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Droplet collision is of relevance to spray combustion, intimately influencing the spray characteristics in the dense spray region. The present study aims to gain fundamental understanding on the mechanisms governing the observed phenomena of permanent coalescence, bouncing, and separation upon droplet collision. Specific issues of interest include the extent of droplet deformation, the dynamics of the inter-droplet flow, the relative importance of the gas resistance force as compared to the collision inertia, and the relevant rheological properties of the gases and liquids. Extensive experiments have been performed for various liquids, environment gases, and system pressures. A unified concept has crystalized regarding the specific mechanisms and factors controlling the five distinct regimes of collision outcomes for both water and hydrocarbon droplets, namely (I) coalescence with slight deformation, (II) bouncing, (III) coalescence with substantial deformation, (IV) coalescence followed by separation for near head-on collisions, and (V) coalescence followed by separation for off-center collisions. A coalescence/separation criterion defining the transition between regimes (III) and (IV) for head-on collisions was also derived and found to agree well with the experimental data. A new effort has been initiated to numerically simulate the present experimental results, particularly on the bouncing mechanism for the transition between regimes (I), (II) and (III).

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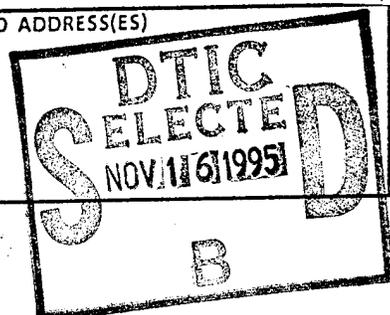
## Abstract

Droplet collision is of relevance to spray combustion, intimately influencing the spray characteristics in the dense spray region. The present study aims to gain fundamental understanding on the mechanisms governing the observed phenomena of permanent coalescence, bouncing, and separation upon droplet collision. Specific issues of interest include the extent of droplet deformation, the dynamics of the inter-droplet flow, the relative importance of the gas resistance force as compared to the collision inertia, and the relevant rheological properties of the gases and liquids. Extensive experiments have been performed for various liquids, environment gases , and system pressures. A unified concept has crystalized regarding the specific mechanisms and factors controlling the five distinct regimes of collision outcomes for both water and hydrocarbon droplets, namely (I) coalescence with slight deformation, (II) bouncing, (III) coalescence with substantial deformation, (IV) coalescence followed by separation for near head-on collisions, and (V) coalescence followed by separation for off-center collisions. A coalescence/separation criterion defining the transition between regimes (III) and (IV) for head-on collisions was also derived and found to agree well with the experimental data. A new effort has been initiated to numerically simulate the present experimental results, particularly on the bouncing mechanism for the transition between regimes (I), (II) and (III).

## Accomplishments

In the early stages of the present investigation we found that the collisional dynamics of hydrocarbon droplets can be significant different from those of water droplets. Specifically, earlier results on water droplet collision at one atmosphere pressure showed that coalescence and separation are respectively favored for small and large Weber number (We). Our experimental observation, however, showed that the transition between coalescence and separation for hydrocarbon droplets at one atmosphere is far from being monotonic. Indeed, as shown in Fig 1, in which B is the collision impact parameter, there are five collision outcome regimes, representing (I) coalescence with small droplet deformation, (II) bouncing, (III) coalescence with large droplet deformation, (IV) Separation after near head-on coalescence, and (V) separation after off-center coalescence. Regimes I to IV occur for near head-on collisions with increasing We, while Regime V is characteristic of large values of We and B. Regime II is very small for water droplet such that Regimes I and III merge.

For the present program we have achieved considerable accomplishments regarding the various physical properties governing the propensity for droplet bouncing, as characterized by the transitions from Regimes I to II to III, and the criterion governing the permanent coalescence of the droplets, as characterized by the transition from Regimes III to IV. These two aspects of accomplishments are separately discussed in the following.

### Criteria Governing the Bouncing Propensity

The crucial factor responsible for the different behavior of water and hydrocarbon droplet is clearly the transition between Regimes I, II and III. Here, as the droplets collide, they become deformed due to the pressure buildup in the gas film between the droplets. This deformation absorbs the kinetic energy of collision, therefore reduces the ability for inter-droplet gas film to be squeezed out in order to effect coalescence. Since the extent of deformation depends on the surface tension of the liquid, it is reasonable to expect a difference behavior for water and hydrocarbon. Further, since displacement of the gas film depends on the density and viscosity of the gas, one may also expect the collision outcome depends on the gas properties.

In the present investigation we have manipulated the effects of the gas and liquid properties by conducting experiments with both water and hydrocarbon droplets in environment of different gases (air, nitrogen, helium, hydrogen and ethylene) and pressures (ranging from 0.6 to 12 atmospheres). The experimental results show that the collision behavior of water and hydrocarbon droplets are actually similar, when the influence of the environment gas density is taken into account.

To substantiate these observation, we note that the gas density can be manipulated in two ways, by changing either gas pressure or the gas molecular weight. Thus in order to promote the

occurrence of bouncing for water droplets, which is not previously observed for one atmosphere air, we should increase the density of the gas. In the course of the experimental exploration, we have found that water droplets actually do exhibit the bouncing phenomenon at one atmosphere air or nitrogen, albeit at high values of B. This regime apparently has been mostly overlooked. We have subsequently found that, with increasing pressure, this regime expands and moves to include small values of B. When the pressure is increased to around 2.8 atmosphere, a fully-developed Regime II is observed in that droplet bouncing now occurs for both off-center and head-on collisions. We have therefore demonstrated that the five collision regimes for hydrocarbons also exist for water, at elevated pressures.

Recognizing that increasing pressure promotes bouncing, it is then reasonable to expect that decreasing pressure should suppress bouncing. We have subsequently demonstrated for tetradecane droplets that this is indeed the case in that, while the five regime response is observed at one atmosphere, the head-on bouncing regime is suppressed as the pressure is reduced to 0.6 atmosphere.

We have further found that, by increasing the pressure to 8 atmospheres for water and 2.4 atmospheres for tetradecane, Regime II can be expanded to such an extent that Regime I can not be experimentally detected. Realistically, of course, two droplets will merge when slowly brought together. We have, however, not been able to simulate such a slow rate of collision in our experiments. The important point to note is that low-We head-on collision at high pressures could very likely result in bouncing. This is to be contrasted with the previous concept, based on water at one atmosphere, that low-We head-on collision always results in coalescence.

To further demonstrate the influence of the inertia of the gas film through the gas density, additional experiments have been conducted for the "lighter" helium environment. The collision response regimes for tetradecane clearly show that, because of the reduced molecular weight and hence density of the helium atmosphere, a higher pressure is needed to induce bouncing in Regime II and suppress merging in Regime I.

Gas density, however, is not the only parameter influencing the collision outcomes. To demonstrate this point, we note that while the gas density for 0.6 atmosphere nitrogen is almost the same as that for 4.4 atmosphere helium, bouncing is clearly more prominent for the helium atmosphere. The difference is possibly caused by the higher dynamic viscosity of helium. As discussed earlier, as the gas is drained from the gap, a higher pressure differential is required to overcome the shear force for gas with higher viscosity, which in turn increases the gas resistance force acting on the droplet. This viscous effect is further demonstrated by recognizing that while the density of helium at 0.7 atmosphere is lower than that of nitrogen at 0.6 atmosphere, bouncing is still observed for the more viscous helium atmosphere.

Another important factor which influences the bouncing property is the similarity of the

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molecular structure of the liquid and gas. We have thus compared the collision outcomes for tetradecane in an environment of nitrogen and ethylene with different compositions. Ethylene is chosen because its molecular structure is similar to that of tetradecane, while its molecular weight is the same as that of nitrogen. It is found that coalescence is promoted with increasing amount of ethylene. This is an important result because the spray interior invariably contains some fuel vapor produced through droplet vaporization. The presence of the fuel vapor thus promotes droplet coalescence. There are two possible causes for this result. The presence of ethylene could modify the surface tension which affects the merging tendency of the two surfaces. Second, since ethylene is readily soluble in tetradecane, its absorption during collision reduces the gas density in the inter-droplet spacing, hence promoting coalescence.

Criteria Governing Permanent Coalescence/Separation

We now consider the transition between Regimes (III) and (IV). Here droplets collide with high kinetic energy to coalesce, while energy dissipated through gas effects is negligible. For collision with Weber number larger than a critical value, say $We_c$, the coalesced droplets can overcome the liquid viscous dissipation and surface tension to breakup. We shall provide in the following a phenomenological analysis for the breakup criterion based on considerations of the kinetic energy of the internal fluid motion, the surface tension energy of the liquid masses, and viscous dissipation. An expression for $We_c$ is derived which agrees well with the experimental results for different liquids.

The droplet collision sequence that results in separation is divided into three periods schematically shown in Fig. 2. In period (1) two droplets first impinge head-on and form an outwardly spreading disk. In period (2) the disk contracts under surface tension to recover the droplet shape, and the internal fluid moves inward in the manner of a counterflow. Finally in period (3) a stretched liquid cylinder is formed, with its two ends moving outward and hence producing a thin inter-connecting ligament which eventually breaks.

At the critical transition from coalescence to separation, the initial kinetic energy is just large enough to overcome the viscous dissipation after coalescence and break the ligament. We can therefore write

$$E = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_r \qquad (1)$$

where E is the initial kinetic energy given by $4/3\rho\pi R^3(U/2)^2$, and $\Phi_1$, $\Phi_2$ and $\Phi_3$ are the dissipative losses during periods (1), (2) and (3). Furthermore, we note that at the instant of breakup the droplet masses are highly deformed, hence possessing an additional surface tension energy as compared to those of the original spherical droplets. This extra energy will be partly dissipated as the separated masses regain their spherical shape, with the rest converted to kinetic energy to the

separated droplets as they move away from each other. Expressing this residue energy $\Phi_r$ as a fraction I of the initial surface tension energy, we have

$$\Phi_r \sim I \cdot 8\pi R^2 \sigma \tag{2}$$

It may be noted that in writing (1) we have neglected the surface energy associated with the small satellite droplets produced during separation.

The viscous dissipation during periods (1), (2) and (3) can be evaluated for the individual periods from

$$\Phi_{1,2,3} = \mu \iint \frac{1}{2} (\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i})^2 dt dx^3 \tag{3}$$

The loss during period (1), $\Phi_1$, has already been evaluated previously as

$$\Phi_1 = \frac{\alpha}{6} \pi r^2 \sigma We \tag{4}$$

where $\alpha$ is the fractional amount of the initial energy dissipated. It is of interest to note that, because the characteristic velocity gradient and the dissipative volume are related to the dissipative process, the viscous dissipative loss in this period turns out to be independent of the viscosity coefficient of the fluid. For the water and hydrocarbon data, $\alpha$ has been empirically determined to be around 0.5.

To evaluate $\Phi_2$, we note that the characteristic liquid velocity $v_2$ towards the center is evaluated from balancing the pressure and surface tension forces

$$\frac{1}{2} \rho v_2^2 = \sigma (\frac{1}{b} + \frac{1}{a+b}) \tag{5}$$

The time which lapses until droplet recovers its quasi-sphere shape is $a/v_2$ and the volume is $8/3\pi R^3$. Consequently $\Phi_2$ can be evaluated as

$$\Phi_2 \sim \frac{1}{2} \mu (\frac{v_2}{b})^2 (\frac{a}{v_2}) \frac{8}{3} \pi R^3 = \frac{8}{3} \pi R^2 \mu \sqrt{\frac{\sigma}{\tilde{b}^{5/2}}} \sqrt{\frac{1}{2}(1 + \frac{1}{1+\tilde{a}/\tilde{b}})} \tag{6}$$

where $\tilde{a}=a/R$ and $\tilde{b}=b/R$.

The viscous dissipation $\Phi_2$ in period (3) is similarly evaluated as

$$\Phi_3 \sim \frac{4}{3} \mu \frac{cv_3}{2} \pi R^3 = \frac{8}{3} \pi R^2 \mu \sqrt{\frac{\sigma}{\rho R}} (\frac{\tilde{c}}{\tilde{d}^{5/2}}) \tag{7}$$

where

$$v_3 = \sqrt{\frac{4\sigma}{\rho d}} \qquad (8)$$

and $\tilde{c}=c/R$ and $\tilde{d}=d/R$

Substituting all the $\Phi$s into (1), and normalizing the resulting expression by the surface energy $\sigma\pi R^2$, we obtain

$$We_c = \beta \cdot Z + \gamma \qquad (9)$$

where $Z=16\mu/(\rho R\sigma)^{1/2}$ is the Ohnesorge number, which represents the ratio of the viscous to surface energies. The parameter $\beta$ is defined as

$$\beta = \frac{1}{1-\alpha}[\frac{\tilde{a}}{\tilde{b}^{5/2}}\sqrt{\frac{1}{2}(1+\frac{1}{1+\tilde{a}/\tilde{b}})} + \frac{\tilde{c}}{\tilde{d}^{5/2}}] \qquad (10)$$

The parameter $\beta$ is a geometry parameter independent of the liquid properties at transition from coalescence to separation. Equation (9) indicates that the initial kinetic energy can be divided into two parts for the breakup of the coalesced liquid, namely the amount needed to overcome viscous dissipation through the internal liquid movement, as indicated by the Ohnesorge number $Z$, and the amount required to achieve the final deformed liquid shape as indicated by $\gamma$. Since there are five independent dimensional parameters $\rho$, $\mu$, $\sigma$, $U$ and $R$, we indeed need only two nondimensional numbers to define the criterion for the transition from coalescence to separation.

Fig. 3 shows the critical Weber number ($We_c$) versus Ohnesorge number ($Z$) for the experimental data of Park (1970), Jiang, Umemura & Law (1992), and the present investigation. The plot yields $\beta$ to be around 30. An independent evaluation of Eq. (10) from the measured values of $\tilde{a}$, $\tilde{b}$, $\tilde{c}$ and $\tilde{d}$ for different liquids yields $\beta$ about 34.9, which agrees well the value determined from Fig. 3. Also note that for liquids with very small viscosity, the minimum required $We_c$ for separation is about 15.
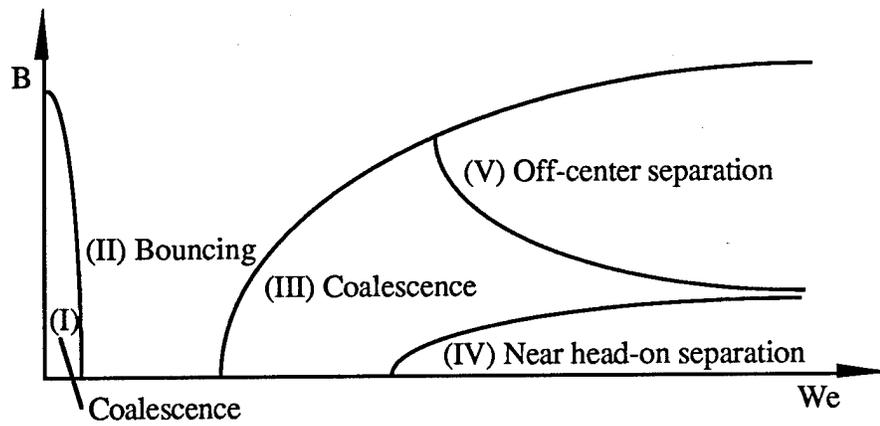
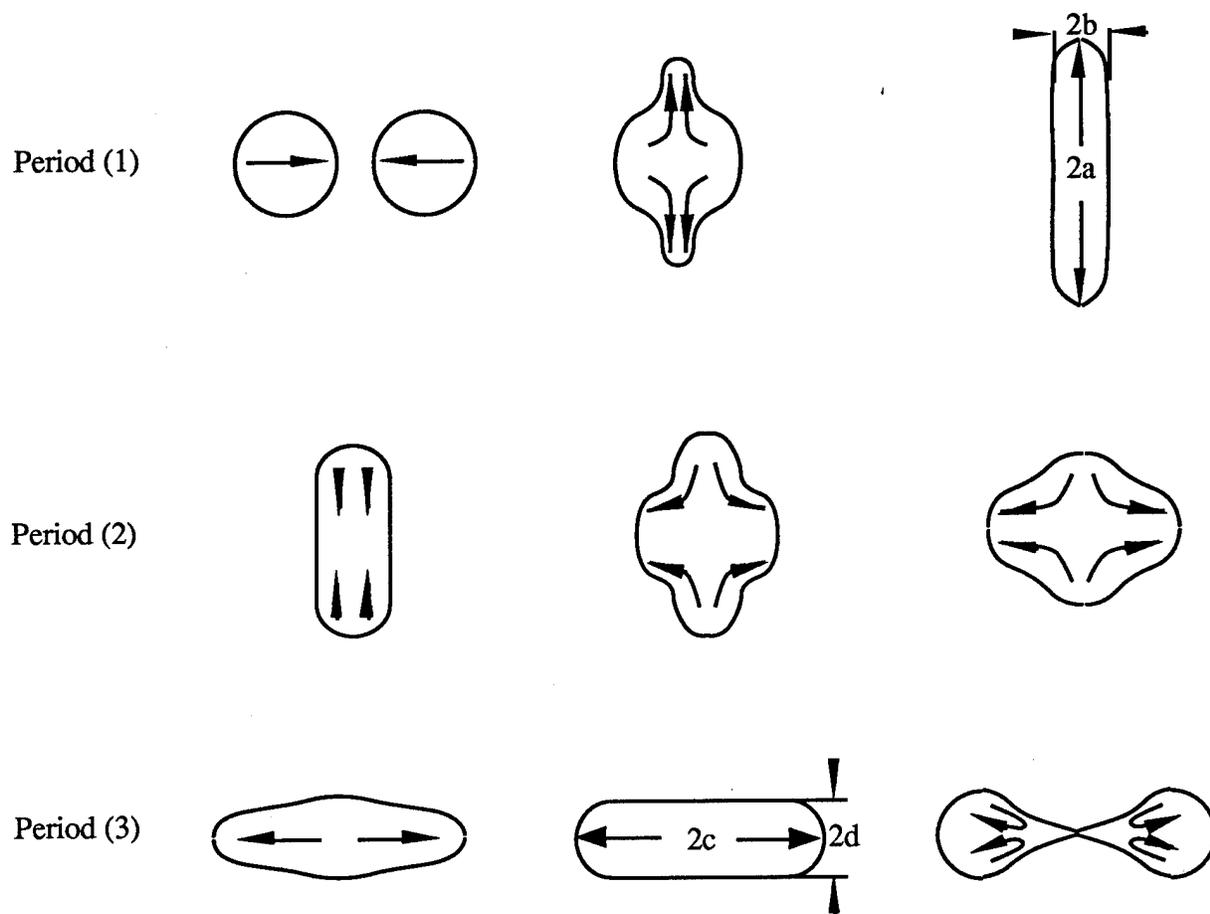Figure 1. Schematic of the various droplet collision regimes.

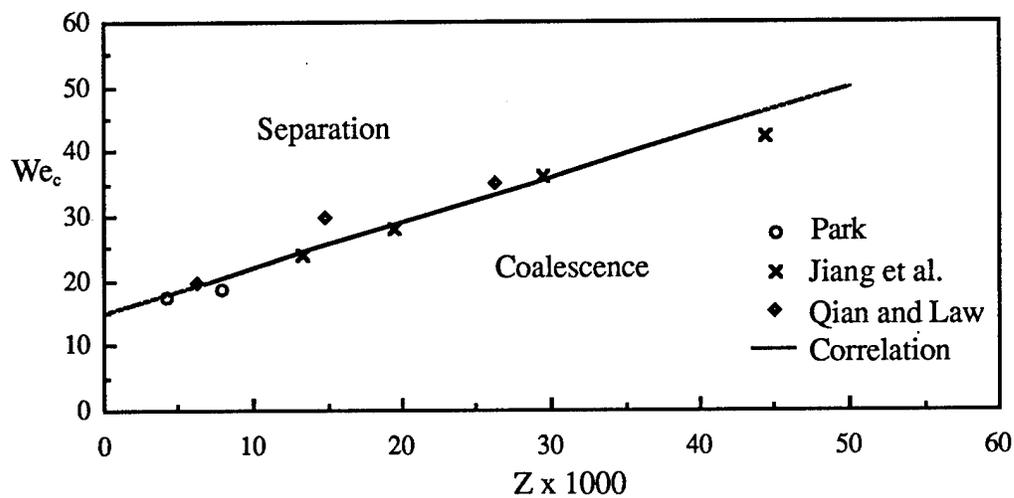Figure 2. Schematic of the three periods of droplet separation sequence.



Figure 3. Critical Weber number ($We_c$) versus Ohnesorge number (Z) for different liquids.

## Publications

1. "Regimes of coalescence and dispersion in droplet collision," by J. Qian, D.L. Zhu, T.G. Kreutz and D.L. Zhu, Paper No. 28, Tech, Meeting of the Eastern States Section of the Combustion Institute, Princeton, NJ, Oct. 25-27, 1993.

2. "Effects of ambient gas pressure on droplet collision," by J. Qian and C.K. Law, AIAA Paper No. 94-0681, 32nd Aerospace Sciences Meeting, Reno, NV, Jan. 10-13, 1994.

3. "Regimes of coalescence and separation in droplet collision," by J. Qian and C.K. Law, submitted to Journal of Fluid Mechanics.

## Research Personnel

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