Comparisons of the Electrostatic Disdrometer with Impactor Slides

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ABSTRACT

Detailed comparisons of measurements from the electrostatic disdrometer and from soot-coated impactor slides show consistent differences in droplet size distributions determined by the two techniques. The disdrometer-derived distribution almost always shows highest concentrations in the first size interval and decreasing concentrations in successively larger size intervals, even in cases when the slides have recorded very few droplets in the smallest sizes. A comparison of the mean radii determined from the two sources for 36 different cases shows that the radii determined from the slides vary between 5.5 and 10 μm, while those determined from the disdrometer vary only between 5.5 and 6.5 μm. Also, as the mean droplet radius increases, the disdrometer measures increasingly higher droplet concentrations than the slides.

Uncertainties and possible errors associated with both the impaction slide and disdrometer measurements are examined. From additional laboratory experiments it is concluded that the disdrometer does not properly size droplets which enter the orifice off center or at an appreciable angle relative to the axis of the orifice. A method for overcoming this problem is suggested.

1. Introduction

Size distribution measurements of cloud droplets are important to the understanding of many microphysical processes in clouds. The most common airborne method of determining these distributions has been to impact droplets on coated slides exposed briefly to the airstream. The impressions remaining on the slides are counted and sized, a tedious process which severely limits the amount of data that can be carefully examined. Any instrument capable of accurate, automatic and continuous measurement of cloud droplet size distributions would be invaluable in cloud microphysical studies.

Keily and Millen (1960) developed the electrostatic disdrometer in the late 1950's, with the hope that the disdrometer would fulfill these requirements. The disdrometer's ability to size droplets is based upon the charge separation that occurs when droplets impact and separate from an electrode. Air containing droplets is drawn through a small orifice at near-sonic velocities and the resulting rapid acceleration experienced by each incoming droplet breaks the droplet into a group of fragments which in turn impact upon an electrode. When these fragments collide with the electrode, a voltage pulse which is proportional in amplitude to the size of the original droplet is generated.

Results obtained from laboratory and field tests of an improved version of the disdrometer reported by Abbott *et al.* (1972, hereafter ADS) seemed to show that the disdrometer was doing a reasonable job of measuring the droplet distribution. However, additional comparisons and checks were made because continuing use of the disdrometer on an NCAR Queen Air and the *Explorer* sailplane gave distributions which always had the highest concentration in the first size interval and decreasing concentrations in successively larger size intervals. These comparisons showed that the disdrometer measurements differed with those from soot-coated impactor slides (1.1 cm wide by 4.4 cm long) in a consistent manner. It is the purpose of this paper to present these comparisons, to discuss possible causes of these differences, and to present the results of additional laboratory tests.

2. Comparisons

For the purpose of comparison, a collection efficiency of 1 was used for the disdrometer; theoretical collection efficiencies for a ribbon, determined by Briggs and Drake [unpublished but similar to Langmuir and Blodgett (1946)] were used for the slides; and the replication factors quoted by Warner (1969) were used to correct the droplet impressions on the slides to actual droplet radii. Uncertainties in the values of these parameters and the influence of possible errors on the comparisons will be discussed in the following section.

All of the comparisons presented here were taken from measurements made in Florida in warm non-

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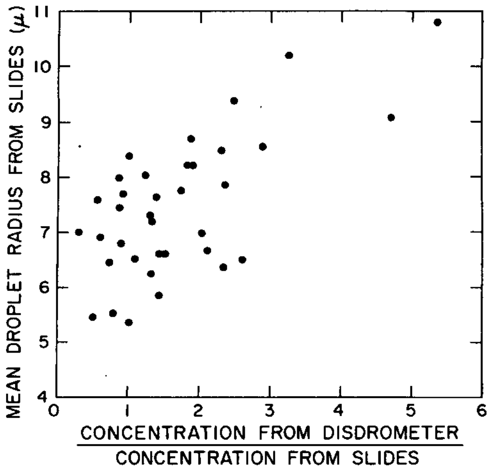

FIG. 1. The ratio of droplet concentration measured by the disdrometer to the droplet concentration measured by the corresponding impactor slide plotted as a function of mean droplet radius determined by the slides for 36 separate distributions measured in warm Florida clouds.

precipitating clouds. Comparisons were used only if both the disdrometer and the Johnson-Williams (J-W) liquid water content meter showed relative uniformity in the region of the cloud in which the impactor slide was exposed. The slides showed very few droplets smaller than 4 μm radius (the lower sizing threshold of the disrometer) in any of the size distributions used for these comparisons.

a. Total concentration

ADS reported comparisons between droplet concentrations obtained with a disdrometer and with impactor slides. There was considerable scatter in the data but neither instrument seemed to give consistently higher concentrations. This scatter was not unexpected since the sampling times vary from about 10 ms for the slides to 0.5 s for the disdrometer; in view of this the agreement was thought to be reasonable. However, if the ratio of droplet concentration measured by the disdrometer to that determined from the corresponding impactor slide is plotted as a function of mean radius determined from the slides, a trend is apparent (Fig. 1). For smaller mean radii the two methods show scatter but agree fairly well, but as the mean radius increases the disdrometer counts more and more relative to the slides until at about 10 μm mean radius the disdrometer is counting from 3–5 times as many as the slides.

Cannon (1975) has compared the concentrations obtained from the Cannon Particle Camera with those obtained from the disdrometer for a 3 min period on one day in NE Colorado. Both of these instruments have a lower detection limit of approximately 4 μm radius. The concentrations agree within the 20–25% error which Cannon has estimated for the camera. Before any general conclusions can be drawn about the agreement between the camera and the disdrometer, comparisons need to be made in many clouds with different droplet concentrations and sizes, and especially larger droplets. For the highly continental clouds found in NE Colorado (Dye *et al.*, 1974), the mean droplet radius found from slides is in the range 4–6 μm and, as we see in Fig. 1, there is little reason to expect significant disagreement between the two techniques in this size region.

b. Liquid water content

As pointed out by ADS, the liquid water contents calculated from the disdrometer data are generally lower than those measured by the J-W liquid water content meter and tend to be lower than those determined from the slides (see Fig. 13 and Table III in ADS). Combining the data from Table III in ADS with other data taken in Florida, we find that for $\frac{1}{2}$ s averages of the disdrometer and the J-W, the mean ratio of the disdrometer values to those of the J-W is 0.5, and the mean ratio of the disdrometer values to those of the slides is 0.7, with considerable variation in these values for individual comparisons. When the liquid water contents measured by the disdrometer

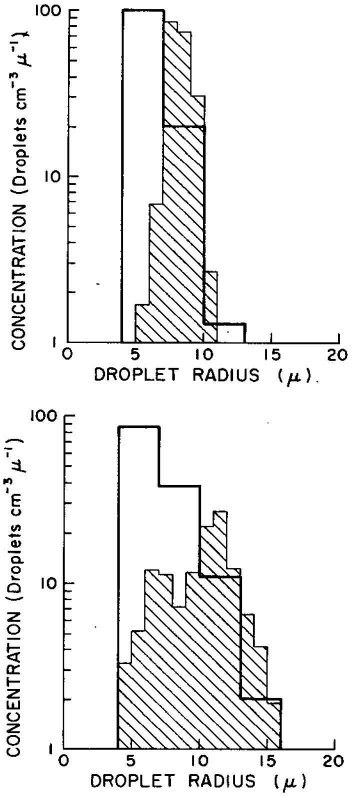

FIG. 2. A comparison of droplet size distributions measured by the electrostatic disdrometer (heavy lines) and soot-coated impactor slides (diagonally ruled areas): (a) 26 February 1971 at 1300 m MSL and a temperature of 16°C and (b) 27 February 1971 at 2500 m MSL and 8°C.

and the J-W are averaged over penetrations through a cloud, the mean ratio of the disdrometer to the J-W is 0.6 with a standard deviation of 0.1.

On rare occasions the disdrometer results were slightly higher than those from the J-W, but in these instances both the slides and the disdrometer measured droplets >15 μm radius. Other investigators have shown that the J-W underestimates the liquid water content when the droplet radii are in excess of 15–20 μm (Spyers-Duran, 1968; Knollenberg, 1972).

c. *Shape of the distribution*

Repeated measurements of droplet size distribution obtained from the disdrometer gave the first indication that the results were possibly less reliable than one might have hoped. The highest concentration for any distribution always appeared in the smallest size intervals. Two disdrometers, one with a 250 μm orifice diameter (presently in use) and one with a 400 μm orifice diameter, were tested side by side in Florida. The first of these operated properly most of the time but the output of the other was usually noisy owing to aircraft vibrations. On the rare occasions that both did work, the shape of the droplet distribution was the same from both.

This characteristic distribution was obtained even in some warm Florida clouds where the impactor slides often showed many fewer drops in the smallest interval (4–7 μm) than in the 7–10 μm interval. The comparisons in Figs. 2a and 2b illustrate this point well. When larger droplets were present the disdrometer almost always showed many more droplets for the smaller sizes than did the slides.

However, examination of comparative distributions such as in Figs. 2a and 2b and in Figs. 12a and 12b of ADS show that the disdrometer and slides do agree rather well concerning the range of the largest droplets and to a fair degree concerning the magnitude of the droplet concentration.

In order to compare many size distributions from both instruments, the mean radii from both sources were calculated for corresponding distributions. The results for 36 cases are plotted in Fig. 3, which clearly demonstrates the extent of the difference. A comparison of the median volume radius, a parameter which has somewhat more physical meaning than mean radius, shows a similar trend. There is reasonable agreement near 5–6 μm, but for the spectra containing many larger droplets the disdrometer data show a median volume radius of about 9 μm while the slide data indicate about 12 μm.

3. Discussion

In order to determine the source of these differences, we have examined the possible errors and uncertainties associated with each method.

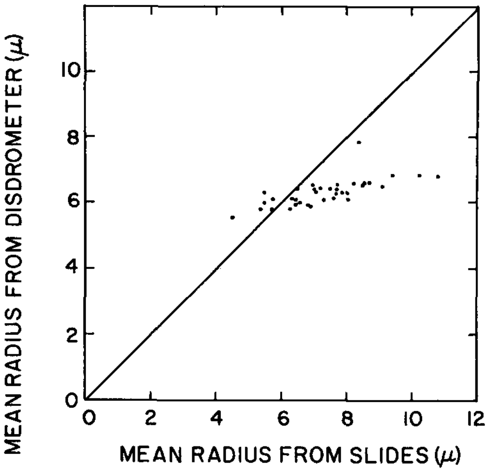

Fig. 3. The mean radius determined from the disdrometer versus the mean radius determined from impactor slides for 36 separate distributions measured in warm Florida clouds.

a. *Uncertainties with the impactor slides*

An accurate determination of the replication factor, the ratio of the size of the replicated droplet to the size of the actual droplet, is important in determining the droplet size distribution from impactor slides. The slides used in these comparisons were coated with soot using a technique similar to that described by Squires and Gillespie (1952). When Warner (1969) used this method he quoted errors of 5% for droplet radii >10 μm, increasing to 15% as the droplet radii decreased to 2.5 μm. Our measurements of droplet radii range from 4 to 15 μm. If we apply a 15% correction (the maximum indicated by Warner) to our measurements, we get a range from 3.4 to 12.8 μ with a negative correction and 4.7 to 17.6 μm using a positive one. Although these corrections do affect the number concentration in each interval as well as change the range, they do not significantly improve the agreement between the slide data and the disdrometer data. As mentioned before, there is relatively good agreement between the slides and the disdrometer as to the size of the largest droplets. Therefore, it is unlikely that the discrepancy in the mean radius can be attributed to large relative calibration errors with the two techniques. The difference is more probably accounted for by the partitioning of droplets into size intervals.

The collection efficiency of the slides is one of the factors that could influence the shape of the distribution. Differences exist between experimental collection efficiencies determined for ribbons by May and Clifford (1967) and Starr (1967) and those determined theoretically by Langmuir and Blodgett (1946) and by Briggs and Drake of NCAR (unpublished). In order to show that it is unlikely that the discrepancy between the disdrometer and slide spectra arises from uncertainty in the slide collection efficiency, we have replotted disdrometer data from Fig. 12b of ADS on a

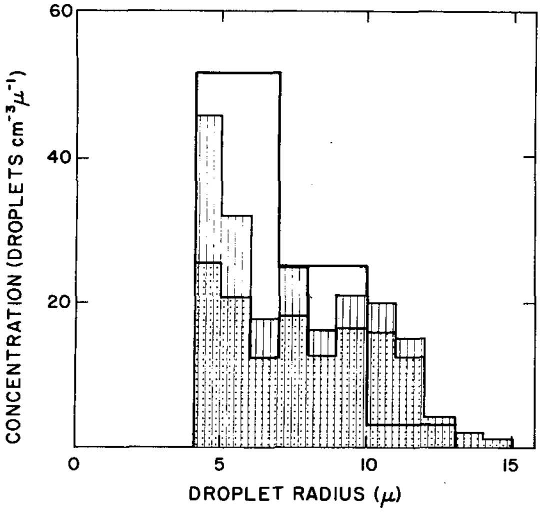

FIG. 4. A droplet size distribution measured by the disdrometer compared to the size distributions determined from soot-coated impactor slides using the experimental values of May and Clifford (1967) (vertically ruled area) or the unpublished values of Briggs and Drake (dotted area) for the collection of slides.

linear scale in Fig. 4 and have compared them with impactor slide data using both experimental and theoretical collection efficiencies. This particular case was one of those showing some of the best agreement between disdrometer and slide data. As the figure shows, the agreement between the disdrometer and the slides is best when the experimentally determined collection efficiencies are used, but the disdrometer still shows more droplets in the smallest size interval than do the slides, even for this "best" case. The collection efficiencies for the impaction device are probably somewhat different than those for a ribbon, but it is difficult to imagine an error in the collection efficiency of the slides that could account for the differences seen in Figs. 1–3.

Other factors may also affect measurements taken with the impactor slides: Errors in exposure time may change the number concentration and the angle of the slide "gun" to the airstream may affect its collection efficiency. The first of these will affect neither the shape of the spectrum nor the mean radius derived from it and the second should be insignificant since the slot into which the "gun" is inserted when fired is designed to prevent rotation. If droplet breakup on the slides is a problem, one would expect many smaller droplets to be produced, and the difference between the slides and the disdrometer would be even more pronounced.

b. Uncertainties with the disdrometer

The comparisons given in this paper and ADS use a collection efficiency of 1 for the disdrometer. However, new theoretical calculations [similar to those of Drake *et al.* (1972) but with improved spatial resolution] of the collection efficiency of the disdrometer for different droplet radii and aircraft speeds give collection efficiencies appreciably less than 1 for droplets in the three smallest size intervals of the disdrometer (Drake, private communication). Although the sense of the values (i.e., less than 1) seems reasonable when one considers that the 250 μm diameter orifice is 100 times smaller than the probe diameter, little confidence can be placed in the values until they have been experimentally verified. If the collection efficiencies are indeed less than 1, correction of the disdrometer data would increase the droplet concentrations, particularly in the smaller size intervals, thereby increasing the discrepancy between the disdrometer and the slides. Drake's values agree qualitatively with, but are closer to 1 than Lewis and Ruggieri's (1957) experimental determination of the local collection efficiency at the stagnation point of ellipsoids of revolution. A direct comparison cannot be made since Drake's calculations are for an ellipsoid which is aspirated at the stagnation point. However, Lewis and Ruggieri's results can serve as a guide to the lower limit for the collection efficiency of the disdrometer. Their work coupled with that of Drake suggests that the collection efficiency of the disdrometer is close to (but probably slightly less than) 1 for usual aircraft speeds. The collection efficiencies given for the disdrometer by ADS are in error in that they were calculated for a 1 mm radius probe orifice and not for the 125 μm radius orifice of the present model.

Since the laboratory calibration of the disdrometer has given reproducible results, it seems unlikely that calibration is the source of the discrepancy. In addition, independent work at NCAR by Glover and Grotewold and by Saunders and Stromberg at the University of Manchester (private communications) has verified the validity of the laboratory calibration.

Another possible source of error in the disdrometer data arises from the 20% variation in pulse amplitude for uniform sized drops (reported by ADS) which results in a 10% droplet sizing variation (see Fig. 7 in ADS). This variation will cause some drops to be counted in size intervals smaller than their actual size and others larger. Since the probability of being counted at a particular size is distributed on either side of the actual droplet size, the oversizing of smaller droplets will tend to balance the undersizing of larger droplets. But because the concentration is not constant for all sizes, the net effect will be to decrease the counts in those channels with high counts and increase the counts in those with lower counts. Correcting the data for this small error would increase the discrepancy between the disdrometer and the slides.

Laboratory tests were conducted to be certain that the disdrometer electronics was not the source of the problem. Similar tests had also been conducted prior to the ADS publication but were repeated in order to ensure that no changes had taken place. Among the possible problems investigated were amplifier bandwidth, dc level shift and overshoot of the amplifier at high counting rates and accuracy of the integrator and storage circuits of the pulse height analyzer. The tests did not show any electronic malfunctions which could account for the discrepancy.

The signal-to-noise ratio in the laboratory is about 6:1 for the 4 μm lower sizing limit but is somewhat lower on an aircraft because of vibration. However, any vibrational noise above the 4 μm threshold is immediately obvious because the disdrometer falsely indicates the presence of droplets out of cloud. Noise of this magnitude has been a problem. We were only partially successful in removing the difficulty in one of the two probes tested on the Queen Air. A disdrometer constructed at the University of Washington according to our specifications had similar difficulties with vibration. Even though the laboratory tests were impressive, the disdrometer was abandoned after considerable effort because of microphonic noise caused by aircraft vibration (Radke, private communication). However, this problem cannot be the source of the differences discussed here because only data with little or no noise were used in the comparisons.

Neither the uncertainties associated with the slides nor those associated with laboratory calibration or performance of the disdrometer electronics seem capable of explaining the observed differences between the disdrometer and impactor slides. Therefore, the only apparent remaining possibility is that the entry and breakup of the droplets in the probe are different during flight than in the carefully controlled laboratory environment. As pointed out by ADS, the process of droplet breakup, as well as the internal geometry of the orifice and electrode, were very important in obtaining uniform pulses in the laboratory. Furthermore, both Abbott and Grotewold found that it was necessary to place the dropmaker as close as possible to the orifice of the disdrometer so that the droplets entered with a minimum of wandering; otherwise, there was considerable variation in the pulse amplitude. Grotewold also observed that if droplets entered the disdrometer at an appreciable angle, water could be seen trickling off the back edge of the orifice. He surmised that this was caused by droplets striking the wall of the orifice.

4. Additional laboratory investigations

In order to investigate the entry and breakup of the droplets, the author set up a disdrometer with glass windows on the tip on a micropositioner that allowed adjustments in three directions. Uniform size droplets produced by a dropmaker similar to that described by Abbott and Cannon (1972) were then drawn into the disdrometer. In order to minimize droplet wandering due to room air motion, the end of the dropmaker and the disdrometer tip were placed inside a 2.5 cm diameter cardboard tube with only small viewing ports cut out. Microscopes above and to the side of the disdrometer allowed viewing of the droplets in both the vertical and horizontal plane as they entered the orifice and were also used to size the incoming drops. A variable time-delay strobe was used to "stop" the motion and show the trajectory of the entering droplets. With this arrangement, the entry of the droplets could be carefully controlled and viewed and the droplet fragments could be seen approaching and impacting on the electrode. The resulting voltage pulses could be displayed on an oscilloscope or recorded on a chart recorder. Droplets of 25 μm radius were used in all of the studies discussed below. No noticeable (<10%) evaporation occurred along the path (~1 mm) from the dropmaker to the disdrometer.

We found for the 250 μm diameter orifice at entry angles of about ±15°–20° that water began to appear on and dribble off the back edge of the orifice. Since the droplets were not striking the front of the disdrometer or the outer edge of the orifice, they must have been impacting on the inner wall of the orifice. At about this same angle the amplitude of the pulses became more erratic with greater and greater reduction in amplitude.

Studies conducted with a 400 μm diameter orifice showed about the same but, as expected, greater entry angles were required before malfunctioning appeared. Pulse amplitudes began to decrease at about 20°. When the entry angle was increased to 25°–30° there was as much as a 35% reduction in pulse amplitude. At about 40° the amplitude was reduced to about 50% and was highly erratic and water began to appear on the back edge of the orifice.

As the entry angle varies, the portion of the electrode which the fragments strike also varies. Fragments originating from droplets entering on the center line are distributed about the center of the electrode, while fragments from droplets entering at an angle are distributed more to the opposite side. Droplets entering the 400 μm diameter orifice at angles of 25°–30° sometimes produced fragments which were noticeably larger than fragments produced from droplets entering at 0° entry angles, and some of the fragments appeared to be missing the electrode.

The entry position of the droplet relative to the center of the orifice also made a difference in pulse amplitude; the largest and most uniform pulses were generated from droplets entering close and almost parallel to the orifice axis. This is not surprising since sharp radial gradients in velocity must exist inside the orifice. Droplets passing through the orifice close to the wall should experience less acceleration and therefore should be broken up less than droplets passing through the center of the orifice.

From these observations, there can be little doubt that pulse amplitudes can vary with varying entry angles and positions. But at what angle and position

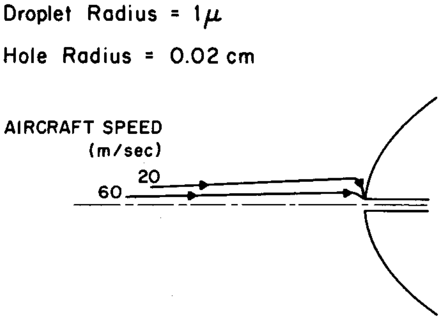

FIG. 5. Calculated trajectories of droplets entering the orifice of the electrostatic disdrometer.

do the droplets enter during flight? Trajectories calculated by Drake (private communication) show droplets entering the probe at angles >30° and also at points close to the wall of the orifice. An example of this is shown in Fig. 5 for the limiting trajectory for collection of 1 μm radius droplets entering at 20 and 60 m s^{-1}. The droplet entering at 20 m s^{-1} started at a position Z_0/R_0 of 1.25, where Z_0 is the distance from the horizontal axis of symmetry of the orifice and R_0 the radius of the orifice. Thus, droplets of this size at this velocity would have a collection efficiency >1. The trajectories for both droplets were started 55 cm ahead of the probe tip. There will be less deflection for larger droplets but the same tendency will certainly exist. Note in Fig. 5 that droplets begin to be deflected away from the probe before they are influenced by the air being drawn through the orifice, and are then drawn into the orifice at appreciable angles. This increases the probability that they will collide with the wall or enter the orifice off center. The latter problem is particularly true for large droplets with more inertia. There is also an increased probability of collision with the outer edge of the orifice for the larger droplets.

5. Conclusions

The above results need to be verified experimentally, but if this does happen in flight it could explain the observed difference between the measurements made by the disdrometer and impactor slides. Some droplets would be sized properly, correctly indicating that the disdrometer saw droplets of this size; but others would not enter along the center of the orifice and would be undersized, thereby shifting much of the distribution to smaller sizes. This would be consistent with the minimal change in droplet radius that the disdrometer shows when compared to slides, and with the lower values of liquid water content compared to the J-W meter. Some droplets might also strike the wall of the orifice. In so doing, more fragments might be produced and water could also collect on the inner edge of the orifice and dribble off to the electrode at times unrelated to the original droplet. These collisions with the wall might explain the comparatively higher droplet concentrations measured by the disdrometer when larger droplets are present.

While the above explanations are clearly speculative and need to be supported by detailed observations made at aircraft speeds, they are not unreasonable in view of the laboratory experiments that have already been conducted.

In order for cloud droplets to be sized with the present electrostatic disdrometer the droplets must be broken up prior to impaction on the electrode; otherwise the pulse amplitude is insufficient to be detectable above noise. If the disdrometer is to work properly in the cloud droplet size range, droplets must be drawn into the orifice so that droplets of the same size are broken up similarly. Both Abbott and Grotewold extensively tested disdrometers with different orifice shapes and orifice-to-electrode geometries including tapered orifices. The one which is presently used gave the greatest uniformity in pulse amplitudes. It may be possible to design an orifice that can break up droplets more uniformly at varying entry angles, but it is not a straightforward task.

An alternate approach would be to design the disdrometer so that the airflow into the orifice is isokinetic but is accelerated further back in the orifice. This would minimize the curvature of the droplet trajectories as they enter the orifice, thereby increasing the likelihood that they will be sized properly, but would still produce the necessary breakup. We plan to make a laboratory prototype (shown in Fig. 6) which will have pressurized air entering the last half of the wall of the orifice through

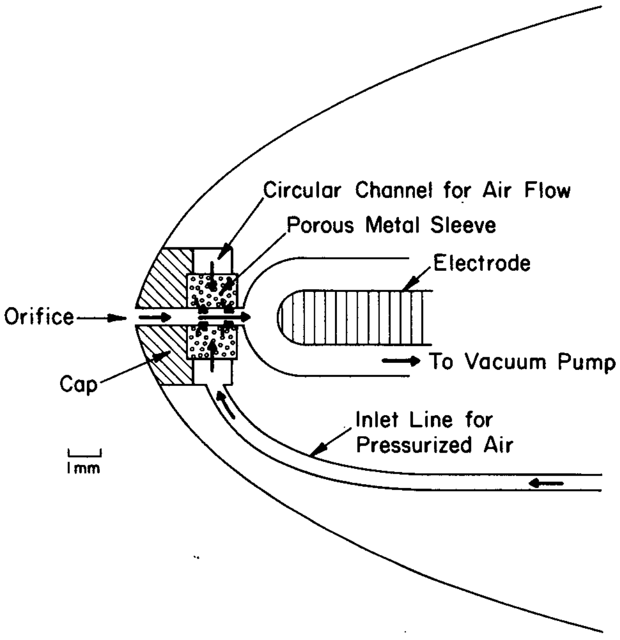

FIG. 6. Schematic showing the proposed modification to the disdrometer orifice which would give isokinetic sampling at the orifice entry.

a porous metal sleeve. By adjusting the flow through the porous sleeve, we can adjust the flow through the orifice entrance. The air entering the porous sleeve should also act as a cushion to inhibit the impaction of droplets on the walls. The results from these tests will be reported at a later date.

The entry difficulty discussed above may not be a problem for an electrostatic disdrometer based on the same principle but designed for use in the larger size ranges. Drops $\gtrsim 50$ μm radius generate pulses of sufficient magnitude to be above noise without needing to be broken up before impacting on the electrode.

The present cloud electrostatic disdrometer, if its measurements are used with some discretion, can provide information on the magnitude of the droplet concentration, the size range of cloud droplets, and with some correction, the liquid water content. However, the shape of the droplet size distribution derived from the disdrometer should not be trusted.

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