The opacity of accreted ice

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SUMMARY

A technique which yields quantitative measurements of the opacity of accreted ice deposits is described. This consists of determining the attenuation of a light beam as it passes through a thin section of the deposit, using a photovoltaic cell as the detector. The transmittance of the deposits is related to the air bubble concentration, and the technique provides a useful supplementary method for analysing the air bubble structures of hailstones.

1. INTRODUCTION

The factors which determine the concentrations and size distributions of air bubbles in accreted ice have been discussed by Carras and Macklin (1975, hereinafter termed ref. 1). It is the bubbles which determine the opacity of accreted ice deposits.

A number of authors have used various visual classifications to describe this opacity. These are essentially slightly different versions of a scheme proposed by Clark (1948), namely: clear ice (virtually no air entrapped); transparent ice (moderate amounts of air entrapped as fairly large bubbles); milky ice (considerable amounts of air entrapped as small bubbles); and opaque rime. The difference between milky ice and opaque rime is that the former has a shiny glazed appearance which the latter lacks. The reason for this has been given by Macklin (1962).

Although convenient such classifications are necessarily subjective. In this paper we describe a simple technique which gives a quantitative measure of the opacity.

2. EXPERIMENTAL

The technique involves the measurement of the attenuation of a light beam as it passes through a section of ice of known thickness. The device used to do this is shown schematically in Fig. 1. The detector is a Mullard BPY 10 silicon photovoltaic cell and the light source is a normal microscope lamp set to give a parallel beam. In order to resolve variations in opacity within an ice section, it is necessary to use a narrow beam of light. Rather than reducing the width of the incident beam, it was found more convenient to encapsulate the cell and to reduce the width of the emergent beam before it reaches the cell surface. This was done by mounting a hypodermic needle, cut to a length of about 0.5cm, in front of the cell. The output from the cell was amplified and fed to a chart recorder. Since the purpose of the instrument is ultimately to analyse hailstones, the attachment on which the ice section is held is located on a screw thread. This is rotated by a synchronous motor so that the section moves past the detector at a rate of 0.1mm s⁻¹. The resolution of the instrument can be varied by using needles of different bores. Using a 27 gauge needle it is possible to measure variations of opacity over distances as small as ~300μm. This was ascertained by passing wires of known diameters through the light beam.

The samples of accreted ice on which the present measurements were made were the cylindrical ice deposits described in ref. 1. In addition, measurements were made on some
artificial hailstones 5 to 6 cm in diameter grown freely suspended in the icing tunnel used (see Bailey and Macklin 1968a). In the former experiments the temperature at which the deposits were grown was determined by direct measurements, while in the latter the temperature was calculated from the heat transfer measurements of Bailey and Macklin (1968b). Spongy ice deposits were allowed to freeze solid in the air stream after the droplet sprays had been turned off. This meant that the rate of heat transfer during complete freezing was approximately the same as that during growth.

Sections of the deposits were made in the manner previously described. A number of preliminary measurements were made using sections of different thickness. The optimum thickness was found to be 1.0 mm as this gave the best range of measured attenuations. The intensity of the incident beam $I_0$ was measured after the beam had passed through the glass plate on which the section was mounted and through a thin layer of diethyl phthalate used to adhere the section to the plate. The diminished intensity of the emergent beam $I$ was then due only to attenuation by the ice section. The accuracy of the technique was checked using neutral density photographic filters. The accuracy ranged from ±1 to ±5% as $I/I_0$ decreased from 1 to 0.2; for values between 0.2 and 0.1 the error increased to ±15%.

3. RESULTS AND DISCUSSION

In Fig. 2 values of the transmittance are displayed as a function of the deposit temperature in the dry growth regime, and of the fraction of liquid water in the deposit in the wet growth regime. These data are for ice deposits formed on the rotating cylinder at an air speed of 33 m s$^{-1}$ with a droplet size distribution having a median volume radius of 15 μm (maximum droplet radius 33 μm). The curves shown are the most self-consistent set that can be drawn through the data. The results for the artificial hailstones have essentially the same form. The curves in Fig. 2 reflect the way in which the air bubble concentration depends on the ambient (i.e. droplet) and deposit temperatures (ref. 1, Fig. 7).

Previously the cylinder samples were classified as clear, transparent or opaque (ref. 1, Fig. 13). This had been done before the transmittance values were determined. Comparison with the present data in Fig. 2 shows that, in the dry growth regime, the boundary between clear and opaque ice occurs at a transmittance of about 0.6, while the boundary between transparent and opaque ice corresponds to a transmittance of 0.4 to 0.5. In the wet growth regime the boundaries between the different classes of ice are somewhat broader.
Figure 2. Values of the transmittance $I/I_0$ for cylindrical deposits as a function of the deposit temperature in the dry growth regime, and of the fraction of liquid water in the deposit in the wet growth regime for various ambient temperatures, $T_d(°C)$.

In Fig. 3 the transmittance is plotted against the air bubble concentration given in ref. 1. The points shown in the diagram are for the cylindrical deposits formed at 33$m$ s$^{-1}$ with the droplet distribution having a median volume radius of 15$\mu$m. Included also are data for cylindrical deposits formed at 15$m$ s$^{-1}$ (marked C), and the data for the artificial hailstones (marked H). The values of the transmittance vary systematically with bubble concentration in both growth regimes. There is somewhat less scatter in the dry growth regime. This is because the mean bubble size, which also affects the opacity, does not vary as much in the dry as in the wet growth regime. An attempt was made to relate the transmittance to the geometrically occluded area $\Sigma nr^2$, where $n$ is the bubble concentration and $r$ the bubble radius, but no simple relation could be found. The probable reason for this is that the opacity is due to multiple scattering from the bubbles.

Figure 3. The transmittance $I/I_0$ as a function of air bubble concentration in accreted ice samples for both wet and dry growth regimes for various ambient temperatures, $T_d(°C)$.

Fig. 3 shows that there is a sharp discontinuity in the transmittance at the wet growth limit. The reason for this is that at temperatures near 0 $°C$ in the dry growth regime the
droplets spread into thin layers before freezing so that the dissolved air escapes by diffusion. However, as soon as the deposit enters the wet growth regime, the manner of freezing becomes more like that of bulk water. The bubble size increases sharply and consequently the transmittance falls. It should be noted also that the discontinuity causes the transmittance to be double-valued, i.e., values of the transmittance greater than about 0.3 can indicate either wet or dry growth. However, the two regimes are readily distinguished simply by ascertaining the bubble size.

The present technique provides a rapid method of determining the concentration of air bubbles in accreted ice. It could well prove a useful supplementary method for analysing the air bubble structure of hailstones.

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REFERENCES


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