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Impact of a compound drop on a dry surface

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Abstract

The impact of a water-in-oil compound drop on a dry quartz surface was studied. The impact outcomes depended on a core-to-overall mass ratio and a Weber number. For a Weber number less than 570 and a core-to-overall mass ratio ranging from 0.07 to 0.7, five collision patterns were observed: complete deposition, shell deposition with core partial rebound, shell splash with core-shell deposition, shell splash with core partial rebound, and shell splash with core-shell partial rebound. Past research has indicated that the splash phenomenon depends strongly on liquid properties such as surface tension and viscosity in addition to the properties of the solid surface and the surrounding gas. The liquid properties in a compound drop were made non-uniform by the presence of additional interfaces in the interior of the liquid drop.

Keywords: Compound drop; Impact; Dry surface; Weber number

1. Introduction

The splash or non-splash of a liquid drop hitting a dry solid surface is crucial to many industrial processes such as spray painting, spray cooling, and ink-jet printing. Numerous researchers [1-3, 5] have attempted to determine the physical parameters governing the so-called "splash threshold," i.e. the parameters governing the transition from deposition to splash.

An inspiring discovery was presented in Xu et al. [7], in which compressible effects in the surrounding gas were found to be responsible for splashing in liquid drops impacting a dry flat surface. They found that the surrounding gas provides a means for creating the corona with a vertical component of momentum and splashing can be completely suppressed by decreasing the pressure of the surrounding gas. Their findings provide a technique to control splashing precisely in industrial processes where splashing is involved.

The study of Vander Wal et al. [6] covered wide ranges of the three relevant dimensionless parameters, namely the Weber, Reynolds, and Ohnesorge numbers with twelve liquids of different values of surface tension and viscosity. The impacted surface was a smooth aluminum surface with or without a thin liquid film. Their goal of obtaining a practical empirical correlation for the splash limit was achieved; however, surface roughness was not included.

Using high resolution microscopic photography, Sikalo and Ganic [4] have shown many unnoticed features of the splash phenomenon. When a drop impacts a rough surface, the expanding lamella tends to lift off the surface; whereas on a smooth surface the expanding lamella tends to remain attached. However, the effect of surface roughness on deposition/splash limit for an isopropanol droplet was not observed. Furthermore, no splash was observed for a water

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droplet on a smooth surface for Weber number up to 1080.

In the numerous past researches on the impact of liquid drops on solid surface, most were devoted to pure liquid drops or blended drops with miscible liquids, a few were on emulsified drops. The studied liquid properties, namely density and viscosity, were basically uniform in the interior of the drop. And there was only one interface on the outmost surface of the drop. The drop was always viewed as a mass of uniform properties moving with consistency. However, for practical applications, many liquid drops may contain more than one interface and thus may have different fluid properties in the interior, e.g., a so-called compound drop.

A compound drop is a liquid drop containing more than one phase. The simplest form of a compound drop is a spherical core drop encapsulated in a spherical shell drop; more complicated constructions of a compound drop can be those containing more than one core drop, more than two phases, many layers, and so on. Compound drops are present in various processes associated with blending, atomization, or boiling of a number of immiscible liquids in the fields of pesticide spraying, fire protection, spray combustion, spray cooling, etc. In many of the above-mentioned industrial processes, the impact of liquid drops on a solid surface is frequently encountered.

Past research has indicated that the splash phenomenon depends strongly on liquid properties such as surface tension and viscosity in addition to the properties of the solid surface and the surrounding gas. The liquid properties in a compound drop were made non-uniform by the presence of additional interfaces in the interior of the liquid drop. This experimental study was set up to determine whether the splash threshold is influenced by the non-uniformity of liquid properties and the additional interface, and in the meantime, to reveal any possible new phenomena due to the presence of a core drop.

2. Experimental apparatus

Our experimental setup is sketched in Fig. 1. A diesel-shell water-core compound drop dispenser was fabricated by inserting a 0.17mm-OD water-carrying stainless needle into a 0.65mm-ID diesel-carrying glass nozzle. By controlling the flows of water and diesel, a compound drop of given water-to-diesel mass ratio could be dripped out periodically from the dispenser. Table 1 lists the properties of diesel oil and water.

A compound drop just coming out of the dispenser is shown in Fig. 2. The compound drop was then accelerated by gravity and impacted the flat quartz plate at a controlled downward distance, H. It should be noted that due to air drag, the shell would be decelerated and the core drop would be squeezed against the bottom inner surface of the shell, as shown in Fig. 3, before it hit the quartz surface. For the identification of the movement of the core drop, the core water drop was dyed red. The evolution of the drop impact was recorded by a B/W high-speed video camera at 2000 frames per second and a color video camera at 30 frames per second with stroboscopic lighting.

The outer diameter, d_o, of the compound drop was measured from the picture while the diameter of the core drop, d_w, was measured by dropping the compound drop in a transparent diesel bath, as shown in Fig. 4. The mass ratio γ can then be expressed by

$$\gamma = \frac{\rho_w d_w^3}{\rho_o (d_o^3 - d_w^3) + \rho_w d_w^3} . \quad (1)$$

Table 1. Physical properties of diesel oil and water

Liquid (25℃)	Density (kg/m³)	Viscosity (cp)	Surface tension coefficient (N/m)
Diesel oil	817	0.02825	3.16
Water	998	0.072	1.005

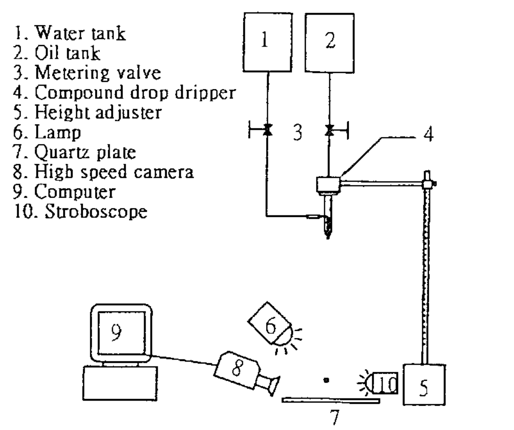


Fig. 1. Experimental setup.

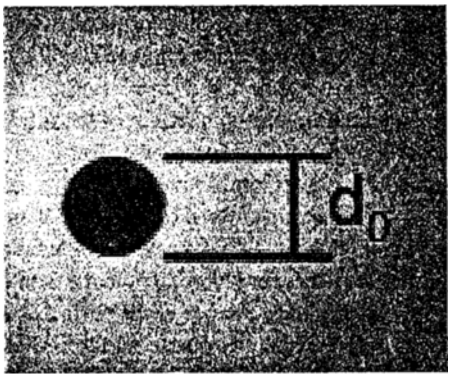


Fig. 2. A compound drop just leaving the dispenser tip (better shows core in exact center).

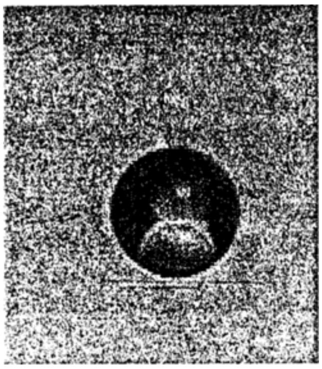


Fig. 3. A compound drop after flying for a distance.

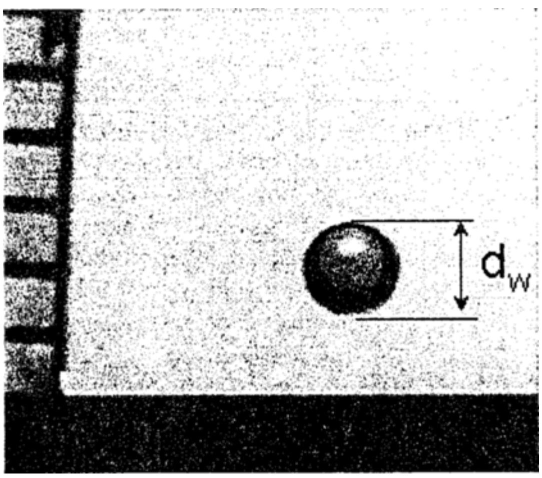


Fig. 4. Core drop size measurement in a diesel oil tank.

The velocity of the compound drop right before hitting the surface was computed by the formula, $V=\sqrt{2gH}$, which was found to be accurate with less than 3% error when checked against high-speed stroboscopic video.

Table 2. Range of related parameters

d_w (mm)	0~2.7
d_o (mm)	2.5~3.2
V (m/s)	0.7~3.0
We	50~570
γ	0~0.7

The collision kinetic energy was calculated by $\frac{\pi}{12}\left[\rho_o(d_o^3-d_w^3)+\rho_w d_w^3\right]V^2$, which takes into account the total mass of the compound drop. And for the correlation of our experimental data, in consideration of easier comparison with pure diesel oil drops impact, we have adopted the surface tension coefficient of the outer surface, i. e., diesel oil. Our Weber number was then defined as the impact kinetic energy divided by the outer surface energy of the compound drop:

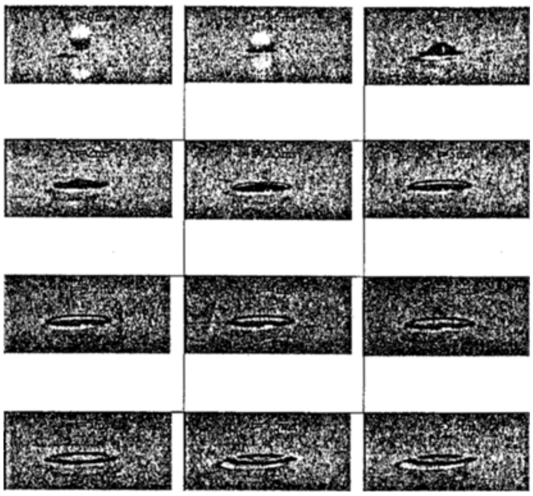
$$We=\frac{\left[\rho_o(d_o^3-d_w^3)+\rho_w d_w^3\right]V^2}{\sigma_o d_o^2} \tag{2}$$

The range of related parameters in this study is shown in Table 2.

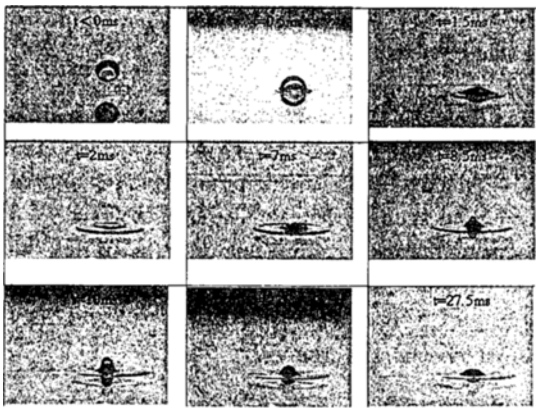
3. Results and discussion

For our compound drop experiments, we first examined if there were any effects on splash from the presence of the core drop. For $\gamma=0$, i. e. a pure diesel oil drop containing no water core, the measured critical Weber number for splash was 250. As we gradually increased the size of the core drop, i. e. γ was increased, the critical Weber number stayed close to 250. If we take experimental errors into consideration we can roughly conclude that the threshold Weber number for splash occurrence is not affected by the presence of a core drop no matter how big the core drop is. The fact that the core drop was at the bottom of the compound drop, and thus the bottom of the compound drop had only a thin layer of diesel oil, strengthens this conclusion. It also infers that the ring of small drops ejected at splash, all of them pure diesel drops, comes not from around the south pole (referring to the bottom contact point of the compound drop, see Fig. 3) but from around the equator of the compound drop.

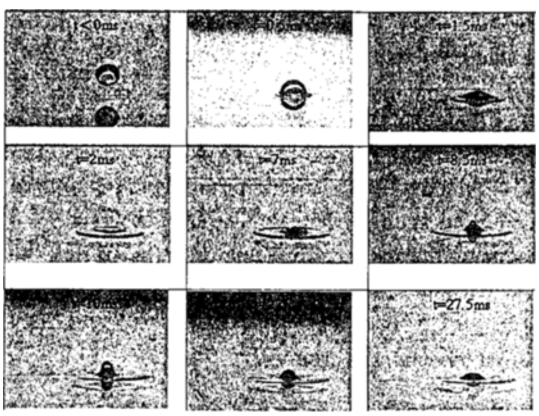
Although the splash thresholds for the water-in-diesel compound drop and the pure diesel drop were



(a)



(b)



(C)

Fig. 5. Deposition for
(a) $(d_o, d_w, V, \gamma, We)$ =(3, 0, 1.32, 0, 150), (b) (2.97, 1.62, 1.06, 0.2,100), (c) (3.07, 2.66, 0.83, 0.7, 70).

not very different, the phenomena associated with the impact of a compound drop did have a great deal of difference from those associated with a pure drop. Five outcomes were observed for a water-in-diesel compound drop impinging on a dry smooth surface. The definitions for these five types of outcomes are illustrated in Figs. 5-9.

In Fig. 5(a-c), depositions under three different conditions are shown. In Fig. 5(a) a pure diesel hit the surface with a $We = 150$ and the drop flattened, spread to a maximum diameter, slightly retracted, and finally deposited on the surface with no further movement, which indicated a near-zero contact angle. This behavior is the typical behavior for a drop hitting a surface of high wettability. In Fig. 5(b), a compound drop $We = 100$ and $\gamma = 0.2$ hit the surface. The outer diesel shell flattened and spread (add some special features) and the inner core water drop, due to its high surface tension and the diesel layer to shield it from the surface, did not deform much and sat right above the diesel oil layer. In Fig. 5(c), a compound drop $We = 70$ and $\gamma = 0.7$ hit the surface. This time the inner core water drop was big enough to deform noticeably into a ring and finally retracted into a flattened drop.

Core partial rebound is shown in Fig. 6. Notice that the core partial rebound regime is below the splash threshold ($We < 250$), which means that the outer shell still only deposits with no splash, while the core water drop would retract and break up into two drops. Of course, the produced secondary drops are all compound drops with a water core and a thin diesel shell.

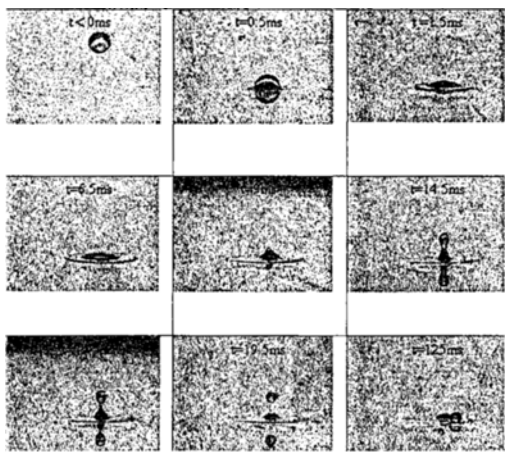


Fig. 6. Core partial rebound,
$(d_o, d_w, V, \gamma, We)$ =(2.94, 1.97, 1.4, 0.34, 178).

The phenomenon of splash/deposition is displayed in Fig. 7. We found that this phenomenon only happens for pure diesel drops or a compound drop with a very small core (gamma < 0.1). Fig. 7 displays a compound drop splash/deposition for gamma=0.07 and We=290. We can see that the Weber number was high enough for splash to happen but not enough for the core to exhibit any appreciable deformation.

Fig. 8 shows the splash/core partial rebound case. For all gammas except those smaller than 0.1, as the Weber number is raised, the impact result will go through deposition, core partial rebound, and then splash/core partial rebound.

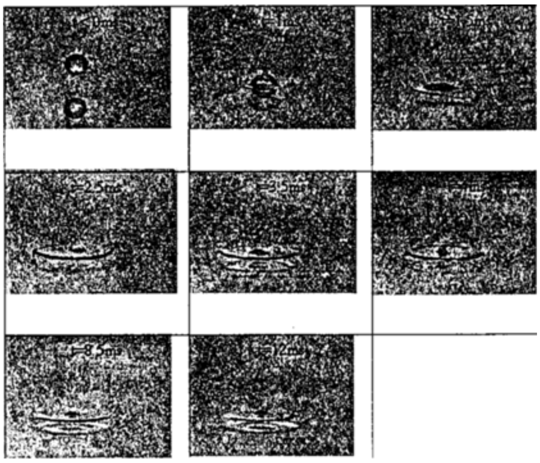


Fig. 7. Splash/deposition, $(d_o, d_w, V, \gamma, We)$ =(2.48, 0.96, 2, 0.07, 290).

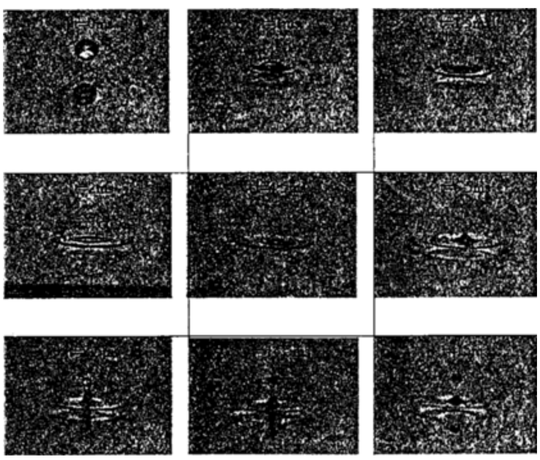


Fig. 8. Splash/core partial rebound, $(d_o, d_w, V, \gamma, We)$ =(2.73, 1.57, 2, 0.22, 330).

Splash/core-shell partial rebound is shown in Fig. 9. Splash occurred during the very early stage of spreading. Unlike the outer diesel shell which deposited on the surface after reaching the maximum spreading diameter, the inner liquids including diesel and water contracted inward and ejected upward like a liquid jet in the center regime of the disk-like drop. The jet was a water-in-diesel compound jet, i.e., a water jet which was encased by a diesel shell. The tip of the liquid jet broke into tiny drops due to Rayleigh's instability. The difference between core partial rebound and core-shell partial rebound is that the secondary drops produced for the former case were compound drops, whereas those produced for the latter case were a combination of shell-liquid drops and compound drops.

Based on the experimental data, the regime map indicating boundaries of each pattern mentioned above is given. As shown in Fig. 10, several points should be noted. First, for pure diesel drops, $\gamma = 0$, and for compound drops, splash was observed at $We \approx 250$, which means splash was only induced by the shell liquid. Second, for $We < 250$, a diesel drop ($\gamma = 0$) and a compound drop with small core drop ($\gamma < 0.10$) simply spread on the plate; however, for a compound drop with large core drop ($\gamma > 0.10$), the core would rebound. Third, in the range of $0.1 < \gamma < 0.5$ and $We > 350$, splash/core and shell partial rebound was observed.

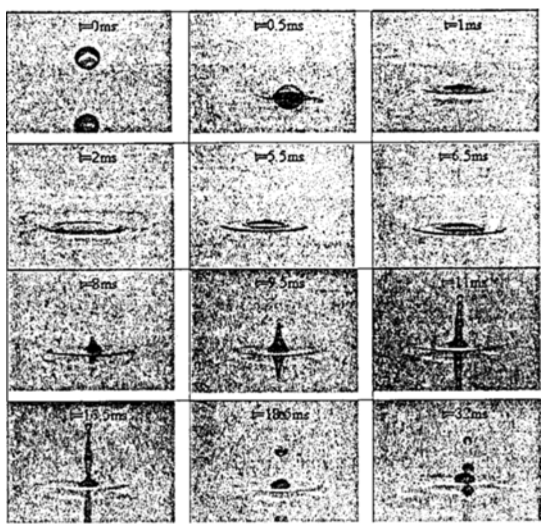


Fig. 9. Splash/core-shell partial rebound, $(d_o, d_w, V, \gamma, We)$ =(2.94, 1.97, 2.28, 0.34, 472).

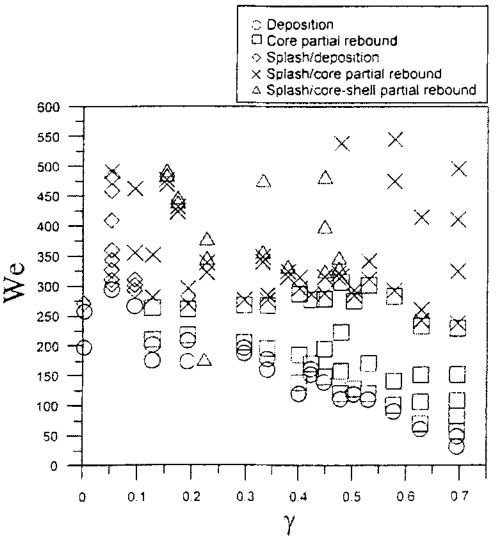


Fig. 10. Regime map of impact patterns.

4. Conclusions

The impact of a water-in-diesel compound drop on a dry quartz surface was investigated experimentally. The water-in-diesel compound drop was generated by a drop dispenser which was fabricated by inserting a 0.17mm-OD water-carrying stainless needle into a 0.65mm-ID diesel-carrying glass nozzle. The evolution of the drop impact was recorded by a B/W high-speed and a color video camera with stroboscopic lighting.

Based on the experimental results, two brief conclusions are given as follows:

The threshold Weber number for splash occurrence seems not affected by the presence of a core drop no matter how big the core drop is. The critical Weber number is about 250.

The phenomena associated with the impact of a compound drop did have a great deal of difference from those associated with a pure drop. For a Weber number less than 570 and a core-to-overall mass ration ranging from 0.07 to 0.7, five collision patterns which were very different from those of an impacting pure drop were observed.

Acknowledgments

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Nomenclature

d_w : Outer diameter of a core drop, mm
d_o : Outer diameter of a compound drop, mm
g : Gravity, m/s^2
H : Distance from nozzle to test surface, m
ID : Inside diameter, mm
OD : Outer diameter, mm
V : Drop velocity, m/s
We : Weber number

Greek symbols

γ : Mass ratio
ρ_o : The density of the shell liquid of a compound drop
ρ_w : The density of the core liquid of a compound drop
σ_o : The surface tension of the outer surface of a compound drop to gas

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