Philosophical Magazine

ISSN: 0031-8086 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tphm19

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The Thermal Conductivity of Ice
New Data on the Temperature Coefficient

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[Received January 27, 1962, and in revised form April 24, 1962]

ABSTRACT

The thermal conductivity of ice in the form of cylindrical specimens has been measured by a steady-state method, the temperature gradients being measured by thermocouples in drill-holes in the ice. The temperature range covered is from 0°C to −180°C, and the results are compared with those of previous observers.

Using the most probable values given, there is a linear relationship within 1 or 2% between the thermal conductivity of ice and the reciprocal of the absolute temperature, down to about 120°K. A quadratic equation is proposed, giving the thermal conductivity as a function of temperature. Lees' work in 1905 is shown to be unsubstantiated, his values being lower than the present ones by about a factor of two, although the possibility of anisotropy at low temperatures is still to be considered.

§ 1. INTRODUCTION

THE first published measurements on the thermal conductivity of ice date from the 1860's. Since then the temperature coefficient has never adequately been studied.

A comprehensive review of past work on the thermal conductivity of ice has already been published by Powell (1958). At about this time the writer was experimenting with a method for measuring the conductivity of ice specimens using a steady-state disc apparatus of a type designed to determine the thermal conductivities of materials such as glass, in disc form, down to mean temperatures of about −180°C (Ratcliffe 1959). The purpose at that time was to prove the feasibility of the test method as applied to ice: the specimens were not mono-crystalline, and there were some air inclusions.

Other work subsequently precluded immediate resumption of the experiments, but since Powell's paper clearly showed a need to present more data, primarily to decide which of two widely divergent conductivity/temperature curves was more likely to be correct, the work was resumed in 1961. The curves concerned were those of Van Dusen (1929) based on Lees (1905) and Jakob and Erk (1929). At the lowest mean specimen temperatures of the measurements, the only previous data were those of Lees which proved to be lower than the present results by about a factor of two.

§ 2. Specimen Preparation

Cylindrical ice specimens were prepared by slowly cooling boiled and pre-cooled distilled water, which was poured into ebonite rings up to the brim. The rings measured internally slightly more than 3 in. in diameter, with a wall thickness of about $\frac{1}{4}$ in., and varied in length up to 3 in.

The rings stood on a flat metal sheet, and after filling were closed on top by a similar sheet. Silicone grease provided an effective water seal between ring and baseplate; this was reinforced by a plasticine fillet on the outside. The outer curved surface of the ring was lagged with cotton wool. The freezing took place overnight in a domestic refrigerator, and was probably complete after about 12 hours. This system of freezing was a compromise between rapid, random freezing and controlled, slow, uni-directional freezing. The specimens produced in this way were fairly clear, but contained some trapped air and were most probably multi-crystalline.

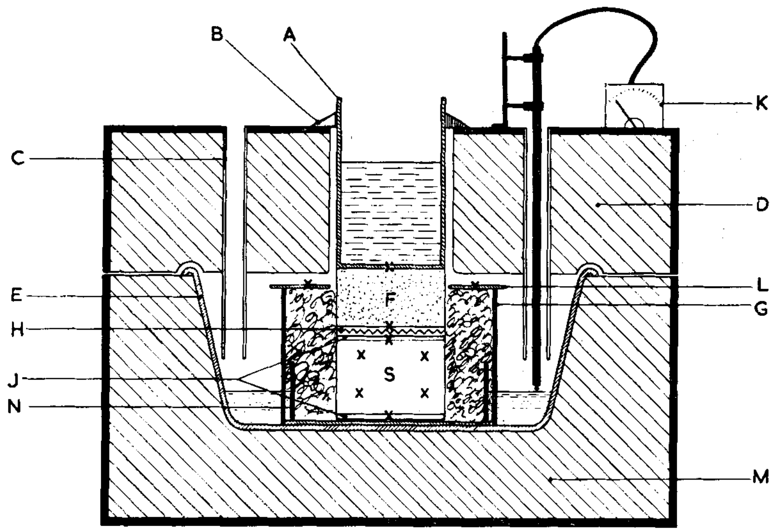
After freezing, the specimen was removed from the refrigerator. The metal closure plates were slid off the ends of the ring and ice, and were replaced by two plated, flat metal discs, 3 in. in diameter and about 1/10 in. thick, each bearing two diametrically opposite co-planar 1 mm wide drill holes, about 1 in. deep. Each disc was frozen inside the ring to the ends of the ice by sinking it into a cushion of water bounded by the inner periphery of the ring, and then applying solid carbon dioxide to its outer surface. The whole was then wedged in an open-topped metal box cooled by solid carbon dioxide, with the axis of the ice cylinder horizontal. Following this, 1 mm diameter holes for thermocouples, about $\frac{3}{4}$ in. deep were machine-drilled into the ice radially from above, through the ebonite ring and the ice, using a pre-cooled drill and chuck to avoid fracture due to thermal shock. The numbers and positions of the drill-holes were purposely varied from specimen to specimen, which differed in thickness up to 3 in. thick. Finally the drilled ice specimen was slid from the ring under pressure with the frozen-on metal discs attached. The whole was replaced in the refrigerator in a plastic wrapping to avoid sublimation, after cleaning the outside faces of the discs and coating them with silicone grease, ready for use in the test apparatus when needed.

§ 3. Apparatus and Assembly

3.1. *Apparatus for Cold-face Temperatures* $-70°$c *and* $-190°$c (*fig.* 1)

This consisted of a circular electrically heated hot-plate H, between a disc of rigid foam thermal insulation F and the ice specimen S bearing the frozen-on metal discs each end, each of these components being 3 in. in diameter. Liquid nitrogen or solid carbon dioxide/acetone was contained in the top hollow cylindrical vessel A and the basin E, depending on the temperature range to be covered. A guard cylinder G about 6 in. in internal diameter, with Lid L, fitted over the base of vessel N in which the ice rested, and was in direct contact with the coolant in the basin: its was notched at the base so that it did not shield N from direct contact with the coolant. Alternatively, instead of this type of guard cylinder, another was often used which was frozen at the base to the inside of vessel N, and electrically heated at the top to roughly simulate the gradients in the ice specimen. Arrangements for thermal insulation, filling and determining the level of liquid nitrogen in the basin, when this was used, are as shown.

Fig. 1



Apparatus for measuring the thermal conductivity of ice at cold-face temperatures of about −70°C and −190°C. A, top container, B, plasticine fillet, C, ebonite filling tube, D, cellular plastic insulation inside wooden lid, E, basin containing liquid nitrogen or solid carbon dioxide/acetone. F, disc of isocyanate rigid foam, G, guard cylinder, H, hot plate, J, plated metal discs frozen to hot and cold ends of ice specimen, K, thermocouple level indicator, L, guard cylinder lid, M, cellular plastic insulation inside wooden box, N, container for ice specimen, X, thermocouples.

Just prior to assembly, the ice specimen was transferred from the refrigerator to a high heat capacity metal box which had been pre-cooled by solid carbon dioxide. Twin-laid glass-silk covered 36 s.w.g. nickel–chromium/constantan thermocouples were inserted in the drill-holes in the ice and in the metal discs, and the whole was placed on the flat base of N, which had been pre-cooled, care being taken to keep the silicone grease film between the cold ice disc and N as free as possible from any condensate. This grease film helped to reduce temperature discontinuities, although it subsequently lost its fluidity at low temperatures. The hot-plate, having been pre-cooled, was put on top of the hot-side ice disc, with a silicone grease film between. The basin was kept well below −15°C at this stage, to avoid melting the top parts of the ice, and the assembly rapidly completed. After lowering the lid of the box over the top vessel, all cracks were sealed, using plasticine and adhesive cellulose tape. Good sealing was essential, not only to avoid icing on plates and specimen and release of latent heat, but also, when liquid nitrogen was used, to avoid a condensate of liquid oxygen forming inside the apparatus on the surfaces of the top vessel, and running down to affect temperature gradients. A 120 volt battery was used as an energy source, and current and voltage were measured potentiometrically.

3.2. *Apparatus for Cold-face Temperatures of about* $-10\,^{\circ}\mathrm{C}$

Arrangements were similar to those for the previous apparatus, except that cooling was effected by a glycerine/water mix pumped from a temperature controlled tank and circulated through hollow, flat-faced cylindrical cold plates, which replaced the containers for liquid nitrogen or solid carbon dioxide/acetone described in § 3.1. (The apparatus was similar in principle to that described in fig. 1 of a previous paper (Ratcliffe 1959).)

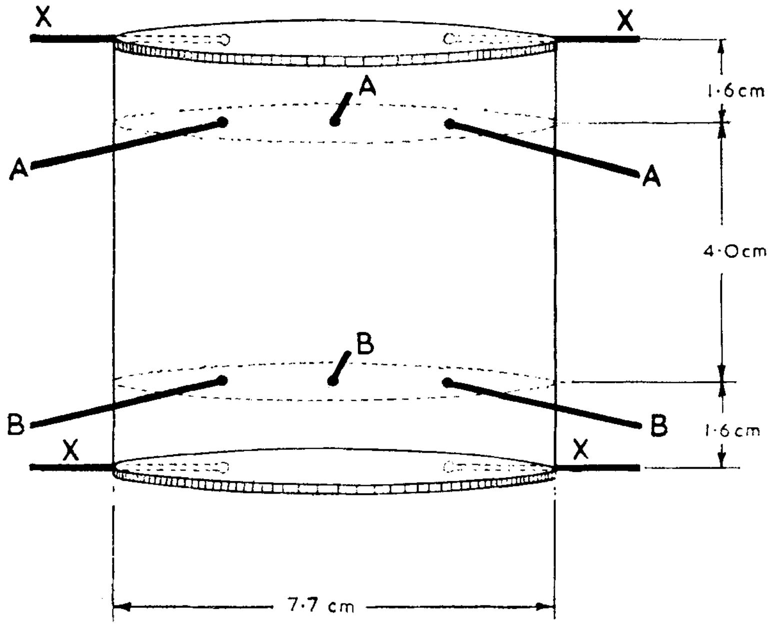
§ 4. Corrections, Sources of Error

Errors in measuring distances between thermocouples were undoubtedly present, but were eliminated as far as possible by three checks: firstly by measuring the distances apart of the drill-holes in the discarded ebonite ring; secondly, by measuring across the actual holes in the ice before inserting the thermocouples, and finally after the test by melting down the ice specimen to measure across the undisturbed thermocouple 'hot-junctions' *in situ*.

The heat flowing through the ice was calculated from the electrical input to the hot-plate, allowing for heat losses through the isocyanate foam and the thermal insulation, which totalled less than 4% of the heat input.

One of the major factors likely to have contributed to the spread of results on the graph, was thought to be the possibility of unequal temperature distribution in the ice due to heat-flow distortion occurring near the ends, as a result of uneven heat transfer across the frozen-on plated discs and the adjacent ice. Several results were discarded where the temperature difference between one end of the ice (temperature found by extrapolation of temperatures inside the ice) and the adjacent disc, seemed excessive, or was very dissimilar to the equivalent temperature difference at the opposite end of the ice. It appeared that a rough, average value for ice/end-plate temperature drop at the lower temperatures was about $0{\cdot}8\,^{\circ}\mathrm{C}$ for a heat-flow across the area of $0{\cdot}01\ \mathrm{cal/cm^2/sec}$. With 3 in. long specimens at these temperatures, requiring more heat flow to maintain a given temperature difference, the total drop across the two ice/plate films could be about a third of the plate/plate drop. At temperatures where carbon dioxide/acetone mixes or glycerine/water were used as coolants, higher contact resistances than would be expected could frequently be obtained, and it was assumed that differential thermal movement tended to loosen the frozen-on plates during cooling to the lower temperatures. Certainly a large proportion of the lower end-plates were not adhering to the ice after a test involving the use of liquid nitrogen as coolant, although it could not be ascertained whether this had actually occurred during test, or during a post-test period prior to removing the ice from the apparatus.

Fig. 2



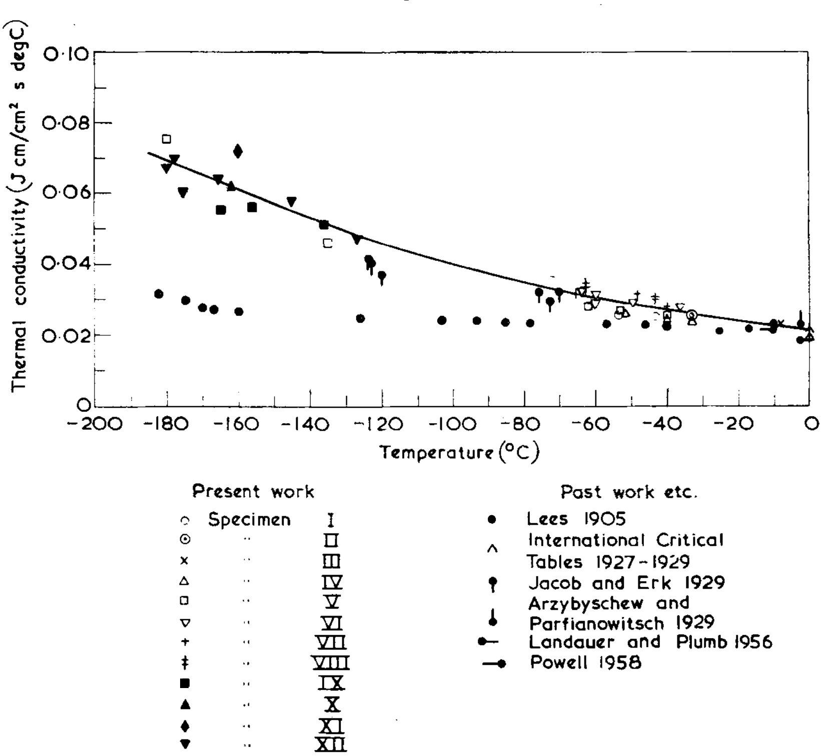
Cylindrical ice specimen containing six thermocouples in drill-holes (AAA, BBB) in two planes parallel to end-plates. (XXX = end-plate thermocouples.)

Even though this ice/end-plate temperature drop (and the end plate/vessel N temperature drop across the silicone grease film) introduced considerable temperature discontinuity between the ice and the coolant, an average run, with six thermocouples in the ice, arranged in two imaginary parallel planes 4 cm apart as shown in fig. 2, with about 42 °c drop between the two sets of thermocouples, showed variations of less than ± 1 °c between the three thermocouples of a set. Considering that the ice temperature gradient was 1 °c/mm, and that the ice/end-plate temperature difference was about 10 °c, the relatively small magnitudes of these variations seemed to be satisfactory, since some heat-flow distortion in the ice was a possibility due to high heat flow across the discontinuities. It was thought that scatter in the final results was due to a variety of factors, one being the difficulty of attaining a steady temperature difference in a reasonable time due to the high thermal capacity of the test specimen. This was associated with the fact that the cold side of the ice was separated from the coolant 'sink' by films of high thermal resistance.

§ 5. Results

Combined with those of previous workers, these (fig. 3) appear to provide, for the first time, data by which a reasonable judgment may be effected on the trend of the thermal conductivity of ice from 0°c to about −180°c. It is evident that there is still no substantiation for *Lees*' results at the lower temperatures, but in view of the possibility of anisotropy at low temperatures, the author intends to experiment further with specimens of ice of differing crystalline orientations, in order to determine the extent of the variation of thermal conductivity. In reproducing Jakob and Erk's results the mean value only of a pair of points has been plotted, where there was extremely close agreement.

Fig. 3



Ice. Variation in thermal conductivity with temperature. (For full references to past work see Powell (1958).)

The following 'most probable' values, from the curve shown, mainly based on the present results, are suggested. It should be noted that if these values are plotted against the reciprocal of the absolute temperature, within 1 or 2% there is a linear relationship, a relation known to apply to some other crystalline materials.

Temperature (°C)	Thermal conductivity (k) (J cm/cm² sec deg. C)	Estimated accuracy
0	$0{\cdot}022_5$	±5%
−50	$0{\cdot}028_5$	±10%
−100	$0{\cdot}039_5$	±10%
−150	$0{\cdot}057_0$	±15%

The values above can also be expressed closely by the following quadratic, in terms of the temperature t (°C):

$$10^6 k = 22500 - 62t + 1{\cdot}15\,t^2.$$

The linear relationship mentioned, for temperatures not lower than about 120°K, is given by

$$k = \frac{7{\cdot}8}{T} - 0{\cdot}00615,$$

where T is the absolute temperature.

Acknowledgment

The author wishes to acknowledge the encouragement of Dr. R. W. Powell in these measurements.

The work described above has been carried out as a part of the research programme of the National Physical Laboratory, and this paper is published by permission of the Director.

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