A Preliminary Investigation of Factors Affecting the Coalescence of Colliding Water Drops

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ABSTRACT

A method is described by which the coalescence process can be examined for different drop and droplet sizes. Preliminary experiments show that factors such as the velocity of collision, the angle of impact, the surface tension, and the electric charges can affect coalescence. It is seen that the coalescence efficiency may be considerably less than unity.

1. Introduction

Although it is well known that the collection process is essential to rain formation, little is known of the coalescence part of the process. According to the *Glossary of Meteorology* (Huschke, 1958), the collection efficiency is defined as the product of the collision and coalescence efficiencies. Most theoretical treatments of the collection process do not consider the coalescence efficiency and experimental work is usually done on the collection process rather than on the collision and coalescence processes separately. As a result, the coalescence efficiency is usually assumed to have the value of unity. The few experiments which have been carried out directly on the coalescence process involved velocities which were *much less* than the relative terminal velocities of the two drops involved [for example, see Magono and Nakamura (1959) or Schotland (1960)].

In this report a new method of examining the coalescence process is described, along with some results of preliminary experiments on the factors which affect it.

2. Method and apparatus

The method of producing collisions to study coalescence is to suspend a water drop on a hypodermic needle in the path of rapidly rising droplets which are ejected by the bursting of air bubbles at an air/water interface. When an air bubble breaks, a jet of water rises from the bottom of the bubble cavity and breaks into four or five small droplets. The top droplet moves vertically with a high velocity to a height of many times its diameter, depending on the bubble size. The diameter of the top droplet, which is the only one used in the experiments, is about one-tenth that of the bubble. Blanchard (1954) described this method of droplet production and Kientzler *et al.* (1954) made photographic observations of the bubble burst and droplet formation.

There are a number of advantages to this method of examining coalescence: the attainment of high collision velocities (of the order of magnitude of the relative terminal velocities of the pairs of colliding drops), easy variation of sizes of both drops and droplets, the position of impact, and the surface and chemical properties and electric charges on the large drop. Also environmental conditions such as temperature, relative humidity and electric field can be easily controlled.

This method also helps to separate the aerodynamic effects from the actual coalescence; the former are small in this experiment compared with those which influence the collection process in nature.

Collisions were produced in an enclosed chamber, shown in Fig. 1, to keep environmental conditions constant. The air bubbles, from which the droplets were formed, were produced at the tip of a drawn glass capillary tube. A gas cylinder provided a regulated supply of clean air. The water used for bubble production was distilled water with specific conductivity of 6×10^{-6} ohm^{-1} cm^{-1}. Observations were made both photographically and visually.

In the experiments described here suspended drops of 2.2 mm diameter and droplets with 134 μ diameter were used. The velocity, angle of impact and the surface properties and charge of the large drop were varied. The environmental air was kept saturated at room temperature.

3. Calibration of droplet source

To insure a uniform source of droplets, and to calibrate the droplet source, three parameters were investigated. The trajectory heights were obtained photographically with a 35 mm camera by comparison with a ruler fixed in the chamber. Measurements made over a period of several days provided an average trajectory height of 10.29±0.13 cm for 329 trials. Droplet diameters, measured by microscopic observations of droplets

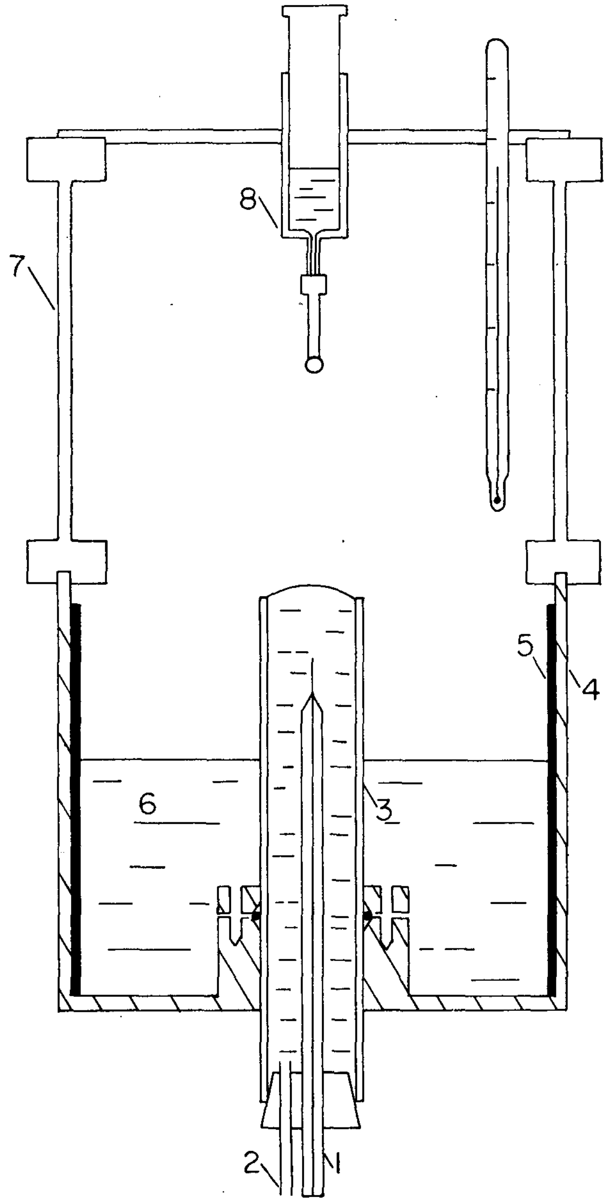

FIG. 1. Schematic diagram of apparatus to study coalescence: 1, glass capillary for bubble production; 2, distilled water inlet; 3, glass tube; 4, brass vessel; 5, blotting paper; 6, water bath; 7, perspex viewing section; 8, syringe and hypodermic needle.

caught in a vaseline-oil mixture, were found to be constant, the value for 104 trials being 134±2 μ. An average velocity vs flight path relationship, shown in Fig. 2, was obtained using a Fastax high speed camera. These measurements of many droplets show an approximately linear relationship between trajectory height and velocity from about 1 cm above the water surface to the top of the trajectory. The suspended drops were not exactly spherical but slightly elongated vertically at the area of suspension. Their equivalent diameter was 2.2±0.1 mm.

4. Experimental results

The coalescence efficiency, i.e., the fraction of the number of collisions which resulted in a coalescence, for various droplet impact velocities is shown in Fig. 3 for three different experiments. Of the four or five droplets which resulted from each bubble burst only the top droplet was used; however, the height to which the second one rose (~ 4 cm) interfered with observations of the top one made at levels below this height, and therefore no observations were made at velocities above 3 m sec^{-1}. (The relative terminal velocity of the two drops is approximately 6.5 m sec^{-1}.) The zero velocity level represents the top of the trajectory. Each experimental value in Fig. 3 represents the average value of between 100 and 200 observations.

Shown on Fig. 3 are the results for distilled water, whose surface tension is 72 dyn cm^{-1}. The coalescence efficiency rises slowly at first from 0 with increasing relative speed and then more abruptly to a value of 1.0 at about 1.6 m sec^{-1}.

Also shown in the same figure are the results for two aqueous solutions of acetic acid, of 0.5 and 5.0% concentration, with surface tensions of 70 and 60 dyn cm^{-1}, respectively. The curve for the weaker solution is quite

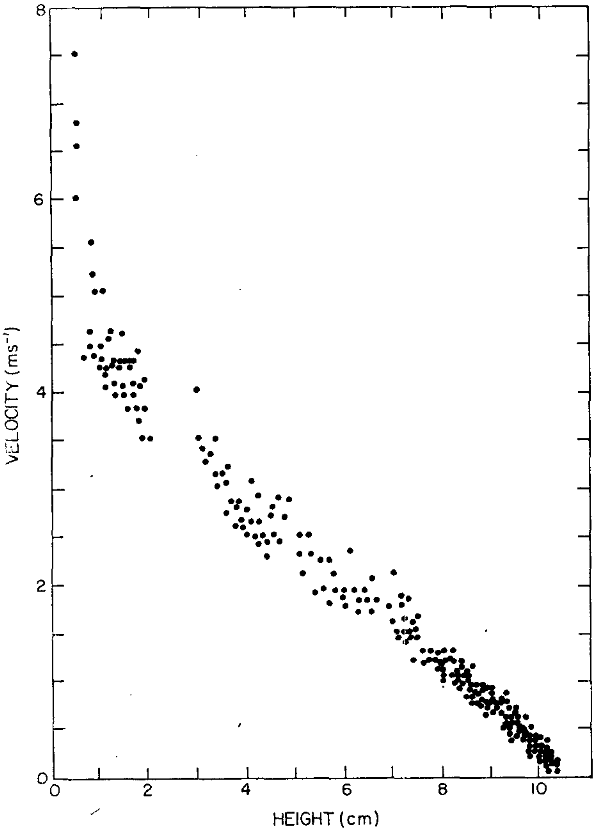

FIG. 2. Droplet velocity vs height above the water surface for 134 μ droplets.

different from that for distilled water at low velocities when the corresponding coalescence efficiency is initially 1.0. It decreases rapidly to a minimum of about 0.05 at about 0.75 m $\sec^{-1}$ and then rises abruptly to 1.0 as with distilled water. The higher concentration solution resulted in a coalescence efficiency of 1.0 at all velocities. Similar results, i.e., a coalescence efficiency of 1.0 at all velocities, were obtained in distilled water when the large drop had a negative charge of the order of 10^{-2} esu and the droplets had a positive charge about two orders of magnitude less.

During all experiments except those with charged drops, it was found, for low velocities, that the position of the collision on the surface of the drop (or the angle of impact) was an important factor in determining whether or not coalescence occurred. Above velocities of approximately 2.0 m $\sec^{-1}$ no dependence on angle was noted; this was the region of a coalescence efficiency of 1.0. At lower velocities a marked dependence on position was observed; between 1.0 and 2.0 m $\sec^{-1}$ collisions which occurred at the edge of the large drop never resulted in coalescence, whereas those occurred in the central area sometimes did. At velocities below 1.0 m $\sec^{-1}$ the dependence on position was erratic. Therefore, all quantitative results represented in Fig. 3 were restricted to collisions which occurred in the central one-quarter cross-sectional area of the drop.

In the region of coalescence efficiency of 0.1 two types of rejected or ejected droplets were observed, i.e., droplets with the same size and approximately the same speed as the collected droplet, and droplets which were appreciably smaller and had a lower speed. In the latter case the incident droplet coalesced and a smaller one was ejected a short time later, as can also be observed when a drop of water falls onto a plane water surface.

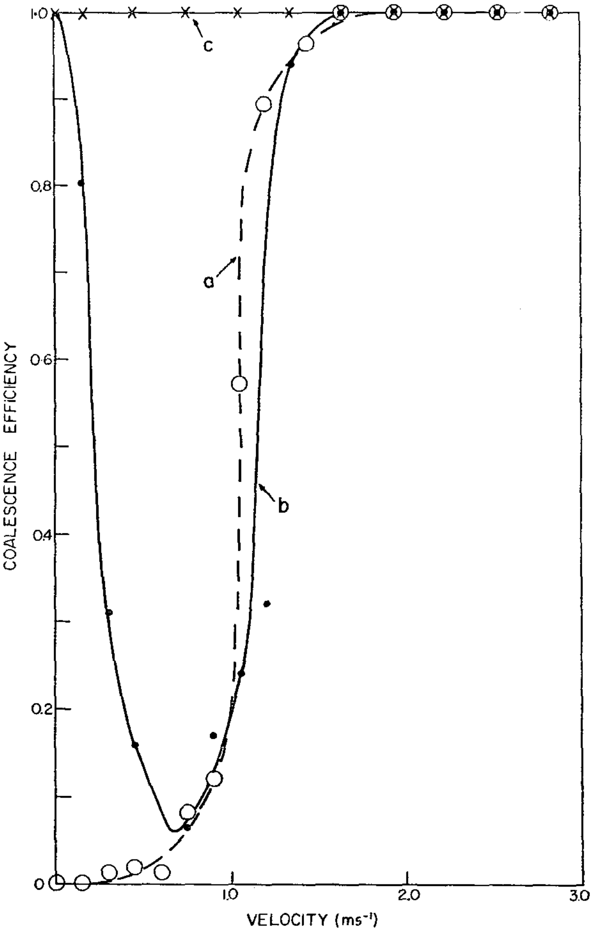

Fig. 3. Coalescence efficiency vs velocity of impact of 134 μ droplets impinging on 2.2 mm drops: a) distilled water, $\sigma=72$ dyn cm^{-1}; b) 0.5% acetic acid solution, $\sigma=70$ dyn cm^{-1}; c) 5% acetic acid solution, $\sigma=60$ dyn cm^{-1}. Curve c) also resulted for distilled water when the drops were oppositely charged.

5. Discussion of results and summary

The experiments showed that the coalescence efficiency depends on the velocity of collision. In general, high velocities resulted in a higher per cent coalescence than did low velocities. An exception was shown for the 0.5% acetic acid solution.

Before coalescence can occur, the air between the two colliding particles must be expelled. Jayaratne and Mason (1964) found that the time during which a colliding water drop was in contact with a plane water surface was directly proportional to the velocity of impact. A longer contact time would presumably aid rather than inhibit the expulsion of the intervening air film and thus favor coalescence. This consideration along with the fact that at higher velocities the droplets have more kinetic energy, and thus a greater chance of overcoming the surface energy of the drop, contributes to the understanding of why the per cent coalescence generally increased with higher velocity. A satisfactory explanation of the exception noted above will require more complete experiments. The surface tension also has an effect upon the coalescence efficiency; however, it seems to be quite complex in nature. At certain velocities the angle of impact was an important factor in determining whether coalescence would occur. The position of collision would be governed also by aerodynamic effects in the atmosphere. For this reason and because of the limited velocity range in which this phenomena is evident, it is difficult to estimate its importance in natural conditions on the basis of data available at present.

Limited experiments showed that coalescence was increased when the drops were oppositely charged; since charged drops and droplets are present in clouds this could be one of the most important factors affecting coalescence. The method used to produce the collisions for the study of coalescence was both reliable and versatile and is preferred over all others used so far because relatively high collision velocities can be obtained. However, the authors are aware that, ultimately, coalescence has to be studied with free-falling drops where internal circulations and oscillations are undisturbed by suspension; the method described at present is a step toward this goal.

Summarizing, one can conclude that the coalescence efficiency should not always be set equal to one.

A more detailed study is presently being made in which the size range of drops and droplets is also varied and where the relative velocities are equivalent to those found in nature.

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