Drop Impactions

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ABSTRACT

Recent attempts to understand the development of intense precipitation has led several investigators to speculate about the role of drop impactions. Working with a large vertical wind tunnel, investigations were carried out on the interactions of millimeter size drops. On the basis of these studies it is concluded that drop impactions produce a rapid increase in the number of precipitation size drops (average four or five per collision) while limiting the growth of larger drops. For drops $\gtrsim$ 4 mm in diameter there exists a spectrum of smaller drops whose relative kinetic energy of impaction exceeds the critical value of 15 ergs, thus preventing permanent coalescence. However, impactions seldom completely destroy the larger drops, but they do remove some mass. Drop impactions reveal a self-regulating mechanism in nature that enables collisions to influence both the initial growth and the determination of final size for large drops.

1. Introduction

It is well established in cloud physics that warm precipitation is formed through collision and coalescence of water drops. The rate of growth of a droplet with initial radius of 30 μ into a precipitation size particle depends on several parameters: the liquid water content of its immediate environment, the dynamics and thermodynamics of the cloud in which it exists, and its present size in the spectrum of other drops. These conditions influence its ability to grow by colliding and coalescing with other liquid drops.

The collection efficiency of drops has been the subject of several investigations. Recently, the studies of impactions between millimeter size drops has had increased interest. Investigations concerning drop impactions have been reported by Magono and Nakamura (1959), Magarvey and Geldart (1962), Gunn (1964), List and Whelpdale (1969), List *et al.* (1970), Montgomery (1971), and Brazier-Smith *et al.* (1971). Except in Montgomery's work, the design of these experiments introduced some unnatural limitations. The present studies of drop impactions are designed to eliminate some of the unnatural restraints of the previous investigations, and in doing so, obtain statistical and specific information concerning drop impactions over a range of raindrop size.

2. Experiments

Using a large vertical wind tunnel (Spengler and Gokhale, 1970) large drops ($\geqslant$4 mm diameter) were freely suspended in the airflow. The level of turbulence of the updraft was 2–3% with respect to the mean flow velocity. The water used was filtered tap water. Since the wind tunnel used outdoor ambient air, the use of distilled water was considered unnecessary. The drops were then impacted by a spectrum of smaller drops (500 μm to 4 mm diameter) introduced into the updraft from below.

The impaction events were recorded with high-speed photography (Spengler and Gokhale, 1971).

The following parameters were measured or determined by analyzing the films:

1. Size of impacted drop. This was in all cases the larger drop and its size was determined by measuring its major and minor axis in the plane of focus.
2. Velocity vector of large drop.
3. Size of smaller impacting drop. If the velocity exceeded 2.5 m sec^{-1} and the framing rates were less than 3000 frames sec^{-1}, the smaller drops produced a slightly blurred image. The smaller the drop and/or the faster the velocity the greater the blurring of the image. Impacting drops > 1 mm in size can be measured with an accuracy of ±0.1 mm.
4. Velocity of the impacting drop. This was determined by knowing the framing rate and by counting the frames as the drop traverses a known distance. This method has a maximum error of ±10 cm sec^{-1} for fast moving drops ($>$2 m sec^{-1}). For slower moving drops ($<$1 m sec^{-1}) the error is less than 5%. Drop motions toward or away from the camera were minimized by injecting the smaller drops in the plane of focus.
5. Impact velocity. Found by vector addition of the velocities of the two drops.
6. Angle of impact. This was measured, based on the assumption that the stable large drop had a flat lower

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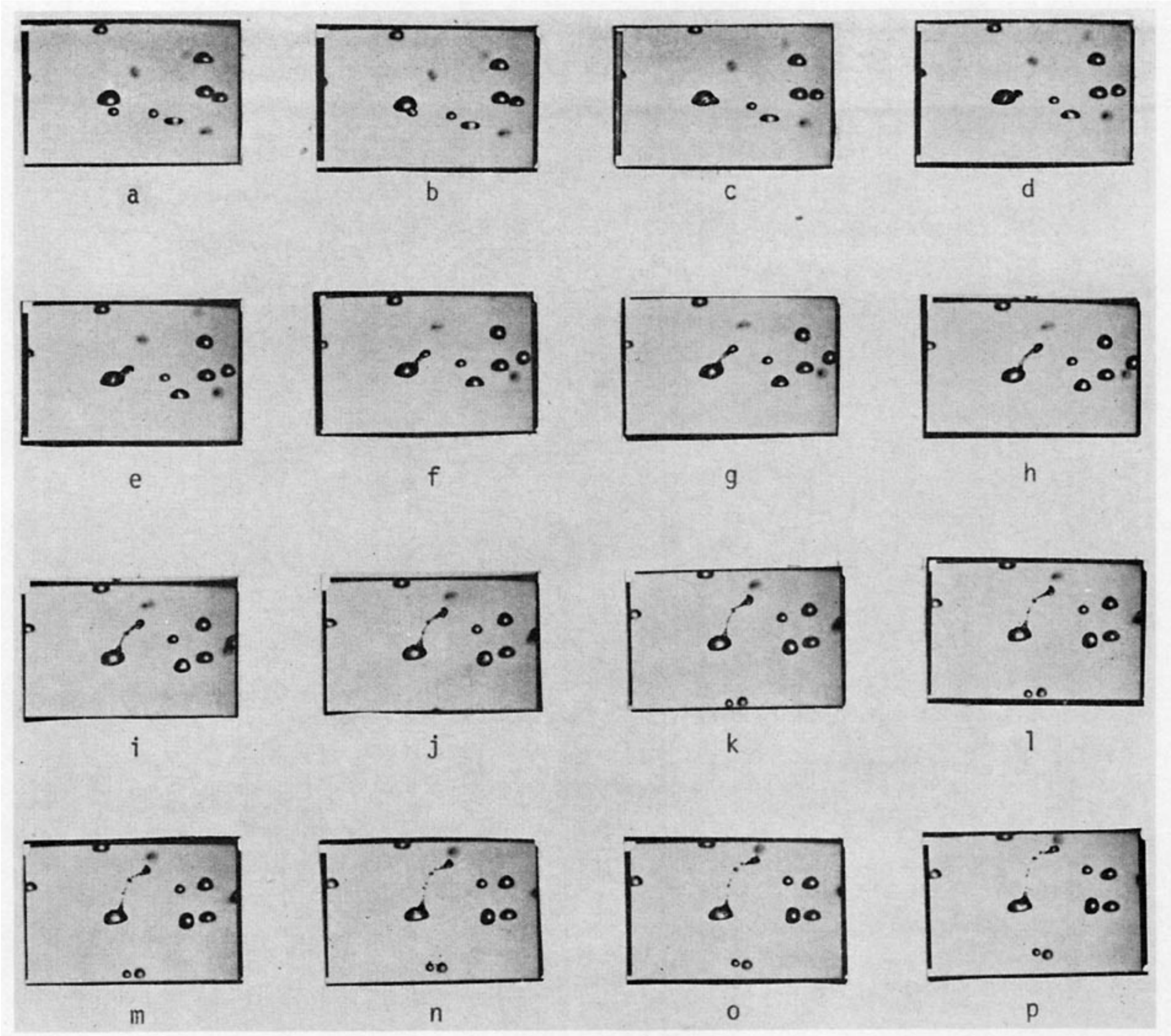

Fig. 1. Filament produced by impacting drops. Large drop has a 6.5 mm horizontal axis, small impacting drop is ~2 mm in diameter. Filament reaches about 10 mm in length before breaking into six small droplets.

surface. For impactions near the edge where the curvature of the drop should be considered and for the impactions involving non-stable drops, the assumption of the flat base can be a source of considerable error.

7. Point of impact. This was noted and measured as a function of horizontal distance from the center of the impacted drop. Even with the limitations of a two-dimensional image, with proper lighting and by carefully noting the result of the impaction, the general location of the contact point could be determined.

8. Type of impaction. Described using the following criteria:

(i) *Coalescence*

(ii) *Filament pulled out.* The length and width of the filament was measured in many cases. A filament is defined as a long strand of water which usually reaches a centimeter or more in length before it breaks (Fig. 1).

(iii) *Splash.* An impaction was labeled a splash when a mass of water was "splashed" (by the force of impaction) beyond the aerodynamic boundary of the larger drop and then broke into free droplets (Fig. 2).

(iv) *Crown.* This is actually a complex and more spectacular form of the splash. An impaction nearer the center will produce a wave which propagates away from the point of contact. This perturbation forces water out beyond the undisturbed boundary of the larger drop. It is then swept up into a shape that resembles a crown. The points of the crown often produce drops 1-3 mm in diameter (Fig. 3).

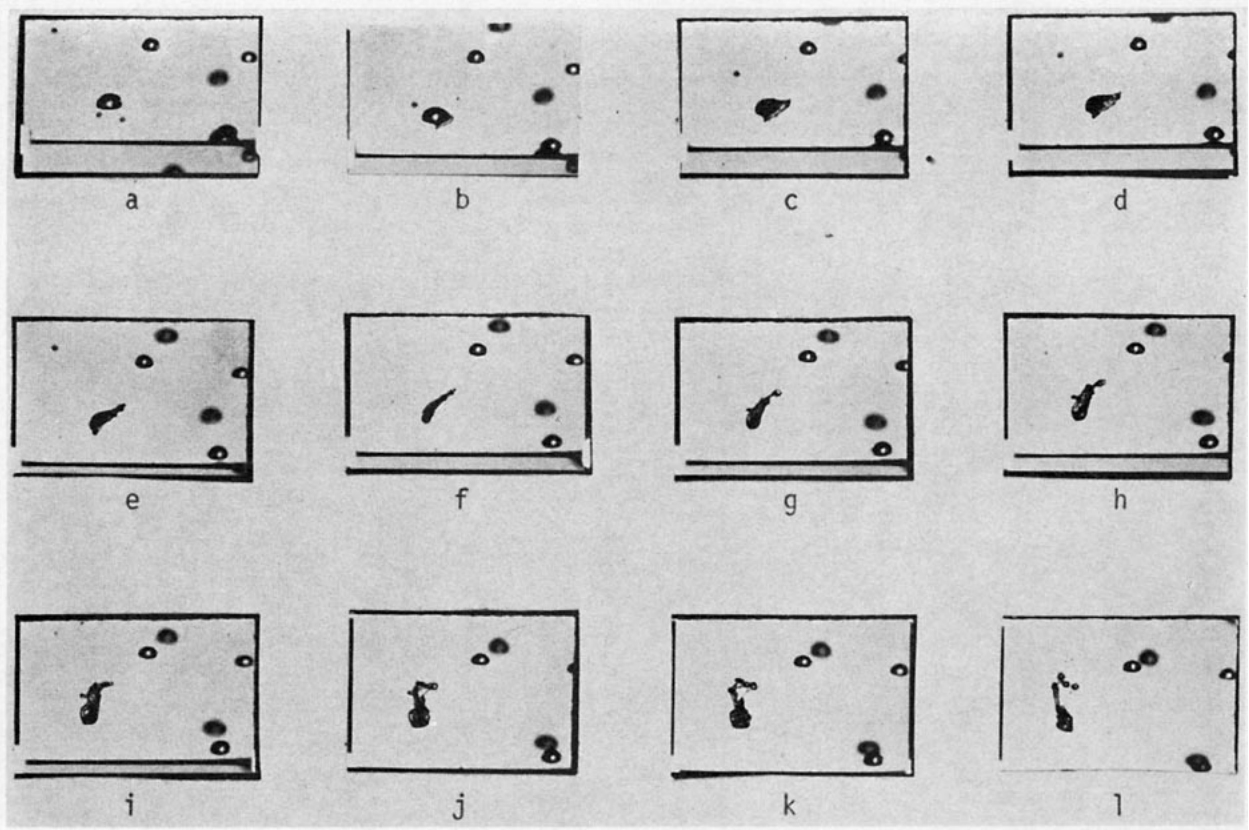

Fig. 2. A 1.8-mm drop impacting a 6-mm equivalent diameter drop at a slight angle causing a splash break-up. Last picture shows three 2 mm diameter drops and three submillimeter-size droplets breaking away from large drop.

(v) *Bounce.* Contact but no mass lost from either drop.

9. Size(s) of the drop(s). Measured when possible.
10. Velocity of the large disturbed drop. Often measured after the collision.

Over 100 interactions were photographed and 66 were analyzed in detail. The larger drops ranged from 4–7.4 mm in equivalent diameter and the smaller drops between 0.5 and 4.8 mm in diameter. The impact velocities varied between 0.29 ΔV_T for a 1.0-mm drop

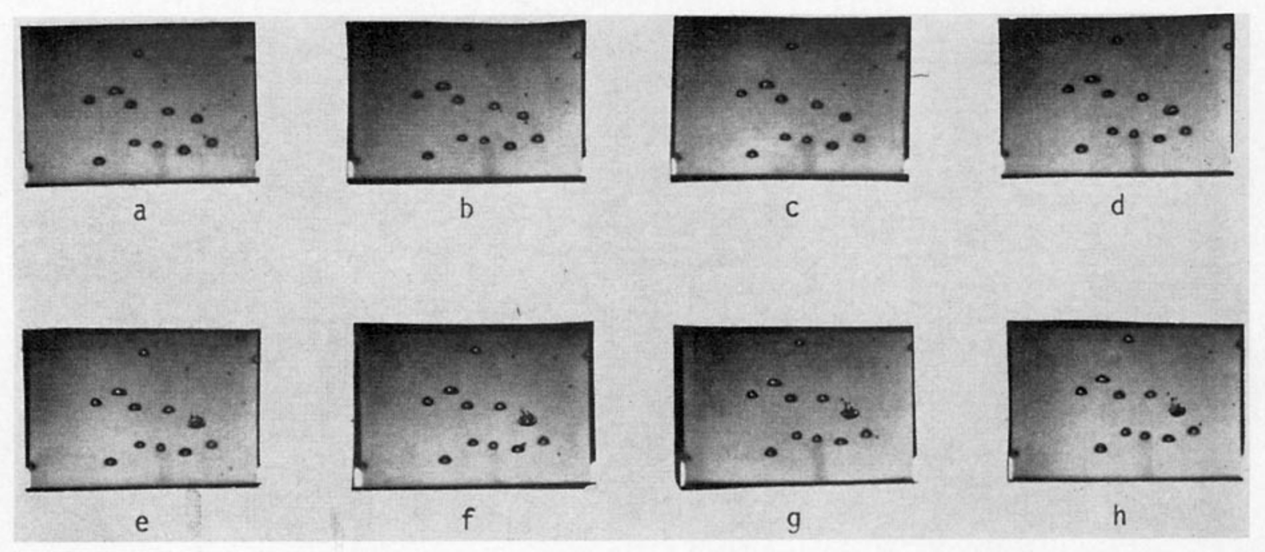

Fig. 3. A 1.5-mm drop impacting a 5.5-mm equivalent diameter drop near the center. The result is a crown break-up producing three drops of ~1 mm diameter. Note that the large drop is not totally destroyed.

impacting a 5.5-mm drop to 11.5 ΔV_T for a 4.8-mm drop impacting a 5.5-mm drop, where ΔV_T is the difference in the terminal velocities of the drops. High values most probably involved some wake acceleration.

3. Results

The purpose of this study was to determine exactly what can be expected from collisions between precipitation size particles. In all impactions observed, the drops coalesced either temporarily or permanently. Bounce collisions did not occur.

Two influential factors which determined partial or permanent coalescence were the kinetic energy of the impacting drop and the point of contact that the smaller impacting drop makes with the larger drop. The kinetic energy of the impacting drops can be dissipated by the following mechanisms: 1) work done in forcing out the air between colliding drops; 2) work done against the hydrostatic pressure forces of the impacted water drops; 3) work done against the surface tension in deforming the water drops; and 4) energy transfers into the energy of surface waves on the larger drop, velocity of the fragmented droplets, internal circulations of the drops, and rotation of the two-drop system. Analysis of the high-speed films clearly shows that the point and angle of impaction influence the number and sizes of the drops produced in a non-permanent coalescing collision.

a. Description of impactions for large drops (>4 mm in diameter)

When a collision occurs within 0.8 mm of the edge of the larger drop, a filament of water is pulled out. This filament reaches an average length of 1.5 cm before disintegrating into millimeter and submillimeter size droplets (see Fig. 1). The average number of drops resulting from an edge impaction is 5.4. (Higher magnification of film with better resolution may reveal more smaller sized droplets.)

Smaller drops impacting further than 0.8 mm from the edge displace surface water while forming a cavity. The amplitude of the surface wave produced is related to the amount of water displaced which, in turn, is a function of the kinetic energy of impact and surface tension. If the interacting drops do not permanently coalesce, the splashed water has a considerable horizontal velocity which rapidly brings it beyond the edge of the larger drop through a region of strong gradient in vertical velocity. This displaced water is then swept upward and begins to contract and breaks off into separate droplets.

If the impaction is within 0.7 mm of the center of the larger drop then the splash pattern will tend to be symmetrical, taking a shape which closely resembles a crown. The points of the crown-like formation can break off into droplets. One to five droplets (average 2.5) in sizes ranging from 1–2.5 mm in diameter can form in this type of impaction.

TABLE 1. Drops produced in impaction break-up.*

Type of break-up	Percent of occurrence	Average number of drops produced	Fraction contribution to overall drop average
Crown	5%	2.5	0.125
Splash	55%	3.65	2.01
Edge filament	40%	5.4	2.16
			4.295

* See text for limitations on sizes of drops involved in collisions.

As the point of impaction occurs farther from the center, the displaced water splashes predominantly to one side. This produces fragments of various sizes and various numbers. A count of the droplets resulting from a splash impaction shows an average of 3.65 drops being formed.

The type of impaction break-up (crown, splash, filament) and the resulting number and size distribution of droplets produced depends on the point of collision, with respect to the impacted drop. Thus, the number of collisions occurring of any particular type will be determined by the area available for that type of collision break-up. The average drop size in Table 1 summarizes what is expected to occur in a collision break-up interaction when a drop of 5.5 mm in equivalent diameter (mean size for experiment) is impacted with drops of 0.8–3.5 mm diameter.

List *et al.* (1970) in studying "collisions of drops with diameters ranging from 2.0 to 4.5 mm found that break-up normally occurred and produced 4.2 fragments on the average." An accurate count and size determination in our studies would have required very high magnification and therefore a subsequent loss in the number of collisions obtained on the same amount of film consumed. Most of the interactions filmed with a 100- or 120-mm lens at 2.25 m with 4XR film would not have recorded droplets $<400\ \mu$m.

It should be mentioned that although mass loss is the common result of an impaction, the large drop usually is not physically destroyed. Very seldom will the large drop disintegrate into small fragments. This implication is discussed in the conclusion.

b. Kinetic energy of impaction

When two liquid drops collide, one of three things is possible: they can bounce off each other; they can partially coalesce and then separate or break-up; and they can coalesce and form one drop. It can be inferred that what occurs depends on the energy involved in the interaction. In the absence of electrical fields, if the kinetic energy is not sufficient to expel the intervening layer of air, the drops will bounce. If the kinetic energy is too great, the drop interaction will not result in

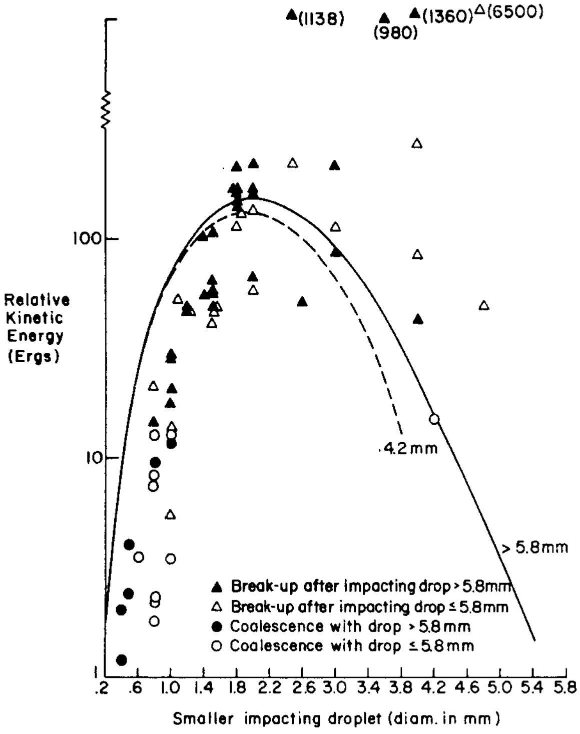

FIG. 4. Relative kinetic energy of impacting smaller drops.

permanent coalescence and some form of break-up will occur. To satisfy the third possibility of coalescence, the kinetic energy must be at some intermediate value between these two extremes. This experiment sought the conditions which rendered coalescence possible or impossible. Close observations of impacting drops revealed the conditions that play an important role. Position and angle of impact influenced the coalescence efficiency through rotational energy considerations. However, very little quantitative data are available because of the dominating role of size and velocity of the impacting drops.

For analysis of the interactions in this experiment the large drop was taken as a fixed frame of reference. This is analogous to moving with the large drop in free fall. All the kinetic energy of an impaction is then associated with the smaller drop. Figs. 4 and 5 are plots of the kinetic energy of a smaller drop relative to a larger impacted drop. Therefore, the kinetic energy is $\frac{1}{2}MV^2$, where M is the mass of the smaller drop and V the velocity relative to the large drop. Because of the wide range of large drop sizes used in this experiment, the data have been separated into two categories: impactions on drops >5.8 mm diameter, and impactions on drops $\geqslant 4.2$ mm but $\leqslant 5.8$ mm diameter.

In Fig. 4 the solid triangles and circles indicate break-up and coalescences, respectively, after an impaction involving a drop >5.8 mm diameter. The open triangles and circles represent break-up and coalescence, respectively, for small drops impacting larger drops $\geqslant 4.2$ mm but $\leqslant 5.8$ mm equivalent diameters. The solid curve represents the calculated relative kinetic energy for small drops travelling at terminal velocity, when they impact drops >5.8 mm diameter having a terminal velocity of 9.3 m sec^{-1}. The dashed line represents the calculated relative kinetic energy for smaller drops impacting 4.2 mm size drops. The shape of these curves is interesting. Small droplets have little mass even though the difference in terminal velocity may be large, whereas large drops have a small difference in terminal velocity. Combining these two effects over the spectrum of impacting drops produces a curve which reveals that the maximum relative kinetic energy is carried by the 1.8–2.2 mm drops.

Because of the difficulty of obtaining impact velocities exactly equal to the difference in terminal velocities, these experiments give scattered values for relative kinetic energy over the spectrum of drops used. Nevertheless, there appears (as we know there should be) a critical kinetic energy of impaction above which permanent coalescence will not occur. For drops >4 mm diameter the value is about 15 ergs. Drops impacting with a relative kinetic energy <15 ergs can coalesce, while drops impacting with relative kinetic energy >15 ergs do not permanently coalesce. From the calculated kinetic energy curve for drops at terminal velocity one might expect that all drops greater than 500 μm and less than 4.2 mm diameter would never

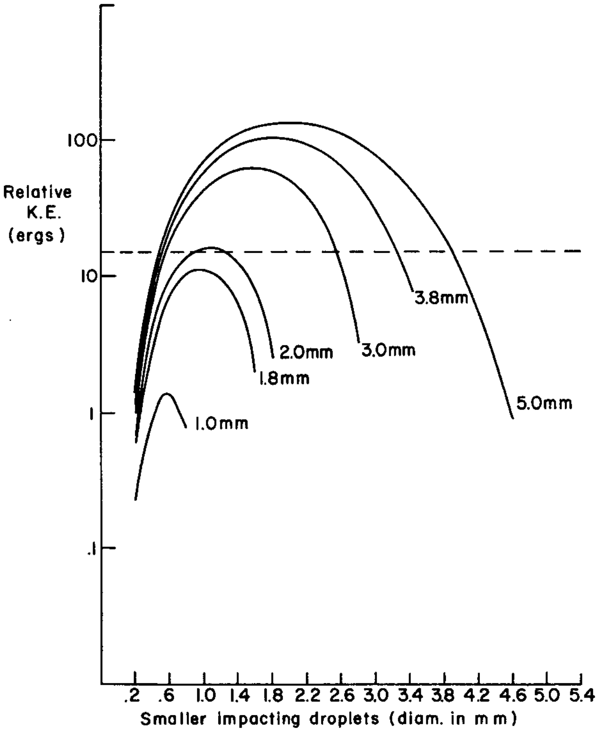

FIG. 5. Relative kinetic energy of impaction. The dashed line is the critical kinetic energy of 15 ergs.

permanently coalesce when impacting drops of diameters greater than 5.8 mm.

As the smaller impacting drop increases in size, wake effects between the two interacting drops become more important. As seen in the results, drops >3.4 mm diameter never impacted with velocities equal to or less than the difference in terminal velocities. It is the acceleration of the downstream drop in the wake of the upstream drop which produces a higher impact velocity. It was found in another study (Spengler and Gokhale, 1972) that 0.5 m sec^{-1} was the critical impact velocity for wake effects involving drops >4 mm diameter above which coalescence could never occur. Making a similar analysis based on relative kinetic energy, a critical value of 12.5 ergs is obtained when using the mass of a 4.5-mm drop, and 25 ergs when using the mass of a 5.8-mm drop. These values bracket the critical relative kinetic energy value for impactions found in this experiment.

c. Significance of impactions

Fig. 5 gives the relative impact kinetic energy for several sizes of larger drops impacted by a spectrum of smaller drops. Using 15 ergs as the energy of demarcation between permanent and non-permanent coalescence, drops <2.0 mm never have collisions with smaller impacting drops that exceed 15 ergs relative kinetic energy. Drops will grow uninhibited to this critical size. As they grow larger, the frequency of non-coalescing impactions also increases. For a 3.0 mm diameter drop the spectrum of drops with a relative kinetic energy in excess of 15 ergs ranges from 500 μm to 2.6 mm in diameter. A similar spectrum of non-coalescing drops for a 5.0 mm diameter drop ranges from 400 μm to 4.0 mm. It is to be noted that during impactions between drops having only a small difference in terminal velocities, wake accelerations can result in an impaction with a relative kinetic energy in excess of the critical value (Spengler and Gokhale, 1972).

4. Conclusions

In summarizing the conclusions of the drop impaction studies, the importance of drop impactions as a precipitation growth mechanism becomes obvious:

1. Drops $\geqslant 2$ mm in diameter have unique spectra of smaller drops which will not permanently coalesce upon collision.
2. The non-coalescing impactions produce several fragmented drops.
3. Photographic observations indicate that such collisions change the mass of the larger impacted drop only slightly.
4. This phenomenon becomes important only when a sufficient number of drops $\geqslant 2$ mm have been grown.
5. Using the Marshall-Palmer (1948) equation, the break-up by impaction would be important only after intensities of 25 mm hr^{-1} or, more likely, 50 mm hr^{-1} had been obtained. This is in agreement with the findings of List *et al.* (1970) on the mean free time between non-coalescing collisions.
6. The importance of these non-coalescing impactions are twofold: (i) After precipitation of a certain intensity develops, there will be a rapid production of millimeter and submillimeter size droplets. This will take place at an average rate of 4 or 5 per collision. (ii) These collisions will restrain the growth of large drops.

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