development of gas flow fields with high velocities. We also recognized that the pressure of the gas flow could play an important role in cleaning techniques, since a substantial velocity may correlate with a substantial pressure, i.e., a shock wave. It should be recalled that in the laser shock cleaning (LSC) method there is a strong correlation between the removal of a particle and the dynamics of the laser-induced shock wave.

We investigate water-droplet impacts with velocities of up to 50 m/s and the subsequent velocity fields, especially focusing on experimental and numerical analysis of the gas velocity fields. We also investigate the pressure fields that developed after the droplet impact. First, the velocity of the splash, which was considered to be a gas-liquid, two-phase flow mist, was evaluated by processing images taken by high-speed photography at rates of up to one million frames per second; then, both the velocity and pressure fields of the gas flow that developed after the droplet impacts were numerically evaluated by solving the Euler equation for a two-phase compressible fluid by using the third-order TVD Runge–Kutta scheme, third-order ENO-LLF scheme, and hybrid particle level set method. Compressible flow analysis is critical in the investigation of high-speed gas flows. In this paper, we will also discuss whether the gas pressure fields that developed after droplet impacts could contribute to the cleaning process by examining the shock wave dynamics in the LSC method.

Experimental and Numerical Methods

Both experimental and numerical analyses were used to investigate water-droplet impacts with velocities of up to 50 m/s and the subsequent velocity fields, focusing on that of the gas, and ex-
amined whether gas flow could contribute to the cleaning process used in semiconductor manufacturing. We performed two types of experiments: free-fall droplet-impact experiments and investigations of droplet impacts on an accelerated solid plate. These two experiments are considered to be equivalent in a Galilean transformation regarding the droplet motion; however, no Galilean transformation of the gas flow field holds in these experiments. Hence, the influence of the gas flow on the development of the subsequent flow field after droplet impact was investigated by comparing these two experimental results.

We observed a single liquid water droplet freely falling onto a solid plate made of a transparent acrylic resin by using a high-speed video camera (Shimadzu Corporation, HyperVision HPV-1). A single liquid-water-droplet with diameters of approximately 2 mm, was generated on the end of a needle with inner and outer diameters of 0.1 mm and 0.25 mm, respectively. After a period of time, the droplet was pinched off from the nozzle due to gravity. The impact velocities of the droplets on the surface, which were controlled by varying the height of the needle above the solid surface from 100 mm to 600 mm, were measured from the pictures taken by the high-speed video camera. This camera can be used at frame rates between 100,000 fps and 525,000 fps. A strobe scope (SA-200F) by Nissin Electronic Co. Ltd. was used as the back light source.

We numerically solved the Euler equation\(^{18,19}\) for a two-phase compressible fluid in an axisymmetric two-dimensional coordinate system:

\[
\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial r} + \frac{\partial G}{\partial z} = S, \tag{1}
\]

where

\[
Q = \left( \begin{array}{c} \rho \\ \rho u_r \\ \rho \frac{u_r^2 + p}{E} \end{array} \right), \quad F = \left( \begin{array}{c} \rho u_r \\ \rho u_r u_z \\ \frac{u_r^2 + p}{E + p} u_r \end{array} \right), \quad G = \left( \begin{array}{c} \rho u_z \\ \rho u_r u_z \\ \frac{u_r^2 + p}{E + p} u_z \end{array} \right),
\]

\[
S = -\frac{1}{r} \left( \begin{array}{c} \rho u_r \\ \rho u_z \\ \rho u_r u_z \end{array} \right)
\]

\[
[2]
\]

where \(\rho\) is the density, \(p\) is the pressure, and \(u_r\) and \(u_z\) are the flow velocity components in the \(r\) and \(z\) directions, respectively. \(E\) is the total energy, which is expressed as

\[
E = \rho e + 0.5 \rho (u_r^2 + u_z^2),
\]

where \(e\) is the internal energy per unit mass.

In this study, we used air for the gas and water for the liquid. In order to close the Euler equations, we employed the following stiffened equation of state:\(^{22}\)

\[
p = (\gamma - 1) \rho e - \gamma \Pi,
\]

where \(\gamma\) and \(\Pi\) are constants (\(\gamma = 1.4\) and \(\Pi = 0\) Pa for air, and \(\gamma = 4.4\) and \(\Pi = 6 \times 10^5\) Pa for water). The third-order TVD Runge–Kutta scheme\(^{23}\) was employed to evolve the equations forward in time. Furthermore, the third-order ENO-LLF scheme\(^{20}\) was used to calculate the convection term.

The level set method\(^{21}\) was employed to locate the gas-liquid interface. The equation that governs the advance of the level set function, \(\phi\), can be expressed as

\[
\frac{\partial \phi}{\partial t} + u_r \frac{\partial \phi}{\partial r} + u_z \frac{\partial \phi}{\partial z} = 0. \tag{5}
\]

The level set function is usually the signed distance function with re-initialization to maintain accuracy. In the present study, Eq. 5 was numerically solved by the third-order TVD Runge–Kutta scheme and fifth-order WENO scheme.\(^{24}\) Additionally, the hybrid particle level set method\(^{25}\) was used to improve the mass conservation properties of the level set method.

The ghost fluid method\(^{26}\) was used to eliminate the dispersion and dissipation errors. This method defines ghost cells in the neighborhood of the interface in the calculation domain. Thus, two fluids were present in this analysis: the real fluid and the ghost fluid. It was sufficient to define the ghost fluid values only in the vicinity of the interface. The ghost fluid of the liquid was defined by using one-sided extrapolation of the entropy and velocities to the other side of

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**Figure 1.** Experimental setup for high-speed droplet impacts with velocity of \(O(10\) m/s). Bullet set at lower end of acrylic cylinder tube was accelerated by compressed air at pressures ranging from 0.05 MPa to 0.60 MPa in gauge.

**Figure 2.** Schematic of the (a) impact plate and (b) bullet. Circular impact plate made of transparent acrylic resin was adhered to T-shaped launch mount.
three measurements taken under the same experimental conditions. The impact plate velocities were found to be approximately in the range from 2 m/s to 50 m/s; hence, the impact plate velocity could be controlled by adjusting the compressed-air pressure from a relatively low velocity (such as the droplet free-fall velocity) to a relatively high velocity, so that the splash could be observed upon impact, as will be discussed later.

First, we discuss the low-velocity cases. The deformation of a single droplet impacting on the solid surface was observed as a function of time. Figure 5a shows the results for the free-fall of a single droplet with an impact droplet velocity, $U_D$, of 3.0 m/s, and Figure 5b shows the results obtained by impacting a plate on a single suspended droplet at a velocity, $U_{ip}$, of 3.0 m/s. An axisymmetric liquid film that flowed radially outward was observed (Figure 6). We could evaluate the radial velocity, $U_R$, of this liquid film by measuring the velocity of its rim, that is, the contact line velocity.

We compare $U_R$ of the contact line obtained from the free-fall and impact-plate experiments. Figure 7 shows the $U_R$ of the contact line in the left direction, measured at various nondimensionalized radial distances, $r_D/r_p$, where $r_p$ is the distance from the axis and $r_D$ is the droplet radius just before impact. The radial velocity of the contact line obtained from the free-fall experiments agrees well with that obtained from the impact-plate experiments. No significant differences are observed between the results obtained from the free-fall and impact-plate experiments in terms of the droplets’ deformation rates upon impact; therefore, we conclude that the influence of the gas flow on the development of the subsequent liquid flow field after droplet impact is insignificant in the low-velocity cases.

Next, we examine the high-velocity cases. Figures 8a and 8b show the droplet deformation on the impact plate when the plate impacted the droplet at higher velocities: $U_D = 22.0$ m/s and $U_D = 53.0$ m/s, respectively. The droplet shapes after the impacts at high velocities are significantly different from those at low velocities. Figure 9 shows a close-up of Figure 8b(2). The area indicated by arrow (a) is darker than

![Figure 3. Schematic of the computational domain. The center of a droplet with 1.00 mm radius was initially set 1.04 mm above rigid solid wall surface in calculation domain with dimensions of 4.00 mm × 4.00 mm.](image)

![Figure 4. Velocity of impact plate, $U_{ip}$, at compressed air pressures from 0.05 MPa to 0.60 MPa in gauge. Impact plate velocities are approximately between 2 m/s and 50 m/s.](image)

![Figure 5. Deformation of single droplet on solid surface immediately after impact: low-impact velocity cases. (a) Freely falling single droplet with impact droplet velocity, $U_D$, of 3.0 m/s with time step of $\Delta t = 100 \mu s$. (b) Impact plate impacting suspended single droplet with impact plate velocity, $U_{ip}$, of 3.0 m/s and time step of $\Delta t = 100 \mu s$.](image)

![Figure 6. Snapshot of axisymmetric liquid film flowing radially outward. Liquid film radial velocity, $U_R$, was calculated by measuring velocity of liquid film edge, i.e., velocity of contact line indicated by arrow.](image)
The surrounding areas, suggesting the existence of a liquid. However, this area is notably brighter than the areas that are known to be filled with liquid, thereby excluding the possibility of a single-phase pure liquid. We consider that the arrow (a) points to the tip of a splash that consists of numerous minute droplets. The $r$-direction velocity of the splash, $U_r$, was calculated by tracking the position of the tip in the sequential images.

Figure 10 shows $U_r$ measured with various values of $U_{ip}$. The uncertainties of $U_r$, which were mainly introduced in the determination of the tip location based on sequential images with an extremely high frame rate, are typically 4.8 m/s and 50 m/s for $O(U_r = 10 \text{ m/s})$ and $O(U_r = 100 \text{ m/s})$, respectively.

The splash/non-splash boundaries of droplet impacts on dry surfaces have been studied. They are most commonly described by the nondimensional numbers Re, We, and Oh, which are given by

$$\text{Re} = \frac{2 \rho r_D U}{\mu}, \quad \text{We} = \frac{2 \rho r_D U^2}{\sigma}, \quad \text{Oh} = \sqrt[3]{\frac{\text{We}}{\text{Re}}}$$

where $\rho$ is the liquid density, $r_D$ is the initial droplet radius, $U$ is the impact velocity, $\mu$ is the liquid viscosity, and $\sigma$ is the surface tension. Cossali et al. proposed that splash can be observed when the following condition is satisfied:

$$\text{Oh} \times \text{Re}^{1.25} > 119.23$$

For lower velocities ($U_{ip} < 2.4 \text{ m/s}$), $U_r$ was substituted into $U_r$. These velocities can be well correlated with the impact velocity as follows:

$$U_r = 1.40U_{ip}^{1.50}$$

where $U_r$ is approximately 500 m/s when $U_{ip} = 50$ m/s. Since a splash can be accelerated by a surrounding gas, the maximum gas velocity may be on approximately the same order as $U_r$. This result suggests that a gas flow field with a substantial velocity can develop following droplet impact. We then numerically analyzed the gas flow field.

Figure 11 shows the distributions of the magnitude of the $r$-direction gas velocity in the rectangular area in Figure 12 that were numerically calculated. The initial radius of the droplet, $r_D$, was 1.0 mm, and the initial position of the center of the droplet was 1.5 mm from the solid surface. Both the liquid and gas were initially at rest. At time $t = 0$, gas velocities of $\pm 50 \text{ m/s}$ were applied to both the gas and the liquid. The resulting $r$-direction gas velocity was of the order of 500 m/s at $t = 10.21 \mu s$ in the vicinity of $r = 0.18 r_D$.

Figure 13 shows both the $r$-direction velocity of the splash, $U_r$ (which is correlated with the experimental results via Eq. 6), and the maximum value, $U_r$, of the numerically calculated $r$-direction gas velocities. A comparison of the velocities, $U_r$ and $U_r$, supports our assumption that the maximum gas velocity may be on approximately the same order as $U_r$; hence, we can conclude that a gas velocity field of the order of 500 m/s indeed develops following a droplet impact at a velocity of the order of 50 m/s. The splash could not be observed in the numerical results because of the insufficient spatial resolution of the calculations. It is expected that splash observation would be possible even in the numerical results if the three-dimensional calculations were performed with sufficient spatial resolution.

In this investigation, we could experimentally measure the gas velocity by utilizing the splash. On the other hand, Visser et al., who performed their own experiments under conditions equivalent to those of the spray cleaning used for semiconductors, did not observe the splash. Visser et al. experimentally investigated the impacts of droplets with diameters of the order of 10 $\mu$s and velocities of up to 50 m/s upon a surface.

The splash/non-splash boundaries of droplet impacts on dry surfaces have been studied. They are most commonly described by the nondimensional numbers Re, We, and Oh, which are given by

$$\text{Re} = \frac{2 \rho r_D U}{\mu}, \quad \text{We} = \frac{2 \rho r_D U^2}{\sigma}, \quad \text{Oh} = \sqrt[3]{\frac{\text{We}}{\text{Re}}}$$

where $\rho$ is the liquid density, $r_D$ is the initial droplet radius, $U$ is the impact velocity, $\mu$ is the liquid viscosity, and $\sigma$ is the surface tension. Cossali et al. proposed that splash can be observed when the following condition is satisfied:

$$\text{Oh} \times \text{Re}^{1.25} > 119.23$$

Figure 7. Comparison of radial velocities, $U_r$, of contact line obtained from free-fall and impact-plate experiments at various nondimensionalized radial distances $r_D/r_D$, where $r_D$ is distance from axis and $r_D$ is droplet radius just before impact. Contact line radial velocity obtained from free-fall and impact-plate experiments agrees well.

Figure 8. Deformation of a single droplet on solid surface immediately after impact: high-impact velocity cases. (a) Impact plate impacting suspended single droplet with velocity, $U_{ip}$, of 22.0 m/s and time step of $\Delta t = 7.6 \mu s$ and (b) with impact plate velocity, $U_{ip}$, of 53.0 m/s and time step of $\Delta t = 1.9 \mu s$. A splash is observed.

Figure 9. Snapshot of splash development.
(i) $t = 9.76 \mu s$

(ii) $t = 10.21 \mu s$

(iii) $t = 10.27 \mu s$

(iv) $t = 10.53 \mu s$

Figure 11. Numerically calculated distributions of $r$-direction gas velocity magnitudes in area shown in Figure 12. $r$-direction gas velocity is of the order of 500 m/s at $t = 10.21 \mu s$ in the vicinity of $r = 0.18 r_D$.

Figure 12. Area (small rectangle) where velocity field is drawn in Figure 11.

Figure 13. Maximum value of numerically calculated $r$-direction gas velocities, $U_g$, compared with experimentally obtained $r$-direction velocity of the splash, $U_s$. $U_g$ is approximately equal to or greater than $U_s$.

The typical Oh $\times$ Re values of Visser et al. and the present study are 87.5 and $4.09 \times 10^3$, respectively. This result indicates that our study may not be equivalent to investigation of the spray cleaning used in semiconductor processes in terms of the liquid flow development after droplet impact; however, it should be emphasized that studies that utilize these three nondimensional numbers neglect the gas flow that develops after liquid droplet impact.

Not only liquid flow but also gas flow plays a significant role in the flow field development after liquid droplet impact, as revealed by Xu et al. They showed that splashing can be completely suppressed by decreasing the pressure of the surrounding gas. Therefore, we cannot determine the flow field development after liquid droplet impact by utilizing only these three nondimensional numbers, especially when the impact velocities are significant, as in this paper.

It is well known in the field of gas dynamics that another nondimensional number, Ma, which is defined as

$$Ma = \frac{U_i}{a_0},$$

where $a_0$ is the speed of sound in the gas, plays a significant role in gas flows. It can be easily shown that both the velocity and pressure fields of the gas strongly depend on Ma; hence, a gas flow of significant velocity can be observed even in the cleaning process used for semiconductor production, since $a_0$, which in general is assumed to be only a function of temperature, and $U_i$ in the present study are of approximately the same order as those used in the cleaning process. Thus, Re, We, and Oh can play only a secondary, not primary, role in high velocity gas flow development.

We observed the high-velocity gas flow field in the strictly limited area in the immediate vicinity of the contact line, as shown in Figure 11ii. An abrupt change in the velocity magnitude distribution in a compressible gas flow is, in general, accompanied by a substantial pressure; hence, we recognize that a considerable pressure can develop after the impact of a droplet at a high velocity. We now discuss the numerical analysis of this possibility. Figure 14 shows the pressure distributions corresponding to those of the $r$-direction gas velocity magnitude that are presented in Figure 11. The gas pressure is of the order of 1.2 MPa at $t = 10.21 \mu s$ in the vicinity of $r = 0.18 r_D$.

This considerable pressure leads to shock wave propagation. We propose that this pressure, together with its associated shock waves, can contribute to the cleaning process used in semiconductor production.
The LSC method is widely known as an effective means of eliminating particulates from solid surfaces. Lim et al. measured the cleaning performance of the LSC method by using micron-sized alumina particles attached to a silicon surface. They confirmed that the removal of particles in the LSC process strongly correlates with the dynamics of the laser-induced breakdown (LIB)-generated shock waves of the order of 1.0 MPa. They also showed that the cleaned area increases almost linearly with the intensity of the laser-generated shock. Furthermore, they clearly explained how the cleaning force acts on a particle first because of the net pressure difference when the shock passes over the particle and then because of the dynamic pressure associated with the high-speed gas flow behind the shock front.

We should recall that shock waves of the order of 1.2 MPa, which is about the same as the order of those measured by Liu et al., can develop in gases after droplet impacts at velocities of the order of 50 m/s. We should also recall that shock waves of the order of 1.2 MPa, which contribute to the cleaning process used in semiconductor production, are experimentally evaluated by processing images of the velocity of the splash, which was considered to be a gas–liquid two-phase flow, was experimentally evaluated by processing images taken by high-speed photography at rates of up to one million frames per second. The r-direction velocity of the splash, $U_r$, was approximately 50 m/s when the droplet impact velocity was $U_\text{impact} = 50$ m/s.

The splash could be accelerated by the surrounding gas; hence, the maximum gas velocity was on approximately the same order as $U_r$. These experimental results led us to conclude that a gas flow field with a high velocity can develop after droplet impact. The maximum value, $U_r$, of the r-directional gas velocity was numerically evaluated by solving the Euler equation for a two-phase compressible fluid. Comparison of the velocities, $U_r$ and $U_\text{impact}$, supported our conclusion that the maximum gas velocity may be on approximately the same order as $U_r$; hence, we conclude that a gas velocity field of the order of 500 m/s indeed developed after the impact of droplets with velocities of the order of 50 m/s.

We observed the high-speed gas flow field in the strictly limited area in the immediate vicinity of the contact line. An abrupt change in the velocity magnitude distribution of a compressible gas flow field is, in general, accompanied by a substantial pressure; hence, we recognized that considerable pressure could develop after a high-velocity droplet impact. This possibility was explored via numerical analysis, and the gas pressure was found to be of the order of 1.0 MPa. This substantial pressure led to shock wave propagation. Therefore, we propose that the shock wave propagation in the subsequent gas flow field can contribute to the cleaning process used in semiconductor production in a similar manner to that of the laser shock cleaning method.

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Conclusions

Both experimental and numerical analyses were used to investigate water-droplet impacts with velocities of up to 50 m/s and the subsequent flow fields, focusing particularly upon the gas flow field. First, the velocity of the splash, which was considered to be a gas–liquid two-phase mist flow, was experimentally evaluated by processing images taken by high-speed photography at rates of up to one million frames per second. The r-direction velocity of the splash, $U_r$, was approximately 50 m/s when the droplet impact velocity was $U_\text{impact} = 50$ m/s.

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