Dynamics of a single droplet with different viscosity impact onto a stainless-steel surface

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Abstract. The phenomena of droplet-surface interaction have important applications in many industrial fields. In different scenarios, the viscosity of the liquid droplet that impacts on the solid surface is usually different, and the viscosity of the droplet has a great impact on the results of the droplet impingement. In this paper, the phenomena of single droplets with different viscosity (deionized water, 50% glycerol/water solution, 99% glycerol/water solution) and different Weber number ($We$) in the range of 147.6-939.4 impacting on a flat stainless-steel plate were recorded by a high-speed camera at 4,000 fps, and the spreading behaviour of droplets with different properties were observed. The effect of droplet viscosity and Weber number on the droplet spread on the solid surface is quantitatively analysed, and the results demonstrate that the increase in Weber number has a promoting effect on the maximum spreading diameter, whereas the increase in viscosity has the opposite effect. For high viscosity drops (99% glycerol/water solution), retraction hardly occurs after the maximum spread diameter is reached. Finally, empirical correlations of the normalized maximum spread diameter as a function of the Weber number for droplet of different fluids were derived based on the present experimental data.

1. Introduction
The phenomena of droplet impacting on solid surface have wide applications in metallurgy, chemical engineering, and materials science, such as the spray of printer ink on paper, the collision of fuel droplets with the inner surface of an internal combustion engine, and the cooling of spray droplets impacting onto hot surfaces [1,2]. For industrial equipment with droplet-laden flows, the phenomena of droplet-surface interactions often occur. For example, in the steam separator of a nuclear power plant, the droplets collide with the separator inner surface as they move along with the steam, and as a result, secondary droplets [3] may be generated, thereby affecting the separation efficiency of the separator. Therefore, it is important to understand the mechanism of droplet impacting on a solid surface, so that the normal operation of many industrial equipment is able to be achieved.

The research of a single droplet impacting onto a solid surface has history of more than 100 years. Due to the complexity of the mechanism of droplet-surface collision, this phenomenon still attracts the interest of many researchers [1,2]. The earliest experimental studies on droplet-surface interaction
were performed by Worthington [4,5] using the method of direct observation with the naked eye, and the impacting process of water droplets and mercury droplets on a dry surface were observed and drawn. With the improvement in experimental techniques, high-speed camera technology has become the main method to study the phenomenon of droplet-surface collision [6]. Rioboo et al [7] systematically divided the results of single droplets impacting onto the dry surface into six types, which are deposition, prompt splash, corona splash, receding breakup, partial rebound and rebound. Compared to the surface tension, the influence of viscosity of the liquid is more complicated for droplet-surface collisions. According to Rioboo et al [7], an increase in the viscosity of the droplets inhibits droplets from splashing when they impact on a surface. However, according to the experimental study of Vander Wal et al [8], when single droplets of different viscosity impact on a dry surface, the increase in viscosity of the droplets promote splashing, but for a wet surface, it will inhibit splashing. The phenomenon of air bubble entrainment and splashing were observed by Julian et al [9], when drops of glycerol/water solution with high-viscosity impact on a dry glass surface.

Thus, in previous studies, although many researchers have studied the effect of droplet viscosity on the results of droplet-surface collisions, their main concern is the effect of droplet viscosity on promoting or suppressing splashing. However, there are few studies about the effect of droplet viscosity on the spreading behaviour of droplets impact on solid surface, and less experimental studies have been conducted either. The spreading behaviour of a droplet on a solid surface is an important process of transition from the dry surface to the wet surface. Because the result and mechanism of droplets impacting the wet surface is very different from that on the dry surface [10], it is necessary to study the spreading behaviour of viscous droplets on the dry surface.

In this study, outcomes during the impact of a single droplet of different viscosities with a flat stainless-steel plate are demonstrated through experimental observations using a high-speed camera at 4000 fps. The effects of droplet viscosity and Weber number on the droplet spreading diameter are analysed qualitatively and quantitatively.

2. Experimental setup
The experimental setup is shown in figure 1. The system includes a droplet generating system which consists of needles with sizes, pipes, and a peristaltic pump (Lab V1, SHENCHEN), an image acquisition system which consists of a high-speed camera (Phantom v711, 8G memory, 32-32000fps, macro lens 100 mm), an auxiliary light source, and a computer, besides a bracket is used to fix the stainless-steel plate.

![Figure 1. Schematic of experiment system.](image-url)
The experiments were conducted at room temperature of 25°C and under normal atmospheric pressure. The fluids used in the experiment are 99% glycerol-water solution (99% G-W), 50% glycerol-water solution (50% G-W) and deionized water (DI water). The properties of fluids are shown in Table 1.

| Fluid            | Density $\rho$ (kg/m$^3$) | Surface Tension $\sigma$ (N·m$^{-1}$) | Viscosity $\mu$ (Pa·s) |
|------------------|-----------------------------|----------------------------------------|------------------------|
| 99% Glycerol/Water | 1255                        | 0.063                                  | 0.776                  |
| 50% Glycerol/Water | 1131                        | 0.067                                  | $5.04\times10^{-3}$   |
| Deionized Water  | 997                         | 0.073                                  | $9.03\times10^{-4}$   |

Droplets are generated by different sizes of needles. One end of the pipe of the peristaltic pump is inserted into a container of the working fluid and the other end is connected to a needle. When the peristaltic pump is turned on and working at a small flow rate, the liquid in container is pumped up into the needle through the pipe, and a single droplet is generated when the gravity overcomes surface tension. The droplet diameter depends on the inner diameters of needles. The equivalent diameter $D_0$ is used to represent the real droplet diameter,

$$D_0 = \left(\frac{D_h^2 D_v}{3}\right)^{1/3}$$

where $D_h$ and $D_v$ are the horizontal and vertical diameter of the droplet before the impact, shown in figure 2. In this study, three different sizes of needles were used to produce droplets with three different diameters, 3.035± 0.137 mm, 3.600± 0.218 mm and 4.268± 0.229 mm, respectively. Weber number ($We = \rho D_0 U_0^2 / \sigma$, where $\rho$ is the density of the fluid, $U_0$ is the impacting speed of the droplet and $\sigma$ is the surface tension of the fluid) is a crucial non-dimensional parameter for droplet impingement, which indicates the relative magnitude of inertia force and capillary force of the droplet.

![Figure 2. Horizontal diameter $D_h$ and vertical diameter $D_v$ of a droplet.](image1.png)  
![Figure 3. Definition of spreading diameter $D_n$ and height of the liquid film $H_n$.](image2.png)

The solid surface used in the experiment is a dry flat stainless-steel surface. Before the experiment, the stainless-steel plate is polished with metallographic sandpaper so that the surface roughness $R_a$ is less than 1 μm. The static contact angle of the surface is 90.0°.

The processes of experiment were captured using the backlight photography method. The spreading diameter $D_n$ and the height of the liquid film $H_n$ of droplets (definition in figure 3) during the impact is measured by pixel analysing using the auxiliary software of the high-speed camera. The error of the measurement is 1 pixel which is equivalent to 0.057 mm, corresponding to a relative error of 1.96 % at most of the actual size. The initial droplet impact velocity is obtained by the displacement change within 1 ms before impacting onto the surface. By adjusting the needle height, the initial droplet impact velocity can be varied from 1.932 m/s to 3.479 m/s. The impacting process is extremely short, and the camera shoots horizontally as the droplet touches the solid surface.
3. Results

3.1. Descriptions of phenomena during the droplet impact

![Images of droplet impact at different times for DI Water, 50% G-W, and 99% G-W]

**Figure 4.** Phenomena of droplets with different viscosity impacting on a solid surface.

Figure 4 shows the temporal variation of the morphology of different viscosity droplets impacting on the stainless-steel surface when the impact velocity ($V_0=1.921\pm0.054$ m/s) and diameters ($D_0=3.098\pm0.184$ mm) of the droplets are the same. The moment when the droplet first touches the surface is set as $t=0$ ms. The deformation process of the three droplets with different viscosity (DI water, 50% G-W, 99% G-W) on the surface are recorded from 0 ms to 27.5 ms. For the case of DI water, when the droplet with a certain amount of kinetic energy touches the surface, the droplet deforms and spreads on the surface plane along the radial direction from the impingement point in the form of a thin liquid sheet. A fingering pattern is formed at the rim of the liquid sheet due to the Rayleigh–Taylor instability [11], during this spreading process. The kinetic energy of the liquid droplet converts into surface energy, and a part of the total energy is dissipated due to the viscous force. After the droplet reaches the maximum spreading diameter, in order to achieve a stable state with the lowest energy and under the effect of capillary force, the liquid sheet gradually retracts, and the height of the liquid film in the center of the impact point gradually increases.

For the case of 50% G-W, where the viscosity is higher than that of DI water, there emerges some differences during the deformation process of droplet on the solid surface. From 0 ms to 5 ms after the droplet impact, the droplet of the 50% G-W also shows the same spreading motion as the DI water droplet does, but the spreading speed is lower and the thickness of the film is larger than the DI water,
which is probably due to the increase in the fluid viscosity. When the droplet reaches its maximum spreading state, the maximum spreading diameter that the 50% G-W droplet can reach is also smaller than that of DI water. Although under the effect of capillary force, after the maximum spreading diameter is reached, the liquid film of the 50% G-W droplet also experiences a retracting process, but the degree and speed of retraction are lower than the previous condition.

For the case of the 99% G-W droplet with the highest viscosity, the morphological change of the droplet after collision with the surface is even more different. Under this condition, no thin liquid sheet is formed after the droplet impact. During the spreading process, the contact angle between the droplet and the surface is greater than 90 degrees. The contact line of the liquid with the solid surface is not at the outermost edge of the spreading direction, and the movement of the contact line in the spreading direction lags behind the liquid slightly above it vertically to the spreading plane. Contrary to the previous conditions, the air-liquid interface under this condition is convex toward the gas side, forming spherical cap-like droplets during the process of reaching the maximum spreading diameter. The process of spreading is more like the process of a soft sphere deforming on the surface. After reaching the maximum spreading diameter, the contact area of the droplet with the surface does not substantially change, but a small portion of liquid at the center of the droplet top sinks downward and then slowly recovers.

3.2. The effect of viscosity

By recording the spreading diameter $D_n$ and the height of the film $H_n$ on the surface after the droplet impact, and normalized by the droplet diameter $D_0$, the normalized spreading diameter $D_n^*$ and the normalized liquid film height $H_n^*$ can be obtained, i.e.,

$$D_n^* = \frac{D_n}{D_0}$$

$$H_n^* = \frac{H_n}{H_0}$$

At the same time, the time during the droplet deformation can be normalized by the characteristic time of the droplet ($t_0 = D_0/V_0$, $V_0$ is the impact velocity of the droplet),

$$T = t/t_0$$

Afterwards, the change in normalized spreading diameters $D_n^*$ and normalized film height $H_n^*$ of the three types of droplets as a function of normalized time $T$ during the impact can be acquired.

Figure 5 demonstrates the variation of dimensionless spreading diameter $D_n^*$ over normalized time $T$, and $T=0$ represents the moment when the droplet first contacts with the surface. It can be seen from figure 5 that for the less viscous droplet, the normalized time $T$ to reach the maximum normalized spread diameter $D_n^{*\text{max}}$ after impact on the surface is slightly longer than the more viscous droplet ($T_{\text{Dmax, DI water}}=2.547> T_{\text{Dmax, 50% G-W}}=1.911> T_{\text{Dmax, 99% G-W}}=0.955$), which is also in line with the results of direct observation. After reaching the $D_n^{*\text{max}}$, both the DI water and the 50% G-W droplet retract, and the DI water droplet retracts faster than the latter. At the moment when two droplets both reach $D_n^{*\text{max}}$, $D_n^{*\text{max, DI water}} > D_n^{*\text{max, 50% G-W}}$. However, when $T>19$, $D_n^{*\text{DI water}}$ gets smaller than $D_n^{*\text{50% G-W}}$. For 99% G-W droplet, the $D_n^*$ does not change after reaching the $D_n^{*\text{max}}$ due to the strong viscous force in a finite time after the droplet impact on the surface.

Figure 5 illustrates the change of dimensionless film height $H_n^*$ over normalized time $T$, and $T=0$ also represents the moment when the droplet first touches the surface. From figure 6, in the direction perpendicular to the surface, the minimum normalized height ($H_n^{*\text{min}}$) of the film formed by droplet with lower viscosity is smaller ($H_n^{*\text{min, DI water}}=0.037<H_n^{*\text{min, 50% G-W}}=0.080<H_n^{*\text{min, 99% G-W}}=0.296$), and it is obvious that $H_n^*$ of three kinds of droplet are all rapidly decreasing. The $H_n^*$ of the DI water droplet rises slightly later than that of 50% G-W, and $H_n^*$ of DI water is also slightly less than that of 50% G-W, but the difference between two cases is not large. After $H_n^*$ reaches the lowest value, both of them begin to recover. In the period of $0<T<11.8$, $H_n^*$ of DI water is slowly recovering. After that, the recovery speed of $H_n^*$ of DI water increases, then $H_n^*$ gradually decreases after reaching
$H_n^* = 0.317$. For a droplet of 50% G-W, the value of $H_n^*$ is basically in a slowly rising state after reaching the minimum $H_n^*$.

![Figure 5](image-url)  
**Figure 5.** Effect of viscosity on dimensionless spreading diameter $D_n^*$.

![Figure 6](image-url)  
**Figure 6.** Effect of viscosity on dimensionless film height $H_n^*$.

Figure 7 shows the variation of the spreading speed $\tau$ with the normalized time $T$ from the moment $T = 0$ to $T = 5$ under three viscosity conditions. It is clear that under the three conditions, the spreading speed of droplets shows a decreasing trend with $T$. The smaller the viscosity of the droplet, the greater the initial spreading speed and the greater the rate of speed decrement. At any moment before $D_n^*_{\text{max}}$ is reached, the spreading speed of the less viscous droplets is always faster.
3.3. The effect of Weber number

Figure 7. Effect of viscosity on spreading speed.
Based on the results of experiment, it is evident that increasing the Weber number will increase the spread diameter of liquid droplets, and under the same Weber number condition, increasing the liquid viscosity...
will decrease the $D_n^{*\text{max}}$. Therefore, we change the Weber number of the droplets by adjusting the droplet diameter and droplet velocity so as to quantitatively calculate the relationship between the droplet Weber number and $D_n^{*\text{max}}$ after impact. Empirical correlation of $D_n^{*\text{max}}$ as a function of Weber number ranged in 147.6-939.4 under different viscosity can be acquired in a form of power function based on the experiment data, as can be seen in figure 9.

$$D_n^{*\text{max}}, \text{DI water} = 0.6685 We^{0.1553}$$  \hspace{1cm} (5)

$$D_n^{*\text{max}}, 50\% \text{ G-W} = 1.4168 We^{0.1473}$$\hspace{1cm} (6)

$$D_n^{*\text{max}}, 99\% \text{ G-W} = 1.2351 We^{0.2244}$$\hspace{1cm} (7)

And the goodness of fit $R^2$ equal to 0.942, 0.817 and 0.846, respectively.

![Figure 9](image-url)

Figure 9. Relationship between Weber number and maximum normalized spreading diameter $D_n^{*\text{max}}$.

4. Conclusion

In this study, the phenomena of a single droplet with different viscosity and Weber number impacting onto a dry flat stainless-steel surface were observed using a high-speed camera at 4000 fps, and the dynamic behaviors of the droplet after collision onto the surface were qualitatively described. The relation between normalized spreading diameters $D_n^*$ of droplets with different Weber numbers and normalized time $T$ are quantitatively studied. The effects of droplet viscosity and Weber number on droplet deformation are discussed in detail. Based on the experimental results, empirical formulas for the normalized maximum spreading diameter $D_n^{*\text{max}}$ and Weber number of droplets under different viscosities are given. The main conclusions are as follows.

- For a single droplet impacting on a dry solid surface, the viscosity of the droplets has a great influence on the spreading characteristics of the droplet. As the viscosity of the droplet increases, $D_n^{*\text{max}}$ that the droplet can reach decreases, the degree of subsequent retraction also declines, and the droplet spreading speed decreases too.

- At different viscosity, $D_n^{*\text{max}}$ of the droplets increases with the increase in Weber number. However, as for the droplets with high viscosity (99% G-W), although $D_n^{*\text{max}}$ of droplets
increases, the retracting phenomenon of the liquid film hardly occurs.

- Based on experiment data, empirical correlations for $D_{\text{n} \text{ max}}$ as a function of Weber number in the range of 147.6-939.4 for DI water, 50% G-W and 99% G-W are obtained, which are $D_{\text{n} \text{ max}}, \text{DI water} = 0.6685 We^{0.1553}$, $D_{\text{n} \text{ max}}, 50\% \text{ G-W} = 1.4168 We^{0.1473}$ and $D_{\text{n} \text{ max}}, 99\% \text{ G-W} = 1.2351 We^{0.2244}$. The goodness of fit $R^2$ is 0.942, 0.817, and 0.846 respectively.

However, in actual industrial applications, it is often the case that not a single droplet impacts on the surface, but multiple droplets continuously impinge on the surface. Under the successive impact of the droplets, a liquid film will gradually form on the surface, and the mechanism of the droplet-film interaction is much different from that of droplet-surface interaction. Therefore, in the future research, we plan to further improve the experimental system to conduct experiments including successive droplets impacting on solid surface and liquid film to further investigate the underlying physical mechanism.

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