

Diesel–diesel and diesel–ethanol drop collisions

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Abstract

In view of the possible occurrence of unlike drop collisions in a diesel spray due to the increasing application of alcoholic fuels as supplementary fuels in diesel engines, collisions of a diesel drop with either a diesel drop or an ethanol drop were studied. Diesel drop collision results do not display appreciable difference, within experimental errors, from those of tetradecane drops except for very small Weber numbers. The collision of an ethanol drop with a diesel drop, when compared to binary diesel drop collisions, exhibits higher tendency towards reflex separation for near head-on collisions and lower tendency towards stretching separation for medium to high impact parameter collisions. These distinctions come from the spreading of ethanol over the diesel drop due to their difference in surface tension.

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1. Introduction

Drop–drop collisions have considerable influence on the characteristics of a diesel spray as the spray comes out of the nozzle and evolves downstream. Spray combustion researchers have been paying attention to the outcomes of binary collisions of liquid drops, e.g., water, hydrocarbons, etc., for the purpose of understanding the collision physics [1–5] or utilizing the measured data in numerical modeling of fuel sprays [6].

Most of the past experiments on drop collisions have been conducted with pure liquids and the collision results are expected to be valid for liquid drops with the same dimensionless parameters. The experimentally observed outcomes for hydrocarbon fuel drop collisions are bouncing, coalescence, reflex separation, and stretching separation. Compared to water drop collisions, the bouncing regime is the most distinct feature for hydrocarbon drop collisions. Direct experiments on diesel oil drops has never been attempted due to its mixture nature; i.e., the proper-

ties are not fixed numbers; however, the collision results are assumed to be similar to those of tetradecane [3]. Up to now the closest data for diesel spray modeling are tetradecane data, but the similarity is yet to be proven.

Recently, the experimental study of the collision of unlike drops have emerged in view of the possibility of those events in the research fields of fire protection, aerosol mixing, blended fuels, emulsified fuels, and twin-spray, etc. Collisions of unlike miscible drops with large surface tension difference, namely, ethanol drops and water drops, were discussed in Gao et al. [7]. In addition to the conventional stretching separation, coalescence, and reflex separation phenomena, new phenomena, such as the splitting of the water drop and the generation of small satellites during the very early stage of the impact, have been discovered. And these new phenomena were attributed to the so-called USF (unbalanced surface force) action defined in that paper.

The utilization of multi-fuels or blended fuels in diesel engines aims at conditioning diesel fuels for better emissions or replacing fossil fuels with bio-recyclable fuels for conservation. Many engine performance tests have been conducted using bio-fuels such as ethanol as a supplementary fuel [8–10]. Various techniques have been developed to

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Nomenclature

b	distance between the centers of the drops before the collision (μm)	γ	the angle between the velocity V_{DE} and the velocity V_D
d	drop diameter (μm)	μ	dynamic viscosity (Ns/m^2)
V_D	the velocity of the diesel oil drop (m/s)	ρ	density (kg/m^3)
V_{DE}	the relative velocity of the two drops (m/s)	σ	surface tension (N/m)
V_E	the velocity of the ethanol drop (m/s)		
We	the Weber number		
X	the impact parameter		
<i>Greek symbols</i>			
α	the angle between the velocity V_E and the velocity V_D		
β	the angle between the center-to-center line and the velocity V_D		
<i>Subscripts</i>			
	D	diesel oil	
	E	ethanol	

introduce ethanol into a compression ignition engine [11]. Available techniques are blending, fumigation, and dual injection. Dual injection has the advantage of high displacement rate of 90% or more, compared to 30% for blending and 50% for fumigation, although the drawbacks of this method include the complexity and expense of a second injection system and the limited space in the combustion chamber for a second injector.

The dual-injector operation can not be applied to a diesel engine easily, at least for now, due to its mechanical difficulties. But this mode of operation does offer some very appealing features: (1) the mass ratio of ethanol to diesel can be very high – not achievable in the blends of diesel and ethanol. (2) No surfactant is needed. (3) For a specific engine torque and rpm, a specific concentration of ethanol can be introduced and this is the best way for controlling the power and emissions. In contrast, for a blended fuel, the ethanol concentration is fixed.

The possibility of unlike-drop collisions in diesel engines increases as more diversified fuels are utilized. Unlike drop collisions are most probable in dual-spray operation, although due to emulsion separation in hot surroundings or incomplete evaporation, there are also chances of unlike-drop collision in blended or fumigation operation in diesel engines.

The aim of this study was first to check if diesel drop collisions results are in fact similar to those of tetradecane drops and then to find out the collision outcomes of ethanol–diesel drop collisions, emphasizing on the differences from those of diesel–diesel drop collisions. In this study, only equal-sized drop collisions were investigated. Although in practice, the collision of unequal-sized drops is certainly much more probable than the collision of equal-sized drops. The phenomena of equal-sized drop collisions serve as a basis for the understanding of the more general unequal-sized drop collisions. Our diesel–diesel and diesel–ethanol drop collision experiments have produced some informative results. The immiscibility and

difference in surface tension indeed change the collision behavior to some extent and the data are expected to be useful for numerical diesel spray modeling.

2. Experimental apparatus

Our experimental setup is shown schematically in Fig. 1. Two piezoelectric drop generators were used to generate two droplets streams of equal size in the range of 700–800 μm with their velocities in the range of 1 m/s–2 m/s. Ethanol and diesel oil were provided through separate pressurized containers. Only one function generator was used to drive these two drop generators and the two streams of drops collided pair by pair in front of a stroboscope. The frequency of the stroboscope was synchronized with the drop-generating frequency so that the collision outcome may be recorded by the video camera as slow

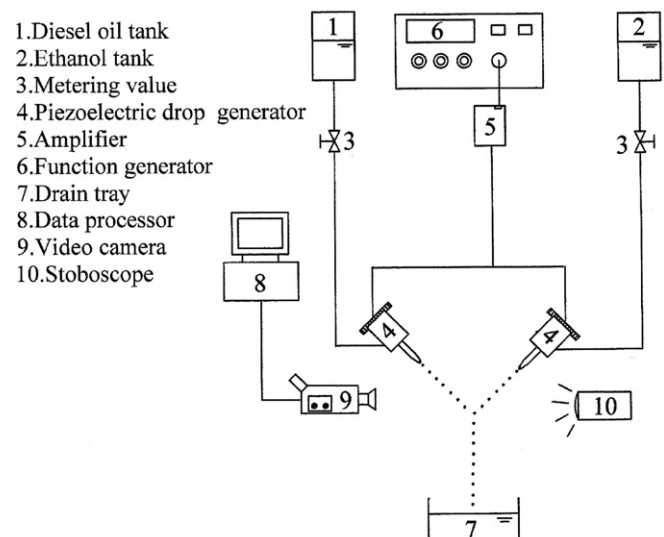


Fig. 1. Experimental Setup.

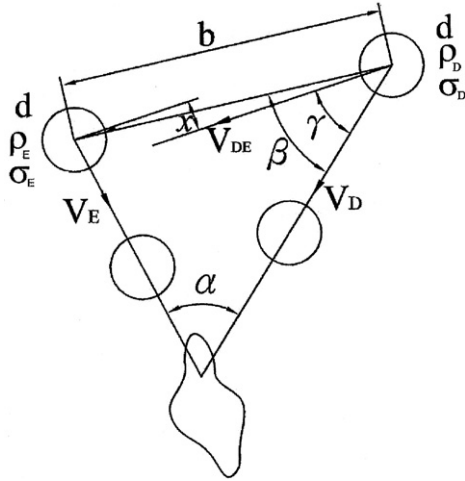


Fig. 2. Geometry for relative velocity and impact parameter calculation.

motion. The sizes, speeds, collision angles of the two streams of liquid drops were varied to change the Weber number and impact parameter of the collision. The measurements were then made on the recorded frames of video, where the dyed ethanol drops appeared red and thus made identification of fluid motion easier.

Fig. 2 is a sketch showing the relative positions of the drops on the recorded frame for the collision of one diesel oil drop with one ethanol drop, with subscript “D” denoting diesel oil and subscript “E” denoting ethanol. The figure is also applicable to the collision of two diesel drops by changing the subscript “E” to “D”. The drops are of densities ρ_D and ρ_E , surface tension coefficients σ_D and σ_E , and equal diameter d , and approach each other with velocities V_D and V_E . Their trajectories form an angle α . The magnitude of the relative velocity of the two drops can be expressed by

$$V_{DE} = (V_D^2 + V_E^2 - 2V_D V_E \cos \alpha)^{\frac{1}{2}} \quad (1)$$

and the angle γ between the relative velocity V_{DE} and the velocity V_D can be found by

$$\gamma = \sin^{-1} \left(\frac{V_E}{V_{DE}} \sin \alpha \right) \quad (2)$$

The impact parameter X , which is defined as the distance from the center of one drop to the relative velocity vector placed on the center of the other drop, can then be calculated by

$$X = \frac{b \sin |\beta - \gamma|}{d} \quad (3)$$

Table 1
Properties of diesel oil, ethanol, and tetradecane

Liquid	Surface Tension (N/m)	Specific Gravity	Viscosity (Ns/m ²)
Diesel oil	0.0283	0.817	3.16×10^{-3}
Ethanol	0.0221	0.801	1.20×10^{-3}
Tetradecane	0.0266	0.776	1.7×10^{-3}

Table 2
Dimensionless groups (Subscript: D = diesel oil; E = ethanol)

Dimensionless variable	Definition	Value or Range
Diameter ratio	d_D/d_E	0.98–1
Impact parameter	Eq. (3)	$0 < X < 1$
Weber number	Eq. (4)	$0.6 < We < 100$
Reynolds number	$V_{DE} d \bar{\rho} / \mu_D$	$30 < Re < 450$
Density ratio	ρ_D / ρ_E	1.02
Surface tension ratio	σ_D / σ_E	1.27
Viscosity ratio	μ_D / μ_E	2.63

The physical properties of diesel oil, ethanol, and tetradecane are listed in Table 1. In our present study, the diameter ratio is unity; the viscous effects are ignored; and the property ratios are constant because we have not studied drops other than ethanol and diesel oil. Therefore, the data are presented with only the Weber number and the impact parameter. In our study, the Weber number is defined as

$$We = \frac{\bar{\rho} d V_{DE}^2}{\sigma_D}; \text{ where } \bar{\rho} = \frac{2\rho_D \rho_E}{\rho_D + \rho_E} \quad (4)$$

An averaged density $\bar{\rho}$, which can be derived from linear momentum conservation, is used to represent the effective collision kinetic energy. The surface tension coefficient of diesel oil was used to define the Weber number for the correlation of the experimental data. However, in Section 3 we shall see that, in different regimes of collisions, this choice does not always represent the correct physics underlying the collision behavior. The coalescence or separation of the two drops after collision is determined by the strength of the liquid bridge formed after the collision. The strength of the liquid bridge is determined by the constituents of the liquid bridge, which is distinct for each collision regime. The present dimensionless groups and their values or ranges are presented in Table 2.

3. Results and discussion

3.1. Diesel–diesel drop collision

First we compare our diesel drop collision results with the published tetradecane results [3]. In Fig. 3 our diesel–diesel drop collision data and regime boundaries are represented by the four types of symbols and the solid lines, whereas the dotted lines are the regime boundaries for the collisions of tetradecane drops published in Qian and Law [3]. One can immediately notice the close similarity of the two sets of boundary lines. The letters in braces, {A} – {G}, indicate the places in the figure where our following discussions will be directed.

The Weber numbers for the onset of coalescence and reflex separation at $X = 0$, points {A} and {B}, match closely. Near $We \approx 80$, the upper and lower coalescence boundaries, {C} and {D}, are seen to differ more. But Qian and Law [3] have just presented a few data points near $We = 80$, perhaps their curve fitting was not quite reliable at the end points.

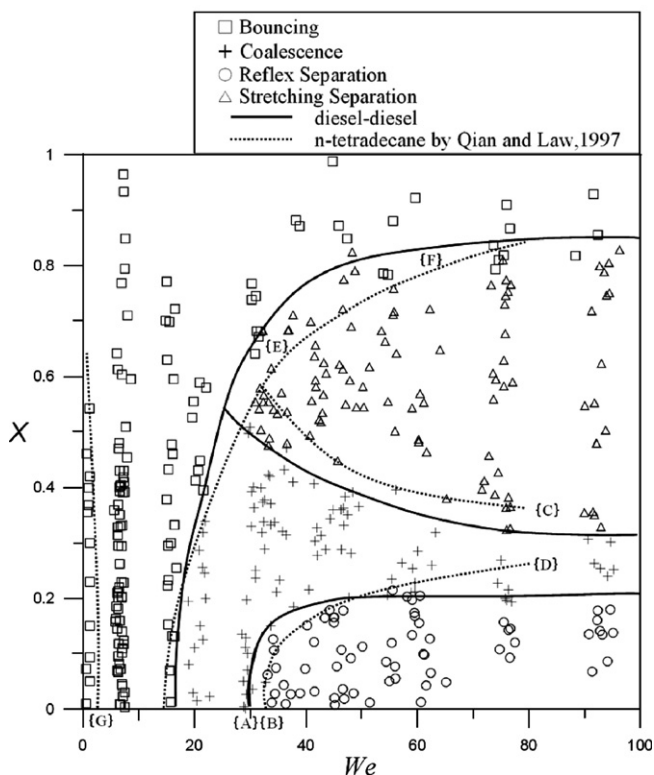


Fig. 3. Diesel–diesel versus tetradecane–tetradecane drop collisions.

With inherent experimental errors, 5%, in mind, the only distinction that we feel confident to say is in the region $35 < We < 60$ and $0.65 < X < 0.8$, {E} and {F}, because both our and their data points are numerous here. Diesel drop collisions seem to produce less bouncing but more stretching separation than tetradecane drop collision do in this region. The reason might be that diesel contains light hydrocarbons which would evaporate easily and would facilitate liquid bridge forming.

There is indeed one major difference in the regime map at very small Weber numbers, {G}. Coalescence occurs for tetradecane drops, while bouncing persists for diesel drops for a Weber number as low as 0.7.

In summary, the comparison in Fig. 3 clearly shows that the collision results of tetradecane drops adequately predict those of diesel drops except for very small Weber numbers.

3.2. Diesel–ethanol drop collision

In Fig. 4, the experimental data and regime boundaries of diesel–ethanol drop collisions are represented by the four types of symbols and the chain lines, whereas the solid lines are the regime boundaries for the collisions of diesel

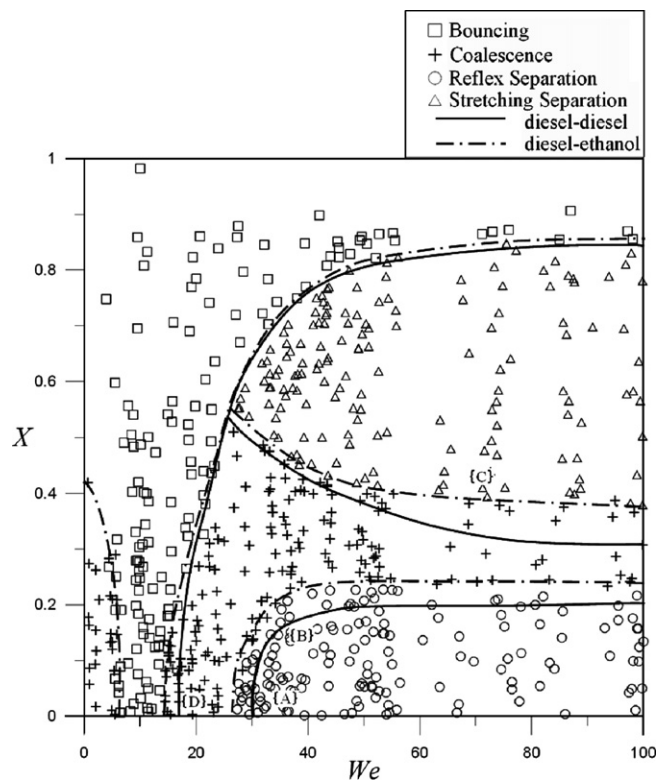


Fig. 4. Diesel–ethanol versus diesel–diesel drop collision.

drops as seen in Fig. 3. Note that the abscissa We is calculated by Eq. (4). In the region $20 < We < 50$ and $0.3 < X < 0.8$, the outcomes of both diesel–diesel and diesel–ethanol are almost the same for this choice of the Weber number. At the other regions, however, there are indeed differences in the values of We and X for the onset of different collision outcomes. The noticeable disagreed parts of the two sets of boundary lines are indicated by the braced alphabets {A}, {B}, {C}, and {D} and they are the points where we will focus our discussions on.

Before discussing the origin of the differences, we first look at a distinct feature of a diesel–ethanol drop collision. In Fig. 5, a head-on collision at a very small Weber number is seen with the ethanol drop dyed red. Soon after the touching of the interface, the red ethanol spread onto the surface of the diesel drop due to the surface tension difference – the surface tension of ethanol being slightly lower than that of diesel oil. For a pair of drop of diameter 780 μm , the first spreading of ethanol from the impact point to the other end of the diesel drop took about 0.1 ms. The movement of ethanol over the surface of the diesel drop continued throughout the evolution of the collision. At the left end



Fig. 5. A head-on collision at a very small Weber number ($We \approx 2$).

of the picture, we can see that only a part of the original ethanol remained at the bottom of the coalesced drop. This spreading of ethanol over the diesel drop would prove to be the key reason in explaining the difference between diesel–diesel and diesel–ethanol collisions.

Firstly, we discuss points {A}, {B}, and {C}, where coalescence from either reflex separation or stretching separation is distinguished due to the action of a liquid bridge. We shall see that each specific difference in the outcomes of diesel–diesel from diesel–ethanol drop collisions comes from the distinct constitution of the liquid bridge, which forms after the merging of the interface and inevitably controls the outcome of coalescence or separation.

At point {A}, i.e., head-on reflex separation, a diesel–diesel drop collision starts its reflex separation at $We \approx 31$; while a diesel–ethanol drop collision starts its reflex separation at $We \approx 26$. This difference tells us that our choice of the representative surface tension must have been inadequate. In Fig. 6(a1) and (b), diesel–ethanol and diesel–diesel drop collisions around point {A} are com-

pared. Judging from the color change in Fig. 6(a1), we can roughly draw the internal structure of the combined diesel–ethanol drop at some stages as shown in Fig. 6(a2). The liquid bridge in stage 4 contained more ethanol at cross section M than at cross section N; and thus the liquid bridge strength at M is weaker than it is at N. In Fig. 6(a1), we see therefore the liquid bridge broke at the lower end, corresponding to cross section M in stage 4 in Fig. 6(a2). Because the liquid bridge was not uniform and contained weak points, the onset of reflex separation occurs at a lower Weber number. In an alternative way of expression, we can say that the surface tension that characterizes a diesel–ethanol head-on collision is an averaged surface tension with a value in between those of the two fluids. Notice in Fig. 6(b), a diesel–diesel collision is quite symmetric.

As mentioned in the above paragraph, the uneven spreading of ethanol over the liquid bridge creates weak point on the liquid bridge and makes reflex separation easier. This phenomenon is manifested by the larger reflex

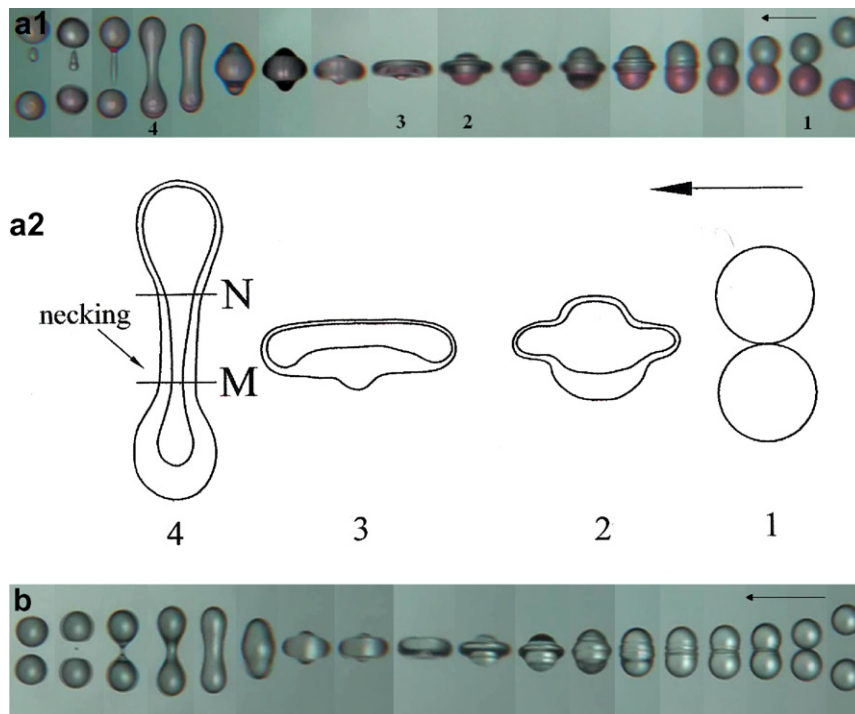


Fig. 6. (a1) Diesel–ethanol head-on reflex separation, (a2) schematic drawing of the internal structure, (b) diesel–diesel reflex separation, at $We \approx 35$.

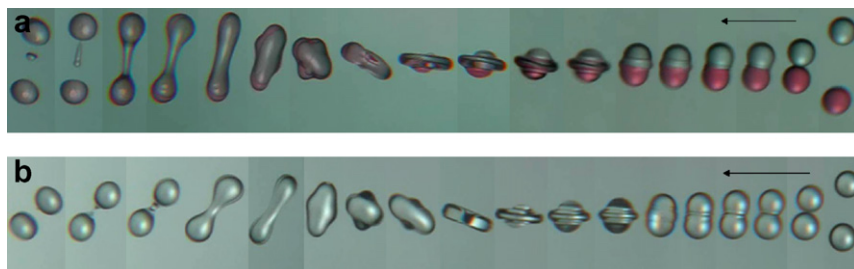


Fig. 7. (a) Diesel–ethanol oblique reflex separation, (b) diesel–diesel oblique reflex separation, at $We \approx 40$ and $X \approx 0.15$.

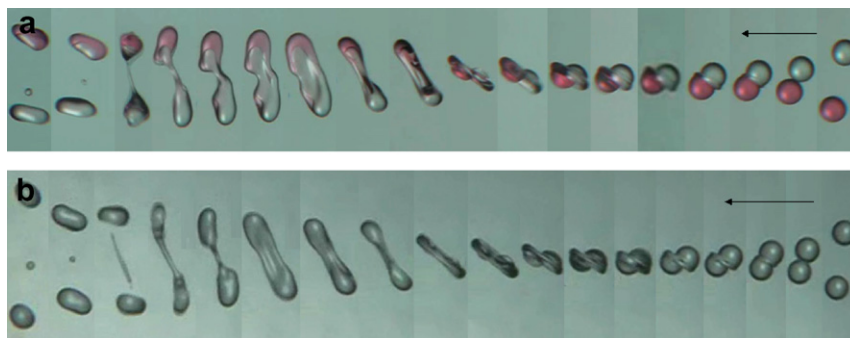


Fig. 8. (a) Diesel–ethanol stretching separation, (b) diesel–diesel stretching separation, at $We \approx 71$ and $X \approx 0.41$.

separation regime for diesel–ethanol collisions than for diesel–diesel collisions. An example of reflex separation near point {B} is shown in Fig. 7. In Fig. 7(a), judged from the color change, it can be clearly seen that ethanol has spread over the liquid bridge. The breakup point was evidently near the weaker bottom end where more ethanol was present. By contrast, the collision in Fig. 7(b) was quite symmetric because both were diesel drops.

Now let us turn to the regime of stretching separation. As can be seen in the regime map, Fig. 4, diesel–ethanol collisions exhibit lower tendency for stretching separation at the boundary between coalescence and stretching separation. For example, at $We = 70$, $X \sim 0.38$, a diesel–diesel collision separates while a diesel–ethanol collision coalesces. The difference can again be attributed to the spreading of ethanol to the liquid bridge. In Fig. 8, a diesel–diesel and a diesel–ethanol collision are compared near point {C}. Basically, the thickness of the liquid bridge is determined by the interacted parts of the two drops. But for diesel–ethanol collisions, an additional action, i.e., the spreading of ethanol over diesel drop, adds to the thickness of the liquid bridge. Therefore, for the same Weber number and impact parameter, a diesel–ethanol collision usually has a thicker, and thus stronger, liquid bridge than a diesel–diesel collision. This explains why a diesel–ethanol collision at high impact parameter is more likely to coalesce than a diesel–diesel collision for the same conditions.

It is noteworthy that compound drops with ethanol shell and diesel core will be produced during coalescence, reflex separation, and stretching separation of a diesel–ethanol drop collision because of the spreading of ethanol over the diesel drop at the early stage of the collision.

Secondly, we will have a few words on the disagreement of the two bouncing regimes for small X and We , near {D}, but agreement at higher X and We . There is also a major difference for very small Weber numbers; while a diesel–ethanol produces coalescence, a diesel–diesel retains bouncing behavior. It is important for the readers to note that the bouncing regime is not characterized by just the Weber number and the impact parameter. This fact has already been realized in the numerous past researches of like drop collisions. The reason is clearly the participation of the vapor phase. Therefore, the bouncing regime is

material and surrounding dependent and should not be discussed based on just the properties of the liquid phases. The present experimental bouncing regimes are specific for diesel–diesel and diesel–ethanol and are not to be extended to other materials.

Finally we would like to have a few words on the size effects of drop collisions. We performed our experiments on drops of 700–800 μm because of experimental simplicity in observation and measurement. It can easily be realized that the importance of viscous effects grows with the decrease of drop size. For the same Weber number, the Reynolds number will be proportional to the 1.5th power of the diameter ratio. Therefore, as the drop size is decreased, eventually the viscous effects can no longer be ignored. Our past experimental evidence has shown that there is no appreciable size effects on drop collision data in the size range from around 200 μm to 1000 μm . For drops outside this range, the present data must be used with care.

4. Conclusions

1. A binary diesel drop collision can be adequately represented by a binary tetradecane drop collision within experimental errors. A major difference exists for very small Weber numbers, where a binary tetradecane drop collision coalesces while a binary diesel drop collision bounces.
2. For a diesel–ethanol drop collision, upon merging of the interface, ethanol spreads very quickly over the diesel drop due to the difference in surface tension. For a pair of 780 μm drops, the spreading of ethanol over the entire diesel drop surface took about 0.1 ms.
3. A near head-on diesel–ethanol collision reflexes to produce a cylindrical liquid bridge covered with uneven layer of ethanol. Because reflex separation could happen at a weak point, it is more likely to happen for a diesel–ethanol collision than for a diesel–diesel collision.
4. During a drop collision at medium or high impact parameters, the action of ethanol spreading over diesel drop adds to the thickness of the liquid bridge and thus creates a stronger liquid bridge, which is less likely to be stretched to breaking.

5. Compound drops with ethanol shell and diesel core will be produced during coalescence, reflex separation, and stretching separation of a diesel–ethanol drop collision.

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