

Collision and Coalescence of Water Drops

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ABSTRACT

The coalescence efficiency of drops of diameter $0.5 \leq d \leq 2.5$ mm colliding in an electric field of 70 V cm^{-1} was found to be about 0.5. The interactions were observed in the test section of a vertical wind tunnel; for events which were not head-on (small impact parameters) collisions, the coalescence efficiency was found to decrease with increasing impact velocity.

1. Introduction

The importance of drop growth by coalescence has been well established in the literature of cloud physics. The emphasis of most work on this problem has been to determine the collision efficiency of drops of various sizes. The parameter which actually controls growth by coalescence is the collection efficiency, the product of the collision and coalescence efficiencies.

Reports of experimental determinations of coalescence efficiency have been relatively scarce. List and Whelpdale (1969) examined collisions of droplets 134μ in diameter with a 2.2-mm diameter drop suspended on a hypodermic needle. Shotland (1960) observed collisions between drops 200–800 μ in diameter with a spherical water surface formed on capillary tubes of diameter 6–30 mm. Magono and Nakamura (1959) observed similar collisions of droplets with a sessile drop resting on a hydrophobic support. In each of the above-mentioned studies, the collisions observed were with a large drop which was unnaturally constrained. In the present work, the drops are supported aerodynamically; the only unnatural constraint existing is the velocity profile necessary to stabilize the drops in the wind tunnel.

In an investigation of influence charging of water drops (Montgomery and Dawson, 1969), a process in which drops collide, fuse temporarily, and then separate, was observed. In this experiment the coalescence efficiency was found to be ~ 0.5 (essentially independent of electric field). This work was done using drops of about the same size, diameter 2 mm, and the results were applied to collisions of drops slightly larger than 2 mm in diameter with drops slightly smaller than 2 mm in diameter. Cotton and Gokhale (1967) found coalescence efficiencies of $\sim 50\%$ for drops of slightly larger size colliding in a field free region. These interactions were also occurring in the test section of a vertical wind tunnel.

2. Experimental results

The primary experimental data consisted of photographs of collisions of drops. The standard operating

procedure was to float the larger drop of a colliding pair in the test section of a vertical wind tunnel and to release a smaller drop from below to effect the collision [details of the wind tunnel are available in Montgomery and Dawson (1969)]. The camera employed was essentially a film transport; illumination and shuttering were provided by a strobe light, normally operated at 416 flashes per second. Bright-field illumination was used in all the photographs.

The range of size of the colliding drops observed in this study was $0.5 \leq d \leq 2.5$, where d is the drop diameter in millimeters. The interactions observed varied widely but could be grouped in three general categories: 1) the drops collide, deform, and coalesce; 2) the drops collide, fuse temporarily, and separate; and 3) the drops collide, deform with no observable temporary fusion, and separate. In the events where temporary fusion occurs, one or more satellite drops are frequently formed on separation. The term temporary fusion is here used to describe the process where a liquid connection is formed between colliding drops which subsequently separate. This process was referred to by Shotland (1960) as partial coalescence, but since the connotation of permanence is given to the term coalescence, it was felt that less confusion would arise by the use of the term temporary fusion. Representative specimens of a temporary fusion and of a coalescence are shown in Figs. 1a and 1b.

Fig. 1a shows a drop 2.0 mm in diameter, floating in the wind tunnel, being struck by a 1.3-mm diameter drop moving up from the drop dispenser. The impact velocity was $\sim 0.6 \text{ m sec}^{-1}$, equivalent to $0.37 \Delta V_T$, where ΔV_T is the difference in terminal velocities for drops of this size. The drops fuse temporarily and separate, forming a satellite droplet. Fig. 1b shows the coalescence of a drop 1.2 mm in diameter with a 1.9-mm diameter drop. The impact velocity was 0.43 m sec^{-1} , or $0.26 \Delta V_T$.

The experimental procedure employed did not allow the operator to select the exact drop sizes for any interaction and repeat them; therefore, the sizes of the colliding drops are scattered in the above-mentioned

range with the target drop roughly twice the diameter of the colliding drop. To determine if any significant variation of coalescence efficiency was occurring in this size range, the interactions were plotted on a scatter diagram in Fig. 2. When these interactions occurred, an approximately uniform vertical electric field of 70 V cm^{-1} existed in the collision region. [for details see Montgomery and Dawson (1969)]. The ordinate on this diagram is the diameter of the target drop and the abscissa the diameter of the colliding drop. The circular rings represent collisions resulting in separation, and the solid circles indicate those events which were coalescences. The perpendicular lines roughly quarter the size region where the interactions occur. No significant variation of coalescence efficiency with size is apparent, with the possible exception of the upper-left-hand quarter; however, the relative scarcity of events in this region make the significance of the higher coalescence efficiency questionable. The coalescence efficiency for the other three quadrants is about 0.5. The overall average coalescence efficiency for these data is 0.6. The impact velocity for the interactions displayed in Fig. 2 ranged from $0.2\text{--}0.7 \Delta V_T$ with an average of $\sim 0.5 \Delta V_T$.

It was anticipated, with the apparatus employed, that more collisions would be occurring with small impact parameters than would occur naturally. Impact parameter is here defined as the horizontal separation of the drop centers at the maximum vertical separation recorded prior to collision. Stereo photographs were taken of drop interactions, and these results indicate that the experiment was biased toward collisions with small impact parameters; therefore, the coalescence efficiency determined is very probably an overestimate of what would be expected for collisions occurring naturally.

The experimental apparatus was modified in an attempt to observe collisions occurring with impact velocity equal to ΔV_T . For those events which occurred with impact parameters large enough for the collision to be classed as a passing collision, i.e., drops collide, fuse temporarily, form a spindle, and separate (as in Fig. 1a), the behavior was very similar to passing collisions occurring with impact velocity less than ΔV_T . The action was more violent and more satellite droplets were formed at separation than in the low velocity events. Those events in which the collisions appeared to occur with small impact parameters, i.e., those involving head-on collisions, resulted in extreme distortion of the drop formed; the shape assumed by the colliding drops initially resembled the splash from a drop after falling a short distance into a shallow pool (Worthington, 1963). The outcome of the head-on collisions observed ranged from the eventual separation of drops approximately the same size as the initial colliding drops to essentially total disruption of the drop, forming numerous small droplets.

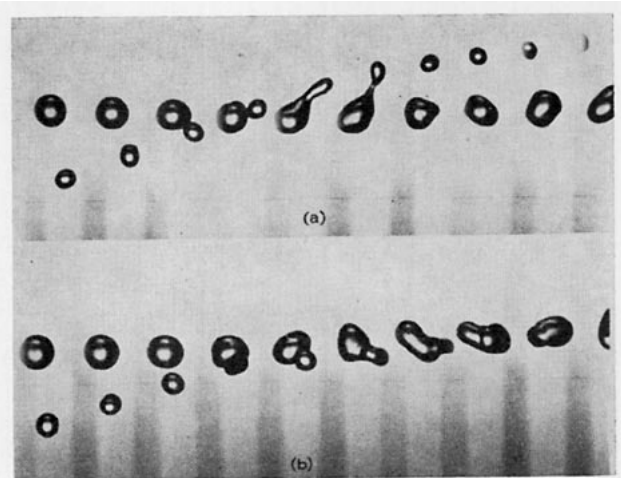


FIG. 1. Examples of drop collisions. In (a) drops collide, fuse temporarily and separate; in (b) the drops coalesce.

The results obtained for higher impact velocities consisted of photographic records of 33 collisions of drops whose diameter ranged from about $1.3\text{--}1.5 \text{ mm}$ with drops of diameter about $2.2\text{--}2.7 \text{ mm}$. In these events, the impact velocity ranged from $1.1\text{--}1.75 \Delta V_T$ with an average of $1.4 \Delta V_T$. With the exception of one event, all of the collisions observed resulted in the eventual separation of the drops. The one exception was a coalescence which occurred after a nearly head-on collision; the drop formed exhibited gross distortion but did not break up into smaller droplets. Due to the undetermined effect of the pre-collision distortion of the drops, these data are only intended to illustrate the apparently large effect impact velocity has on coalescence efficiency for drops in this size range. A variation of impact velocity from about $0.5\text{--}1.5 \Delta V_T$ produced a change in coalescence efficiency from about 0.5 to practically zero.

3. Conclusions

The coalescence efficiency determined from drops of diameter $0.5 \leq d \leq 2.4 \text{ mm}$ colliding in an electric field of 70 V cm^{-1} was not found to be significantly different from 0.5. The existing experimental conditions of low impact velocity and small impact parameter cause this coalescence efficiency to be an overestimate of what would be expected in naturally occurring collisions.

The coalescence efficiency was found to vary markedly with impact velocity, from a value of 0.5 at an impact velocity of $0.5 \Delta V_T$ to nearly zero at an average impact velocity of $1.4 \Delta V_T$. This variation with impact velocity is exactly opposite to the recent findings of List and Whelpdale (1969); however, their results were restricted to collisions occurring with very small impact

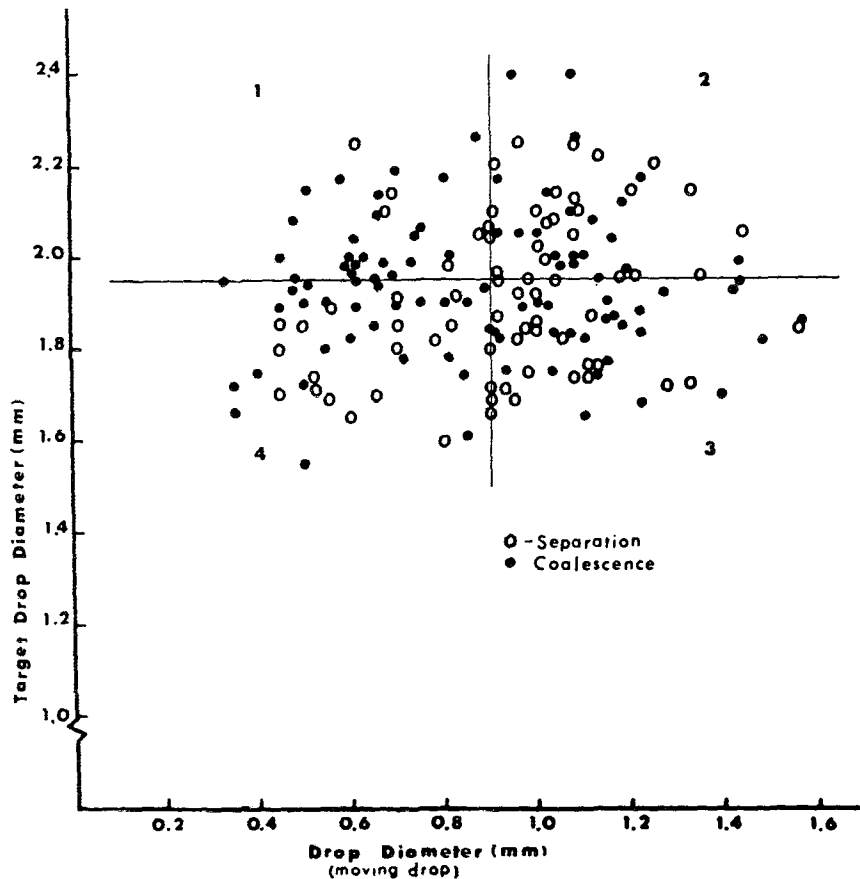


FIG. 2. Scatter diagram showing the range of collision and separation, and collision and coalescence events observed.

parameters, i.e., nearly head-on collisions. The collision-separation shown in Fig. 1a illustrates a quite different class of collisions, and it is not unreasonable to expect a vastly different dependence on impact velocity in the two classes of collisions.

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