Collisions of Raindrops with Chaff

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ABSTRACT

The purpose of this study is to assess the entrainment by rain of chaff which is used to track air motions by radar. Experiments are described where 214 individual water drops with diameters of 4.9 mm and falling at 78% of terminal velocity collide with single strands of (cylindrical) chaff fibres (diameters of 25 μm and lengths of 10.7 cm), which were falling freely at the time of collision. The length of the fibres investigated is adequate to be used by 10 cm wavelength tracking radars. On the average the water drops carried the chaff over a distance of 4.5 cm from the point of original contact. The actual distance of carry depends on the initial point of contact with respect to both the drop and the fibre; it is greatest for centered collisions.

A simple model is outlined on the basis of the equal but opposite drag forces the chaff experiences within the drop and within the air. Extrapolations for the carrying distance were then made for drops of various sizes, falling at terminal velocities, and drop spectra exhibiting a given Marshall–Palmer distribution. The main conclusion is that the average increase in the downward motion of the chaff due to rain is quite small as compared with the free fallspeed of the chaff and can be neglected in practical applications to the tracking of air motions by radar.

1. Introduction

Air motions or the entrainment of air into thunderstorms can be studied by radar tracking of metallic chaff (normally mylar fibres coated with aluminum) (Warner and Bowen, 1953; Battan, 1958; Jessup, 1971; Fankhauser, 1971; Summers *et al.*, 1972; Marwitz, 1972a,b,1973). Chaff fibres have been observed to emerge from a thunderstorm without much apparent deviation from the air motion by falling precipitation (Jessup, 1971). Nevertheless, the degree by which chaff is affected by rain remained unknown. This led to the study of collisions of single water drops with single fibres and the subsequent displacement of the fibres by the drops. The fibres used were 25 μm in diameter and had a length of 10.7 cm, adequate to respond to the 10 cm wavelength radiation of the tracking radar used by Jessup. If these fibres, which fall in a horizontal position, are dry, their terminal velocity is ~26 cm sec^{-1}; when wet, they fall at ~42 cm sec^{-1} (Jessup, 1971).

2. Experimental techniques

In the experiment a water drop was allowed to fall freely through a height of 3.4 m and strike a single chaff fibre in free suspension. The collision and the fibre entrainment by the drops were recorded photographically (see Fig. 1) with the help of a multiple flash unit (EG&G, LS10B), normally operating at a frequency of 400 Hz. The dropper and shutter system used were of the same type as reported by List *et al.* (1970). The chaff fibre was held at the tips of two brass nozzles by light air suction and was released by a photoelectric pickup and delay system as the drop was approaching. A similar system triggered the flash unit which produced a total of eight flashes, so that the drop and fibre could be seen before, during and after the collision. The fibre was nearly at terminal speed (26 cm sec^{-1}) before collision and nearly at drop speed during collision. The spatial positioning of drop and fibre was recorded through a mirror system, one view being taken along the fibre, the other perpendicular to it. The analysis of the collision sequences was made from the negatives with a Projectina projection microscope. To improve the photographic images of the drops Ecoline white paint was mixed with the water in a concentration of 5.2×10^{-4} gm cm^{-3}. (This led to a change in surface tension of $<1\%$.)

The entire apparatus was shielded by a Faraday cage, and the brass nozzle and chaff mount were grounded in order to minimize electrical effects.

The equivalent spherical diameters of the drops were approximated by averaging their major and minor axes, giving a mean drop diameter of 4.9 mm with a standard deviation $\sigma=\pm0.25$ mm. The fallspeed at the collision point was 7.1 m sec^{-1}, or 78% of the drops terminal velocity (Gunn and Kinzer, 1949).

3. Results

In each collision the chaff slices through the water drop and, after falling a few centimeters, separates

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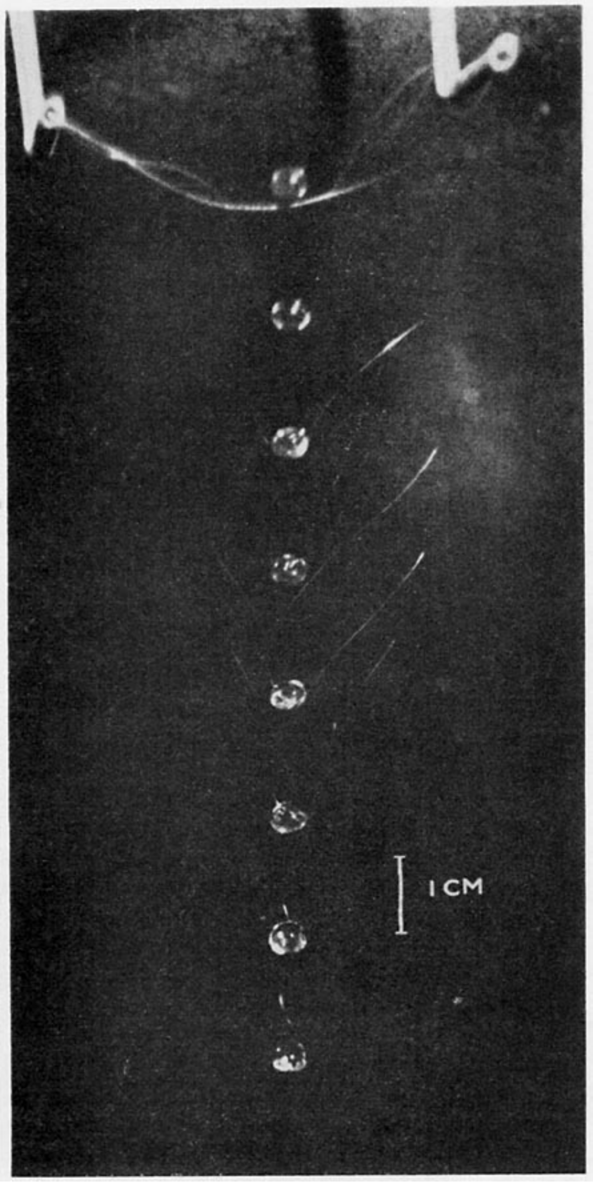

FIG. 1. Stroboscopic photograph of a 4.8-mm drop striking a chaff fibre. The time lapse between images was 2.5 msec and the distance carried was 9.8 cm. Suction ports to suspend fibres are visible in the top part of the photograph.

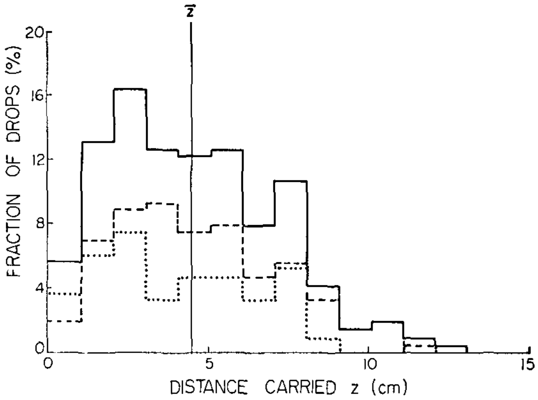

FIG. 2. Frequency distribution of distance z chaff fibres were carried by water drops of diameter 4.9 mm after collisions; the distance $\bar{z}$[$=4.5$ cm; $\sigma=2.5$ cm] is the average carrying distance for the 214 experiments. The data are broken down in terms of hits in the middle (dots) or outer thirds (dashes) of the chaff.

from it after disintegration of a small thread of water between the fibre and the drop. In case of non-central collisions relative to the drop this thread will prevent a final separation until the chaff has been rotated to the rear stagnation point of the drop. The mean distance carried before separation occurred was $\bar{z}=4.5$ cm with $\sigma=2.6$ cm (Fig. 2). In 90% of all the collisions the chaff was carried less than 8 cm. The average distance carried was 4.0 cm when the drop hit one of the outer thirds of the chaff fibres (lengthwise) as compared to 4.8 cm for hits in the middle third. Similarly, hits in the outer third of the drop radius (taken perpendicular to the fibre) also gave reduced carrying distances, namely 2.8 cm as compared to 5.9 cm in the inner third and 4.3 cm in the intermediate third. In summary, collisions at the centers of the drops and the fibres produced the longest carrying distances prior to separation.

4. Interpretation of results

A simple model can be designed to interpret the results during the phase where a rigidly falling and horizontally oriented fibre cuts through a falling drop. Neglecting surface tension, buoyancy and other forces, the following balance between the drag force acting upon the fibre in the water drop and in the air can be assumed during the time of collision:

$$C_1V_{cw}^2 \approx C_2V_{ca}^2, \tag{1}$$

where V_{cw} and V_{ca} are the chaff velocities during collision in water and air, respectively. This balance equation implies also that the speed at which the fibre cuts through the drop is roughly constant. The constants are defined as

$$C_1=0.5C_{Dw}\rho_wWD' \tag{2}$$

$$C_2=0.5C_{Da}\rho_aW(L'-D'), \tag{3}$$

where C_{Dw} and C_{Da} are the drag coefficients of the fibre in water and air, and ρ_w and ρ_a the respective water and air densities. By approximating the chaff as a thin circular cylinder with a length L and a length L' as projected into the horizontal (only this part has a major effect on the force balance in the vertical) and diameter W, the drag coefficients are given according to Tritton (1959) by $C_D=10.9\ \mathrm{Re}^{-0.562}$ for Reynolds numbers Re corresponding to these experiments.

To simplify the calculations average chaff velocities were used and the roughly spherical water drops of diameter D were modelled by cubical drops with sides

$D'=0.5\pi^{\frac{1}{2}}D$, in order to preserve the cross-sectional areas. Drop mass and terminal velocity, however, were not changed.

Using V_T as the drop terminal velocity, V_{ca} can be replaced by V_T-V_{cw} in Eq. (1), yielding

$$V_{cw}=V_T[(C_1/C_2)^{\frac{1}{2}}+1]^{-1}. \tag{4}$$

The distance of fall $\bar{z}$ during which chaff and drop remain together is obtained by integration over that time interval, giving

$$\bar{z}=[(C_1/C_2)^{\frac{1}{2}}+1]D'. \tag{5}$$

Solutions of this equation for drops with 2 mm$<D<$6 mm, freely falling at sea sevel, are given in Fig. 3 as a function of effective chaff length. The distance of fall due to collision increases as the horizontally projected chaff length L' diminishes. It may be emphasized here that the projected horizontal chaff length is the variable and not the real chaff length, meaning that this curve is also applicable to chaff shorter than 10.7 cm. If the chaff becomes curved due to collision so that the horizontal projection decreases for example to an average of $L/3$ for a 4.9-mm drop, the carrying distance increases from 2.7 cm for a rigid horizontal fibre to 4.8 cm for a real (flexible) one. As the fibres curl (Fig. 1) this assumption of $L/3$ is not unreasonable for 10.7 cm chaff.

How does this simple model compare with the experimental results? When the velocity of fall for the drops is decreased to 78% of the terminal velocity (which represents experimental conditions), the resultant changes in Re and drag coefficients increase the carrying distance $\bar{z}$ by less than 1%. Thus, Fig. 3 for freely falling drops adequately describes the test results. Drops 4.9 mm in diameter carry chaff 4.5 cm on the average; according to calculations and taking into account observed horizontally projected lengths between $L/2$ and $L/3$, the carrying distances are between 3.8 and 4.8 cm. The agreement is adequate and leads to the assumption that the data are not only applicable to other chaff lengths but also for first-order approximations to other drop sizes. The authors feel that an extrapolation to drop diameters as low as 0.5 mm is appropriate. For smaller drops surface tension and adhesion may lead to a rolling over effect and not anymore to slicing. However, experiments are needed to prove this suggestion.

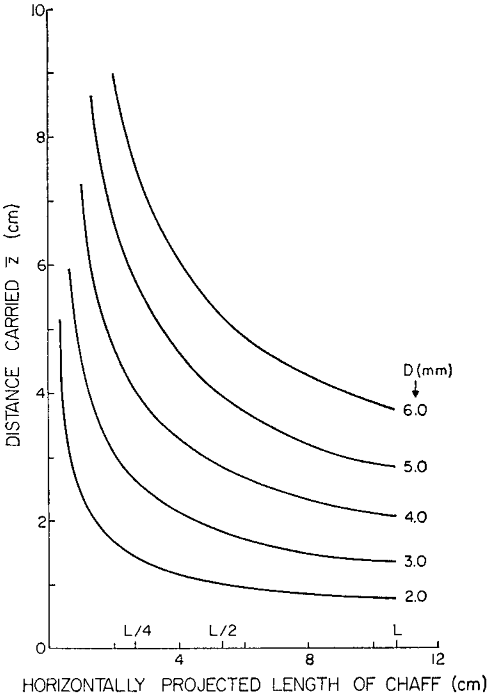

FIG. 3. Distance $\bar{z}$ chaff is carried by freely falling drops of various diameters D if the whole fibre or a fraction of it (for example $L/2$ or $L/3$) is facing the flow.

5. Application to rain

The model can be used to estimate total carrying distances of fibres by (non-freezing) rain by considering multiple collision processes limiting the drop sizes to a range between 0.5 mm$<D<$6 mm. Because the collision rate experienced by one fibre is small ($<$4 sec^{-1} for rainfall rates of 500 mm hr^{-1}) [since the time that the drop and fibre stay together is short ($<$0.02 sec)] and because experiments show that a curled fibre stretches out into its aerodynamically favored horizontal position within about 0.1 sec (or less for fibres shorter than 10.7 cm), a summing up of isolated effects of individual collisions is adequate.

The effective geometric collision cross section A_i of a drop with an equivalent spherical diameter D_i with a fibre of length L and diameter W is

$$A_i=WD_i+0.25\pi D_i^2+L(D_i+W). \tag{6}$$

The sweep-out volume δ_i of a drop between D_i and $D_i+\Delta D$ of a drop spectrum for a time interval $\Delta\tau$ is

$$\delta_i=A_i(V_{Ti}-V_{cai})\Delta\tau. \tag{7}$$

The assumption of geometrical sweep-out seems justified considering the particle sizes and speeds involved; unkown electrical effects, though, could change the situation. A Marshall-Palmer distribution (Marshall and Palmer, 1948) giving the number density $N_i=N_o e^{-\Omega D_i}\Delta D$ for the drops in the diameter interval considered, with $N_o=0.88$ cm^{-4}, $\Omega=41R^{-0.12}$ cm^{-1}, and R the rainfall rate (mm hr^{-1}), can now be used to calculate the total number of collisions per second and the cumulative distance the fibres, with an effective length of $L/3$ (according experimental results), are dragged along during the same time by the drops. In this way the carrying distance rates can be averaged over time and expressed in terms of average carrying speeds (Fig. 4).

For rainfall rates of 5 mm hr^{-1} drops with $D\geqslant 0.1$ cm are colliding with chaff at a rate of 0.11 sec^{-1} and the

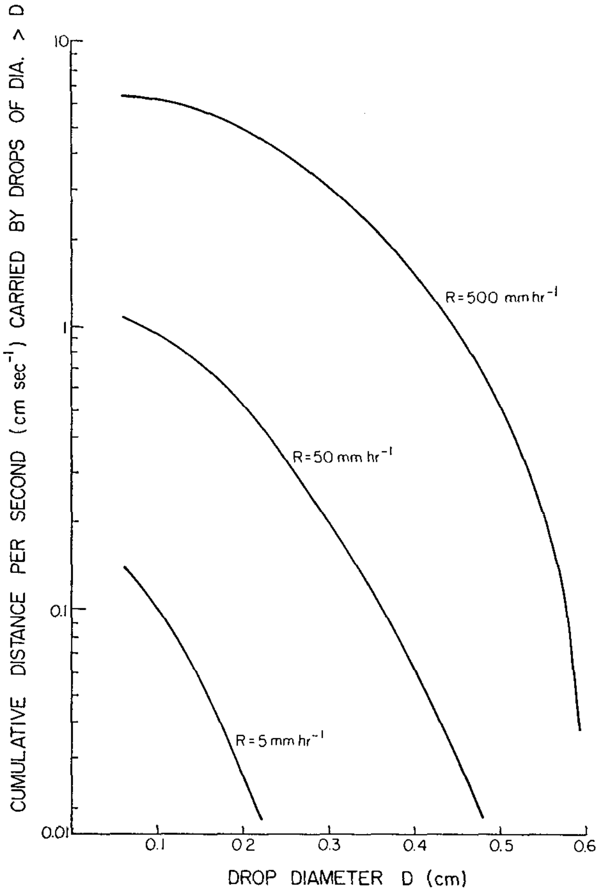

Fig. 4. Cumulative carrying velocity for chaff fibres with effective lengths of $L/3$ ($L=10.7$ cm), colliding with drops having diameters $>D$, for different rainfall rates R.

fibers are carried at an average speed of 0.11 cm sec^{-1}; for rainfall rates of 50 mm hr^{-1} the respective values are 0.76 sec^{-1} and 0.99 cm sec^{-1}; and for rainfall rates of 500 mm hr^{-1} the equivalent values are 3.3 collisions per second and a fallspeed due to collisions of 6.4 cm sec^{-1}. The largest contribution to the speed is from drops with 0.15 mm$<D<$0.25 mm.

6. Summary and conclusions

A total of 214 drops moving at 78% of their terminal fallspeed of 9.1 m sec^{-1} were found to carry freely floating chaff fibres with a length of 10.7 cm an average distance of 4.5 cm. During this joint travel the fibre cuts through the drop without causing any breakup of the drop. The carrying distance depends on the point of impact; the largest observed was <13 cm.

A model which balances the drag on the fibre in air with that in water is adequate to describe the results, and allows extrapolation to drops of a wide range of sizes falling at terminal speeds, and also to shorter fibers. Estimates of collisions with raindrops in rain of various fall rates and exhibiting Marshall-Palmer distributions give low collision rates ($\leqslant 4$ sec^{-1} for the heaviest rain of 500 mm hr^{-1}), and lead to average downward carrying speeds for chaff fibres which are considerably less than the free fallspeed of the chaff fibres.

In summary, for practical applications the effect of nonfreezing rain on chaff is negligible; air motions can be tracked directly by following chaff with radar. One may only need to take account of the free fallspeed of chaff. Special experiments at temperatures below the freezing point would have to be carried out to make substantiated conclusions for the effect by icing. The authors are aware of the fact that radar presently allows chaff tracking in rain only for rates not exceeding ~10 mm hr^{-1}; higher rates were considered here because chaff might be picked up after passing through heavy rain.

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