NOTES AND CORRESPONDENCE

A Method of Measuring Drop Size Distributions in Laboratory Clouds

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ABSTRACT

A method of measuring drop size distribution in clouds, especially adapted for wind tunnels and other cloud chambers in which the cloud is carried in an air stream, is presented. It consists of photographing the cloud illuminated both by a continuous source and a stroboscopic light. The fall velocities of the drops determined from the photographs are used with tables of terminal velocities to give the size distributions. The advantages of the method are discussed.

1. Introduction

The usual methods of determining droplet size in fog and cloud involve impaction of the droplets on a slide or rod coated with a material (dye, carbon soot, magnesium oxide or gelatin). The imprints left by the droplets are measured. If the relationship between droplet size and imprint size at the same velocity can be determined for the particular rod and coating (e.g., by calibrating with drops of known sizes) and if the collision efficiency of the rod for the droplets is known, the droplet size spectrum is thereby determined.

However, there are several difficulties in applying these methods. Calibration assumes availability of drops of prescribed sizes moving with specified velocities. Production of such drops is not readily attainable. Differences in thickness of coating between the rods used in calibration and those used in cloud sampling may result in differences in size of the imprint from the same sized drops. Splashing may result in ejection of small drops, leading to erroneous results. The collision efficiency of the rods is usually only roughly known at best. For small droplets and small velocities the collision efficiency of the rod is small and large numbers of samples must be taken to obtain statistically valid distributions. In addition, some coatings are unsuitable for low impact velocity, at which the drops leave no imprint. Finally, the coating procedure involves tedious measurement of the imprints using microscopes, and the handling and storage of the exposed rods or slides require special measures to avoid marring and damage to the coating by moisture and dust which tend to eliminate the imprints.

The present method alleviates most of these difficulties, although it does not eliminate them completely.

2. Procedure and setup

The method uses a "streak and strobe" photographic technique to determine the velocity of the droplets, and the known relationship of the terminal velocity to the size in order to convert the velocity measurements to a size distribution. The streak, produced by continuous illumination, identifies the droplet, while enhanced superposed dots produced by the strobe light show the positions at specified time intervals, thereby enabling the determination of its velocity.

The method is an extension of the "streak and strobe" technique used by Woods and Mason (1965). They did not use the method for determining drop size, and limited their experiments to drops of radii >35 μm. Because the drops were large and close together in their setup, nearby drops influenced the speed of the drops which were photographed. For smaller drops in concentrations occurring in natural clouds, the wake effects are insignificant and the drops are sufficiently far apart not to influence each other's rate of fall.

We used the procedure to determine the size distribution in a cloud being carried upward through the observation section of our cloud tunnel. The air velocity V_a in the tunnel is known. The drops fall relative to the air at their terminal velocity V_T. The distance d between successive dots along the streak in a photo-

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graph or its projection on a screen is

$$d=(V_a-V_T)tM,$$

where t is the time interval between strobe flashes and M the magnification. Solving for the terminal velocity of the drop, we have

$$V_T=V_a-\frac{d}{tM}. \qquad (1)$$

The values of V_T are evaluated for all drops for which the streaks are in focus and have at least three dots in the field. The requirement that a streak have at least three dots with equal spacing between successive pairs eliminates the possibility of mistakenly attributing to a single drop dots produced by different drops. The terminal velocities thus determined are converted to drop sizes by using tables of terminal velocity vs radius for the conditions of the experiment. As will be shown, with the accuracy to which the quantities involved can be determined, cloud drops down to 8 μm radius or smaller can be measured by this technique.

The apparatus is shown schematically in Fig. 1. A General Electric Sun Gun II and a strobe were placed at about 30° from the camera axis in a horizontal plane, with the strobe behind a focusing lens to increase the intensity of the light scattered by the drops in the sample volume. The light from the two sources passed through small holes in a black background to limit the illuminated volume of cloud as it was carried upward by the air stream in the tunnel. The volume illuminated and viewed by the camera was about 1.5 cm^3.

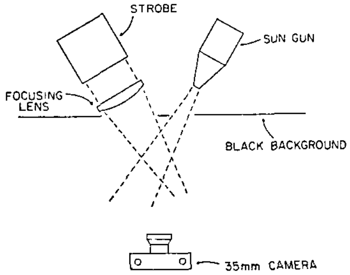

Fig. 1. Schematic diagram of the photographic setup.

The exposure for the air speeds and drop sizes used was usually 1/60 sec, and the strobe flash interval was 4 msec. High-speed recording film (KODAK Recording Film 2475) used with extended developing time gave the best images of the streaks and dots. Fig. 2 shows an example of the resulting photograph.

The magnification of the photographs is varied by insertion of extension tubes of appropriate length between the lens and the camera, selected according to the tunnel speed to provide the necessary period (at least 12 msec) for droplets to remain in the field of view. This meant that at higher tunnel speeds smaller magnification was used. For analysis the photographs were projected onto a screen, which increased the total magnification and enabled adequate precision of the measurement of d.

The accuracy of the radius determination depends, of course, on the accuracy of measurement of the quantities on the right side of Eq. (1). In the Stokes regime,

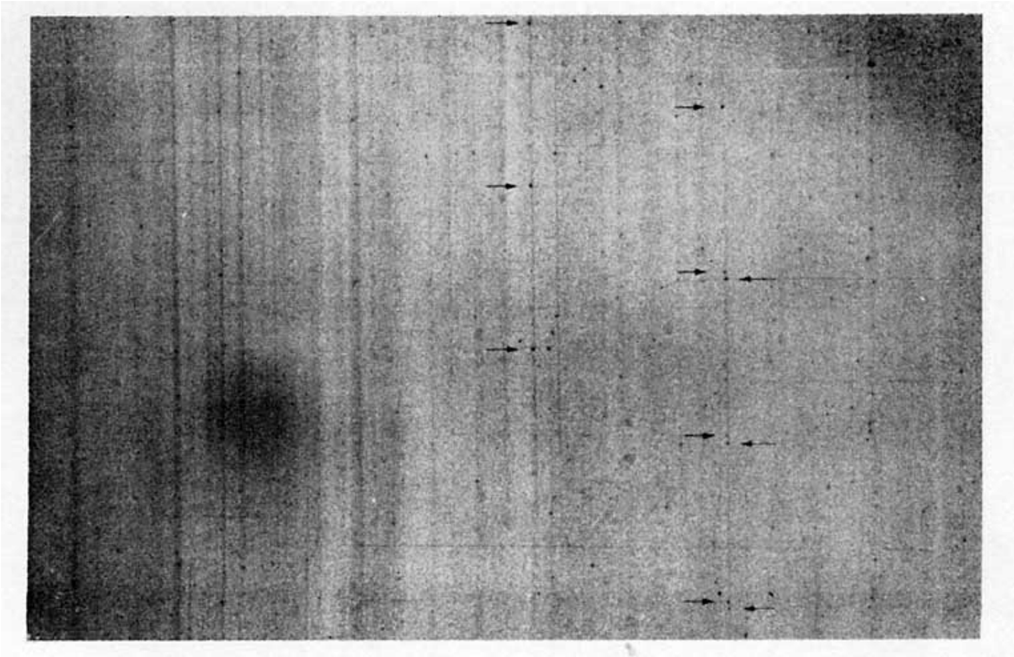

Fig. 2. Negative print of streaks and dots formed by drops passing through field of view.

in which $V_T = ka^2$, the error in radius is given by

$$\Delta a = \frac{1}{2ka}\Delta V_a - \frac{\Delta d}{tM} + \frac{d\Delta M}{tM^2}, \qquad (2)$$

where $k \approx 1.27 \times 10^{-2}$ when a is in microns and the velocities are in centimeters per second. In the cloud tunnel V_a is known to better than 0.15 cm sec^{-1}. The streak intervals d on the projected photographs could be measured to 0.0025 cm (0.001 inch). To determine the magnification M, a slide having a scale with 0.1-mm divisions was photographed in the tunnel and the photographic image projected on the screen. The projector distance was adjusted until the divisions on the screen were exactly one-quarter of an inch apart, resulting in a value of M of 63.5 with an uncertainty less than 0.25. The uncertainty due to the depth of field is smaller than that due to the error in measurement. Inserting these values in (2) we obtain

$$\Delta a \leqslant 15/a.$$

Thus, in our experiments the error in the measurements of a was less than 1 μm for drops with radius >15 μm, and less than 2 μm for 8 μm drops. It would be possible to use a larger magnification determined to the same or better accuracy if measurements of smaller drops are desired.

3. Results and discussion

The drop size distribution for the drops photographed in Fig. 2 is shown in Fig. 3. This cloud was produced by condensation of steam onto drops generated by an ultrasonic nebulizer in the cloud tunnel. The liquid content was determined independently by measuring the dew point of an air sample in which the drops have been evaporated by heating. Using the measured liquid content the drop size distribution can be converted to absolute concentrations. The method has been applied to many cloud drop distributions, ranging up to 40 μm in radius.

One of the chief advantages of the method is that the sampling does not disturb the flow in the tunnel (or in the free air, if it were applied there). One need not be concerned about the collision efficiency since collection on slides or rods is not involved. Other advantages include facilitation of the reduction of the data and storage of the original record.

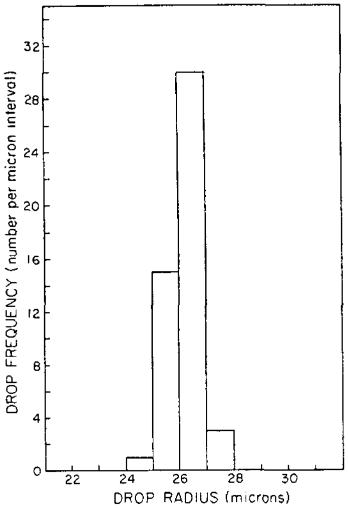

FIG. 3. Drop size distribution derived from photograph shown in Fig. 2 and additional photographs taken at same time.

If the volume of the field of view could be determined precisely and all the drops in it measured, the liquid content and drop concentration could be estimated. However, the depth of field is not sharply delineated, and of the drops in any one photograph only those for which there were three strobe images were measured. Therefore, we used the dew point method for determining the liquid content.

The method is particularly applicable to measurement of droplet distributions in vertical wind tunnels with controlled speeds and fairly laminar flow, or measurement of fog at the ground (or on mountains). Use on aircraft seems doubtful since the speed of the airplane will probably prevent an adequate number of strobe dots in the field of view. A method for cloud measurements which is independent of airplane speed was discussed by Cannon (1970).

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