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SHORT CONTRIBUTION

Settling velocities of small ice crystals

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ABSTRACT

Settling velocities, masses and external dimensions were determined experimentally for small freely falling ice crystals grown for about 100 s at 12 different temperatures within the range −3.4 to −20 °C. The corresponding terminal velocities were calculated using the above measurements, together with the empirical Be–Re relationships, deduced from previous model experiments. Reasonably good agreement was found between theory and experiment.

SYMBOLS

V	calculated terminal velocity
V_m	measured settling velocity
V_f	flatwise t.v.
V_e	edgewise t.v.
ν	kinematic viscosity of air
$\mathrm{Re} = d \cdot V/\nu$	Reynolds number
C_D	drag coefficient
$\mathrm{Be} = C_D \,\mathrm{Re}^2$	Best number
$c = \bar{L}$	average length of columnar and thickness of plate-like ice crystals
$2a = \bar{d}$	average diameter of length of a-axis for plate-like and columnar ice crystals
ρ	density of air
g	gravitational acceleration
$\bar{m}$	average mass of the ice crystal sample

1. Introduction

Knowledge of the settling velocities of solid hydrometeors is of obvious importance to cloud physics. Fukuta (1969) measured the settling velocities of small ice crystals in the temperature range −3.2 to −20.4 °C. Further experimental determinations of settling velocities of small ice crystals were conducted by Jayaweera & Ryan (1972) and Kajikawa (1973), with crystals grown at temperatures of −7 to −8.5 °C and −14 to −16 °C respectively. These two experiments were also supplemented with terminal velocity calculations, based on Be–Re relationships deduced from model experiments by Jayaweera & Cottis (1969), List & Schemenauer (1971) and Kajikawa (1971).

Further experiments by Jayaweera (1972) indicated that the terminal velocities of hexagonal plate-like crystals are almost identical to those of circular discs having the same mass and external diameter, while star-shaped crystals show a 25% decrease.

We present here measurements of settling velocities of small ice crystals, $d \leq 80$ μm, of various types, at 12 different temperatures within the range −3.4 to −20°C. They were grown for 100 ± 10 s and were then sampled, measured (to deduce their external dimensions) and subsequently melted to calculate the average mass. This set of experiments was supplemented by calculating their terminal velocities, using the empirical Be–Re relationships found by Kajikawa (1971) for cylinders and discs.

2. Experimental

The experiment was conducted using a cloud chamber described in detail by Michaeli (1975). It consisted of a vertical brass tube, 80 mm in internal diameter with a height of 200 cm. It was cooled continuously by circulating a cooled 50% aqueous glycol solution in copper tubing wound around its external wall. The temperature at the lower end of the cloud chamber, which served as its observation section, was always kept 0.5 to 1 °C colder than the ambient temperature in the rest of the chamber. This procedure was necessary to subdue thermal convection within the observation section.

The upper part of the observation section consisted of an akulon (nylon) dish, 30 mm deep and about 77 mm in diameter, tightly fitted into the cloud chamber. It had a circular opening 14 mm in diameter covered by a shutter through which the falling ice crystals entered into the observation section. This procedure prevented most of the disturbing "wall effects" as all measurements were confined to crystals falling mainly along the central axis of the cylindric cloud chamber.

The settling velocities of the ice crystals were calculated from streak photographs taken through a double-glazed window as they fell through the heat-filtered collimated beam of a 6-V microscope lamp. This beam was chopped at a constant frequency of 20 Hz by an electronically stabilized chopper (Ithaco, model 382). A Nikon F reflex camera was used, equipped with a micro-Nikkor auto 55 mm f/3.5 lens, and placed in a position perpendicular to the illuminating system. At a time interval of 90–100 s, with the chopper operating, photographs were taken at a shutter speed of 1 s, so that the falling ice crystals were recorded as chopped streaks of light.

The distances on the photograph were calibrated by photographing a ruler introduced into the il-

Table 1. *Measured $\bar{m}$, $\bar{d}/L$ and V_m values and calculated B_e and V values of small freely falling ice crystals, grown for 100 ± 10 s at 12 temperatures in the range −3.4 to −20.0° C*

$-T$ (° C)	Crystal type code*	$\bar{m}$ ±15% (ng)	$\bar{d}$ (μm)	$\bar{d}/\bar{L}$	B_e	V ± 20% (cm s^{-1}) V_f	V_e	V_m ± 15% (cm s^{-1}) Low‡	High‡
3.4	P1a	15	50	1.5	2.2	2.5	3.3	1.2 (0.3)	1.6 (0.7)
5.6	N1a	55	14	0.2	1.1	2.0	2.7§	2.1	—
7.0	N1e	25	16	0.5	1.2	2.0	2.3§	2.0	—
8.5	C1f	25	15	0,6	1.3	3.0	3.0§	2.1	—
10.0	C1g	15	15	0.45	0.6	1.4	2.6§	1.8 (0.7)	1.8 (0.3)
11.5	P1a	20	70	3.5	3.0	1.8	4.3	1.7	—
13.1	P2e	22	80	4.0†	2.9	1.7	4.2	1.6	—
13.6	P1c	23	70	4.2†	3.0	1.9	4.7	2.0 (0.5)	2.7
15.0	1P1d	25	110	4.4†	3.2	2.2	3.0	1.8 (0.6)	2.9 (0.4)
16.5	P1a	65	100	4.1†	10.7	2.5	5.6	1.8 (0.6)	2.2 (0.4)
18.2	P1b	55	100	3.3†	8.0	1.8	6.4	1.5	—
20.0	P1a	20	90	7.5	2.9	1.3	5.5	1.4 (0.8)	2.8 (0.2)

* According to Magono & Lee (1966).

† Calculated from the measured $\bar{d}$ values using the corresponding empirical dimensionsal relationships of Auer & Veal (1970).

‡ The corresponding fractional weights of the V_m values are in brackets.

§ Roundwise falling velocity of cylinders calculated using Fig. 10, Kajikawa (1971).

luminated observation section of the chamber through the same optical system used for recording the falling ice crystals.

The crystals were collected on glass slides coated with viscous silicone oil (DC200/1000) positioned 7.5 cm below the illuminating beam's path. They were photographed and then melted to determine their mass, as described in detail by Michaeli (1975).

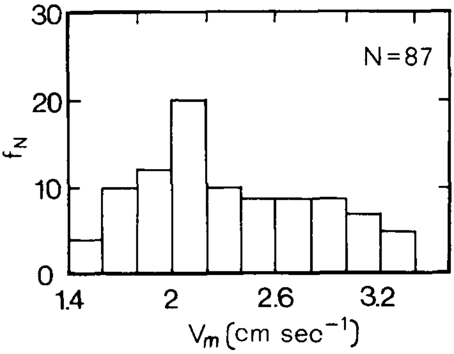

Fig. 1. Frequency distribution curve of V_m values of 87 ice crystals, at −13.6 °C.

3. Results

The sampled ice crystals were divided into two categories: plate-like and columnar, the terminal velocities of which were calculated by the following procedure:

(a) The Be numbers were calculated using the ice crystals' average mass, external dimensions and $2a/c$ ratio. The Be for columns is given by:

$$\mathrm{Be} = C_D \mathrm{Re}^2 = \frac{2\bar{m}g}{v^2\rho} \frac{d}{L} \tag{1}$$

while for the plate-likes Be is given by:

$$\mathrm{Be} = C_D \mathrm{Re}^2 = \frac{16}{3\sqrt{3}} \frac{\bar{m}g}{v^2\rho} \tag{2}$$

(b) From the empirical Be–Re relationships found for cylinders and discs, at various $\overline{d/L}$ ratios, as described by Kajikawa (1971, Figs. 10, 15), we deduced the Re numbers which correspond to the terminal velocities of the falling ice crystals, given by:

$$V = \nu \mathrm{Re}/d \tag{3}$$

Both V_e and V_f were calculated from eqn. (3) using Kajikawa's data, and are presented in Table 1.

At several temperatures the measured settling velocities produce a bimodal frequency distribution curve, as illustrated in Fig. 1. The V_m values calculated from these curves are presented in Table 1 together with their respective fractional weights in brackets.

4. Discussion and conclusions

The significant scatter in most of the V_m values, evident from Table 1 and illustrated in Fig. 1, is primarily due to:

(1) The unhomogeneous character of the measured ice crystals in terms of their mass and crystalline forms.

(2) The inherent complex motion exhibited by freely falling non-spherical bodies in a viscous medium, discussed in detail by Happel & Brenner (1973).

Good agreement between the calculated flatwise terminal fall velocities and the corresponding measured settling velocities was found for most temperatures. This suggests that nearly all the ice crystals measured by us settled flatwise.

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