An assessment of the Keily probe for the ground-based measurement of drop size distributions in clouds

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SUMMARY

A series of experiments has been performed to calibrate and assess the reliability of the Keily probe for ground-based measurements of droplet size distributions in cloud. Tests were conducted in natural and artificially produced water clouds at our field research station on Great Dun Fell, and in a specially constructed cloud tunnel. Comparisons were made with drop size distributions measured with a Knollenberg ASSP device and with MgO coated slides. Collection efficiencies were obtained for the Keily probe for various values of ventilation speed and orifice size. It was concluded that the instrument operated consistently and reliably within the range of conditions applicable to our ground-based field research.

1. INTRODUCTION

The Atmospheric Physics Research Group at UMIST has a field research station on the summit of Great Dun Fell (GDF, 850 m a.s.l) in Cumbria. This site possesses the advantage, from the viewpoint of cloud physics research, that it is enveloped in cloud for parts of about 250 days per annum. A measurement crucial to the studies of cloud droplet evolution being conducted at GDF (Corbin et al. 1977) is that of droplet size distribution within clouds. This paper describes a series of tests and calibration experiments designed to establish the applicability to research at this site of the electrostatic drop disdrometer (Keily probe) invented by Keily and Millen (1960) and improved by Abbott, Dye and Sartor (1972).

There were several motivations for pursuing research on the Keily probe. In this device cloudy air is drawn at near sonic speeds down a narrow orifice. Each drop in this airstream is atomized during its passage through the orifice, to produce a closely separated assemblage of droplets which provides a single electrical pulse - related in a known manner to the total liquid volume - as it collides with a charged electrode. The pulses are then sorted and processed electronically. The air is abstracted from a stream which is ventilating the aerodynamically shaped nose of the device with a speed \( V \). Because of inertial effects smaller drops are more readily sucked into the hole than larger ones. Thus it is necessary to determine the collection efficiency, \( E \), of the device. \( E \) depends on both drop size and ventilation speed, and no values of \( E \) are available for the combination of speeds and sizes employed at GDF. Secondly, and perhaps more importantly, the favourable assessment of this device by Abbott et al. has recently been challenged by Dye (1976), who performed airborne tests in which size spectra within a cloud were determined simultaneously by the Keily probe and the tedious but reliable sooted slide technique. The agreement between the pairs of spectra so obtained was poor. Thus the validity of the device was placed in doubt, and a series of tests designed to establish its applicability to ground-based research was required.

2. TESTS AND CALIBRATION EXPERIMENTS

Tests on the Keily probe were conducted both at GDF and in our laboratories in Manchester. In the former case droplet size distributions were obtained simultaneously
Figure 1. Size distributions measured (in a cloud produced with an ultrasonic atomizer) by A, the Keily probe, and B the Meteorological Office's Knollenberg ASSP device. The Keily probe spectrum is uncorrected. The ordinate is in arbitrary units. $V = 20 \text{ms}^{-1}; D = 440 \mu\text{m}$.

with both the probe and the Knollenberg Axially Scattering Spectrometer probe (ASSP) belonging to the Meteorological Office. This was done both in natural cloud enveloping the field research station and in a cloud produced artificially by means of an ultrasonic atomizer. In both cases the probe was ventilated artificially at a measured speed. An example of spectra obtained with these two devices in one of the latter runs is presented in Fig. 1. In this test the Keily probe was placed on the axis towards the front of a tube, of diameter 0.15 m, through which cloud was drawn at a constant ventilation speed of $20 \text{ms}^{-1}$. This particular probe possessed an orifice diameter, $D$, of 440 $\mu\text{m}$. In other experiments different values of $D$ were used but all the Keily probes were built (in their essential features) to the specifications of Abbott et al., supplied by these scientists. The two spectra presented in Fig. 1 have very different shapes, because no account has been taken of the variation of $E$ with $r$ for the Keily probe. It is reassuring, however, that the two techniques give similar values for the size of the largest drops in the spectrum. This was consistently found to be the case, in both natural and artificial clouds.

Figure 2. Schematic diagram of the cloud tunnel used in tests on the Keily probe and the hot-wire device.
A comprehensive series of tests of the Keily probe were conducted, in Manchester, in a horizontal cloud tunnel specially designed for this purpose. It is illustrated in Fig. 2, and was used to provide a cloud of drops of controlled size distribution and water content, \( L \), which could be drawn past the Keily probe at a predetermined speed \( V \).

An electrical fan blew laboratory air through a parallel vane humidifier into a chamber, into which drops were fed from a spinning top generator (May 1950). In this section the horizontal air speed was sufficiently slow for the drops to become well mixed into the airstream. The stream then passed into a venturi section where it was accelerated to the velocities required for the tests. The ventilation speed could be varied from 6 to 25 m s\(^{-1}\). The figure shows the customary location, within this test section, of the Keily probe. In addition, drop samples could be taken, in this region, by means of cylinders coated with magnesium oxide; the associated collection efficiencies have been determined by Langmuir and Blodgett (1946), and the relationship between the size of the drop to that of its impression in the MgO coating has been established by May (1949). The liquid water content was measured by means of an impaction device specially constructed to fit into the test section. Cloudy air from the test section was sampled isokinetically across its diameter, accelerated in a nozzle to achieve unit collection efficiency for all drop sizes of interest, and impacted upon a small cylinder of absorbent filter paper, which was weighed before and after sampling. The volume of air sampled was measured using a flowmeter, and thus values of \( L \) could be determined after corrections had been made for evaporative losses and the non-uniformity of drop concentration within the test section. It was found that the humidification system was very efficient. The maximum liquid water content that could be produced decreased with increasing wind speed. At 6 m s\(^{-1}\) it was 0.8 g m\(^{-3}\).

The time required to produce an acceptable Keily probe histogram was generally between 10 and 60 seconds. Tests showed that the cloud properties could be maintained constant over periods of about 10 or 20 minutes, so it was possible to conduct a variety of experiments on the same cloud. The performance of the Keily probe was examined at

![Figure 3. Size distributions measured in a typical cloud tunnel experiment with A, the Keily probe, and B, MgO-coated slides. The Keily probe spectrum is uncorrected. \( V = 20 \text{ m s}^{-1}; D = 220 \mu\text{m} \).](image-url)
ventilation speeds varying from 6 to 20 m s\(^{-1}\), for orifice diameters of 220 and 440 \(\mu m\). In addition, some experiments were conducted to determine the sensitivity of the device to the 'angle of attack', the angle between the axis of the cloud chamber and that of the Keily probe. Tests showed that in order to achieve optimum reliability of the device, the probe tip had to be carefully aligned with the axis of the orifice.

Two series of tests confirmed the validity of the relationship between droplet size and pulse height, \(h\), presented by Abbott \textit{et al}. \(h\) increases approximately as the cube of the droplet radius.

Fig. 3 shows the results of a typical experiment, in which spectra were obtained with the Keily probe and with the MgO slide technique. The MgO slide spectrum has been corrected for collection efficiency variations with drop radius, but the raw data have been used to produce the Keily probe spectrum. As was the case with the Keily probe/Knollenberg comparison, illustrated in Fig. 1, the two spectra were very different but the higher cut-off threshold was identical.

![Graph showing Keily probe spectra](image)

**Figure 4.** Uncorrected Keily probe spectra obtained in a cloud tunnel experiment with probes of different orifice diameter \(D\). A, \(D = 440 \mu m\); B, \(D = 220 \mu m\). \(V = 20\) m s\(^{-1}\).

Fig. 4 presents raw spectra obtained for the same cloud with two Keily probes of different orifice diameter. The size of the largest drops detected was more or less the same for both values of \(D\) but the larger orifice is clearly much more efficient in sampling the larger drops. Presumably this is because the probability of collision with the walls of the wider orifice is less than that for the narrower one.

The influence of ventilation speed \(V\) on the spectra recorded by the Keily probe is illustrated in Table 1. Results are presented for three experiments; one, A, conducted in the cloud tunnel, and the others in natural cloud at Great Dun Fell. In the cloud tunnel study the orifice diameter was 220 \(\mu m\), whilst it was twice this value in the field experiments. The value of \(D\) has an appreciable effect on the variation of the spectra with \(V\). For the larger orifice diameter we see that the spectral changes as \(V\) is reduced are in agreement with the basic theory of the device – as the speed decreases more drops are pulled in from outside the projected capture area. Because of inertial effects some of these drops of all
TABLE 1. The influence of ventilation speed $V$ on measured (uncorrected) Keily probe spectra. Results are presented for three experiments: A, in the cloud tunnel; B and C, in natural cloud at Great Dun Fell. The uncorrected spectra at 20 m s$^{-1}$ are shown in the lower part of the table. In the upper part the droplet numbers at lower velocities are shown for each channel; they are expressed as percentages of the number measured, in each channel, at 20 m s$^{-1}$.

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sizes do not enter the Keily probe, but the efficiency of collection of the smaller ones is greater than that of the larger ones. However, this finding was not confirmed in the laboratory tests with the smaller orifice diameter. Here, the proportion of larger drops increases with decreasing ventilation speed. Possibly this is because the dominant effect (Dye 1976) is that at the higher speeds some of the larger drops are broken up into two or more fragments on entering the Keily probe (prior to their atomization). If these were separated temporally by more than about 50 μs only the first fragment colliding with the probe would be counted and sized – thus providing a true drop count, but an underestimate of the size of those drops which are fragmented. This would happen because the pulse-sorting electronics were arranged so that there is a ‘dead-time’ of about 0.5 ms following each pulse – during which period no signals are accepted. Further support for the idea that some drops fragment on entering the Keily probe was provided by a series of cloud tunnel tests employing narrow spectra of drops of diameters around 30 μm. The disdrometer recorded substantial numbers of apparently much smaller drops.

Fig. 5 presents the results of a series of tests, conducted within the cloud tunnel, to

![Figure 5](image_url)

**Figure 5.** Corrected Keily probe spectra for various angles of attack, $\theta$. Cloud tunnel experiment. B, $\theta = 0^\circ$; C, $\theta = 10^\circ$; D, $\theta = 20^\circ$. A is the corrected MgO slide spectrum. $V = 20$ m s$^{-1}$, $D = 220$ μm.
examine the influence of the 'angle of attack', \( \theta \), upon the Keily probe spectra. It is reassuring to find that they are not significantly influenced by likely values of possible misorientation of the probe in the air stream, which were estimated to be not greater than 10°.

3. COLLECTION EFFICIENCIES AND SENSITIVITIES

The absolute collection efficiency, \( E_a \), of the Keily probe for drops of a chosen radius is defined, for our purposes, as the ratio of the number of such drops sampled by the device in unit time to the number contained in a volume \( \pi D^2 V/4 \) of the cloud, which equals the volume of the projected cylinder of length \( V \) and diameter \( D \) equal to that of the orifice. The value of \( E_a \) will depend upon the ventilation speed \( V \), the orifice diameter \( D \) and the drop radius \( r \). Values of \( E_a \) were obtained by comparing, for each class, the numbers counted by the Keily probe and those measured, in the same cloud, by an established, calibrated technique.

In the tests at Great Dun Fell the Meteorological Office's Knollenberg (ASSP) device was used to provide the absolute calibration. In the cloud tunnel tests magnesium oxide coated slides, in conjunction with the liquid water content impactor, were employed. In some of the cloud tunnel experiments the impactor was not used and, in these cases, since the total liquid water content was unknown, comparison of the Keily probe spectra with those determined from the MgO slides gave values of the relative collection efficiencies of the probe.

Fig. 6 presents two experimentally determined curves illustrating the variation of absolute collection efficiency with drop radius for a ventilation speed of 20 m s\(^{-1}\). Despite the considerable scatter in the individual values of \( E_a \) (shown only in curve A) the rapid

![Figure 6](image)

**Figure 6.** The variation of absolute collection efficiency \( E_a \) with drop radius \( r \) for the Keily probe. \( V = 20 \text{ m s}^{-1} \). A, cloud tunnel experiment with MgO slides. \( D = 220 \mu \text{m} \). B, Great Dun Fell experiment with Knollenberg ASSP device. \( D = 440 \mu \text{m} \).
increase with decreasing drop size is well established. This is clearly a consequence of the greater ease with which the smaller drops can be drawn into the orifice from outside the projected cylinder. Curves A and B are seen to be in reasonable agreement for the smaller drop sizes, but for radii in excess of about 8 µm the values of \( E_a \) for curve A (orifice diameter 220 µm) fall towards a lower limit of about 0.25, whereas those for curve B \( (D = 440 \mu m) \) tend towards unity. We suspect that this difference between the two experimental curves is primarily a consequence of the tendency – described in the preceding section – for larger drops sampled at higher ventilation speeds to collide with the interior wall of the orifice and fragment.

4. Discussion

The various tests described in the preceding sections have indicated that – within the range of conditions investigated – the Keily probe is a reliable instrument for the ground-based measurement of drop size distributions in fogs and clouds. Comparisons with other, established, devices have shown that it correctly defines the bounds of a given spectrum, and thus it has been possible to obtain absolute collection efficiency curves. Particular advantages of the Keily probe are that it is small and inexpensive and that it performs the sizing automatically, at a high rate. Also, it is rugged and reliable; it has operated continuously in warm or supercooled clouds at GDF for many hours without requiring attention. However, although we conclude that the device is suitable for studies of clouds at the ground the tests conducted by Dye (1976) \( (V \sim 70 \text{ m s}^{-1}, D = 250 \mu m) \) indicate that it is unacceptable for airborne use, at much higher ventilation speeds. Presumably this is because of substantial drop-fragmentation at high speeds, especially with the small value of the orifice diameter.

It was shown in Fig. 4 that the two uncorrected Keily probe spectra – obtained for two values of orifice diameter – agreed with each other, and with the magnesium oxide coated slides, in defining the size of the largest drops present. Thus, in principle, it does not matter which value of \( D \) is chosen for the instrument, since it is possible – in either case – to obtain collection efficiency curves and so correct the raw data and produce a representative size distribution. However, there are substantial advantages to the larger orifice. It is more efficient in sampling larger drops, which are almost always less plentiful. A limitation on the extent to which high resolution of temporal or spatial variations in drop size distributions in clouds can be achieved has been the problem of sampling sufficient numbers of the larger particles to construct a statistically meaningful spectrum. Also, the sampling rate for drops of all sizes increases with increasing orifice size.

Drop fragmentation, although an undesirable feature of the performance of the Keily probe, does not provide a major impediment to its use. The primary reason for this is that it is allowed for in determining the collection efficiency curves experimentally. In addition (for our purposes at least, where we are interested in studying clouds at the ground) fragmentation is significant only for the largest droplets at the highest ventilation speeds of interest (in the region of 20 m s\(^{-1}\)). The efficacy of the ‘dead-time’ system incorporated into the electronics was tested by performing a statistical analysis of the time intervals between consecutive pulses over a long period. These experiments were performed in the cloud tunnel. It was found that the distribution of time intervals was consistent with that expected from a randomly distributed collection of particles. There was no evidence for double or higher multiple pulses. Thus we conclude that if a larger drop is fragmented on entry into the device it is counted just once, as a smaller one. As mentioned earlier, this effect is incorporated into the measured collection efficiencies – though we cannot see how it could be covered in a theoretical treatment of this problem.
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