Interactions between Equal-Sized Droplets Due to the Wake Effect

ROBERT CATANEO, JOHN R. ADAM AND RICHARD G. SEMONIN
Illinois State Water Survey, Urbana

(Manuscript received 8 September 1970, in revised form 4 December 1970)

ABSTRACT

In the development of raindrops from cloud droplets in warm rain, the collision-coalescence process is considered to be the main growth mechanism for droplets of unequal size greater than 20 μm in diameter. However, due to the wake effect, the possibility of equal-sized droplets colliding does exist for some maximum vertical separation of the droplets. An empirical study has been performed which led to the determination of the maximum vertical separation required, as a function of droplet size, for equal-sized droplets to be influenced by the wake effect.

1. Introduction

In early studies of the collision-coalescence process (Langmuir, 1948; Houghton, 1950), it was assumed that water droplets of nearly equal size in a cloud are in equilibrium with each other, and therefore, coalescence would not take place unless larger droplets were present. However, later experiments (Telford *et al.*, 1955; Woods and Mason, 1965) indicated that collision efficiencies for equal-sized droplets were non-zero and, in fact, were unexpectedly quite large. These results emphasized the importance of the asymmetric flow around a droplet in the collision-coalescence process for droplets of equal size. A recent empirical study (Steinberger *et al.*, 1968) noted, for Reynolds numbers as low as Re $=0.06$, which is the approximate Reynolds number of a 30-μm diameter droplet falling at terminal velocity, that asymmetric flow exists around the droplet. Conceivably then, two 30-μm droplets falling one above the other could approach each other if their vertical separation were sufficiently small, allowing the decreased drag force in the wake of the leading droplet to act upon the upper droplet. It then becomes important to determine the maximum vertical separation possible, as a function of droplet size, for equal-sized droplets to approach one another. In this paper the experimental procedure used to determine this distance is described along with the results.

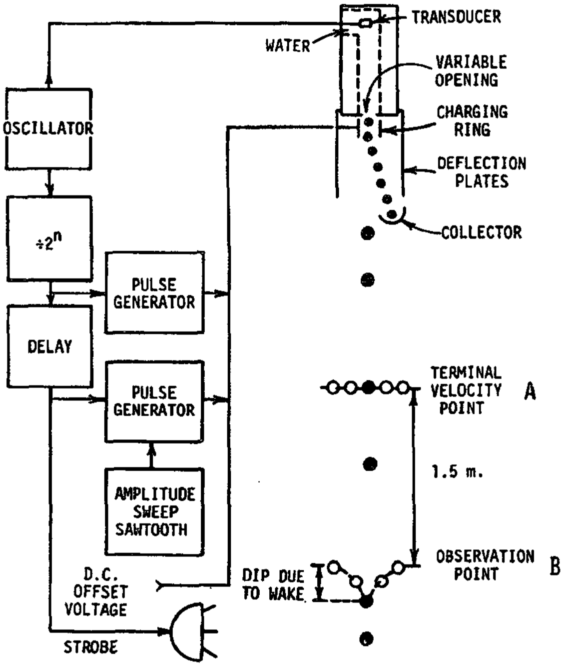

FIG. 1. Block diagram of apparatus to study wake effect.

2. Experimental apparatus and procedure

The experimental apparatus is shown in Fig. 1. A stream of water droplets is produced by forcing water through a small opening of the desired size. A vibrating piezo-electric strip (transducer) in the water supply upstream of the water exit point forces the exiting water jet to break up into uniform-sized, equally spaced droplets. Single, charged or uncharged, droplets can be removed from the stream by applying a voltage pulse at controlled intervals to a charging ring placed around the jet break-up point, and then passing the stream through an electric field (Lindblad and Schneider, 1965). A pair of droplets may be produced in a similar way by applying a second, independent pulse to the ring; this was the technique used. The vertical separation between droplets in the pair can be controlled by varying the time between the first and second pulses. The horizontal position of the two droplets is determined by the pulse amplitude which controls the difference between droplet and stream charge. An automatic sawtooth-amplitude sweep was incorporated in the circuitry to allow the upper droplet in the pair to move from one side of the lower droplet, over it, then to the other side in a sweeping fashion at a rate of 5 cycles per minute. The spacing between pairs was always set much greater than the distance between two droplets in a pair.

When viewed under stroboscopic light, the droplets appear to stand in space with the upper one sweeping back and forth across the lower one as is shown at point A in Fig. 1. If a wake effect is present, it is observed as a dip in the sweeping trajectory of the upper drop as it passes over and accelerates toward the lower drop (point B in Fig. 1). The droplets investigated were allowed to reach terminal velocity before the presence of a wake effect was determined. The distance at which terminal velocity is reached was calculated and was also measured for each pair (Cataneo and Semonin, 1969). The experimental apparatus permitted the droplets to be observed for wake effect at a maximum distance of 1.5 m below the point at which they reached terminal velocity. If a wake effect was observed, the vertical separation was increased until the effect was no longer visible. The vertical separation at which the phenomenon visually disappeared was then measured at the terminal velocity point. The minimum detectable dip induced by the wake was approximately one droplet diameter. Charge on the droplets was varied from 10^{-12} to 10^{-16} coulombs per drop and had no effect on the maximum separation measured. The experiment was carried out for four droplet sizes, 115, 195, 325 and 700 μm in diameter. The maximum vertical separation as a function of droplet size is plotted in Fig. 2.

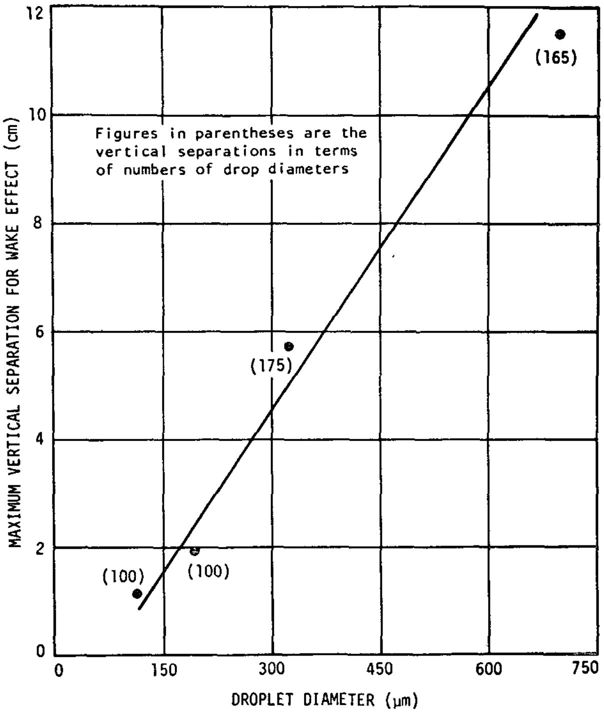

Fig. 2. The maximum vertical separation for presence of a wake effect as a function of droplet size.

3. Discussion

The results were indeed surprising. The wake effect was noted as far away as 11.5 cm for the 700-μm diameter droplets, the distances decreasing directly with droplet size. However, even for the 115-μm droplet, the distance was still quite sizable (1.15 cm, or 100 diameters). The implications of these results with respect to precipitation physics are far reaching in regard to the mechanism for warm rain production.

The wake effect at the maximum vertical distance was observed to be present at radial distances of 2–3 droplet diameters from the bottom droplet. There appears then to be a right circular cone of influence downstream of the leading droplet, which is the cone apex, whose radius at the maximum vertical distance is 2–3 droplet diameters. If we consider that the number density of 100-μm diameter drops may be 3–4 cm^{-3} in a cumulus congestus cloud (Mason, 1957), and if we consider the "wake cone" to be as described above, then the probability of any one of four 100-μm droplets in a cubic centimeter volume being influenced by the wake of one of the other three is $\sim 1\%$. If we extrapolate this probability to a cubic meter, the number of drops being influenced by the wake effect becomes 10^4. Of course, the number density of larger size droplets in a cloud decreases sharply so that the influence of the wake effect becomes increasingly small. However, the wake effect for smaller sizes, where Re < 1, becomes important since their number density in clouds is greater. We are presently investigating these droplet sizes.

4. Conclusions

An experimental procedure has been devised to investigate the magnitude of the wake effect for equal-sized water droplets. From the data obtained to date, we conclude that this phenomenon has a large influence on the collision-coalescence process, and may be a major factor in the rapid growth of raindrops from cloud droplets.

Acknowledgments. This research was sponsored by the Atomic Energy Commission under Contract AT(11-1)-1199 and by the National Science Foundation under Grant GA-4576. We would also like to express our appreciation to Mr. Terry Flach, Mr. Wayne Smith, Mr. David Vercellino and Mr. Timothy Thornburn for their assistance in this project.

REFERENCES

Cataneo, R., and R. G. Semonin, 1969: Fall velocities of small water droplets in still air. *J. Rech. Atmos.*, 4, 57–63.

Houghton, H. G., 1950: A preliminary quantitative analysis of precipitation mechanisms. *J. Meteor.*, **7**, 363–369.

Langmuir, I., 1948: The production of rain by a chain reaction in cumulus clouds at temperatures above freezing. *J. Meteor.*, **5**, 175–192.

Lindblad, N. R., and J. M. Schneider, 1965: Production of uniform-sized liquid droplets. *J. Sci. Instr.*, **42**, 635–638.

Mason, B. J., 1957: *The Physics of Clouds*. Oxford University Press, 481 pp.

Steinberger, E. H., H. R. Pruppacher and M. Neiburger, 1968: On the hydrodynamics of pairs of spheres falling along their line of centers in a viscous medium. *J. Fluid Mech.*, **34**, 809–819.

Telford, J. W., N. S. Thorndyke and E. G. Bowen, 1955: The coalescence between small water drops. *Quart. J. Roy. Meteor. Soc.*, **81**, 241–250.

Woods, J. D., and B. J. Mason, 1965: The wake capture of water drops in air. *Quart. J. Roy. Meteor. Soc.*, **91**, 35–43.