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THERMAL CONDUCTIVITY MEASUREMENT (TCM) OF ICE CORES: DEVICES AND PROCEDURES

ABSTRACT: FESTA C. & ROSSI A., *Thermal Conductivity Measurement (Tcm) of ice cores: Devices and Procedures.* (IT ISSN 0391-9838, 1997).

An apparatus has been developed expressly to operate at temperatures below 0°C for the determination of the thermal conductivity of ice, which can be measured by the transient hot wire method.

Thermal conductivity is determined by tracking the thermal pulse propagation induced in the sample by a heating source consisting of a Pt resistance. A central segment of the same heating platinum resistance acts as a thermal sensor.

The heat impulse transferred to the ice for a period of 40 s gives a maximum temperature increment of about 7-14°C. Each measurement requires a few minutes only.

In good experimental conditions, the expected repeatability of the measurements is within ±3%. The precision of this method depends on whether the instrument has been calibrated by reliable standard samples, certified by absolute methods.

A programme of routine measurements of ice cores and a sequence of experimental standard procedures are proposed.

KEY WORDS: Thermal Conductivity, Ice Cores.

RIASSUNTO: FESTA C. & ROSSI A., *Misura della conducibilità termica (Tcm) su carote di ghiaccio. Strumenti e procedure.* (IT ISSN 0391-9838, 1997).

È stato sviluppato uno strumento in grado di misurare a temperature minori di 0°C il valore relativo della conducibilità termica secondo il metodo a filo caldo in regime transitorio, anche su campioni di ghiaccio. La determinazione della conducibilità è eseguita misurando sulla superficie del campione la variazione di temperatura che si sviluppa applicando una sorgente di calore costituita da una termoresistenza di Pt.

Il sensore termico è costituito da un segmento centrale della stessa resistenza di platino riscaldante.

L' impulso termico fornito al campione di ghiaccio per 40 secondi provoca incrementi di temperatura massimi da 7 a 14°C. L'esecuzione di una misura richiede solo qualche minuto.

In buone condizioni sperimentali la ripetibilità della misura prevista è contenuta entro ±3%. La precisione di questo metodo relativo è legata ad una buona calibrazione dello strumento e alla disponibilità di campioni standard affidabili con valore di conducibilità certificato con metodi assoluti.

È proposto un programma di misure in serie sulle carote di ghiaccio di un pozzo profondo, sulla base di un protocollo di procedure sperimentali standard.

TERMINI CHIAVE: Conducibilità termica, Carote di ghiaccio.

INTRODUCTION

This research has been developed within the framework of the «European Project for Ice Coring in Antarctica» (Epica). The main target of Epica is to drill a borehole to more than 3000 m depth in the Antarctic ice cap, at Dome C, from the surface to the bedrock, recovering a complete ice core of the entire vertical section of the ice cap, aged at least 300,000 years.

The heat flow developing through polar ice sheets can be determined quantitatively by means of precise measurement of the thermal gradient profile dT/dz in the hole, from the surface to the bedrock, and the punctual measurement of thermal conductivity λ in the ice cores (Tcm).

The well-known Fourier equation $Q = \lambda\ (dT/dz)$ for thermal steady-state conditions, gives the value of the vertical component of the heat flow Q, provided very slow movements and compaction of the ice sheet are accounted for and accurately modelled. The anomalies induced by climatic oscillations should be detected. The experimental measurement of the thermal conductivity of the ice cores from the ice cap is therefore as important as the thermal logging of the borehole.

THE INSTRUMENT

An apparatus has been developed expressly to operate at temperatures below 0°C to determine the thermal conductivity of the ice, which can be measured by the line source method.

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Research was carried out in the framework of a Project on Glaciology and Paleoclimatology of the Italian Programme for Antarctic Research, and financially supported by Enea through a cooperation agreement with the Università degli Studi di Milano.

The theoretical model adopted was studied by Carslaw & Jaeger (1959) and developed with many applications (Blackwell, 1954; Jaeger, 1956; Von Herzen & Maxwell, 1959; Zierfuss, 1963; Jaeger & Sass, 1964; Ito & *alii*, 1977; etc.).

The brief description given below should clarify the practical application of our apparatus.

THE THEORETICAL MODEL

The model adopted is an application of the line-source method suitable for use with cylindrical cores of rocks in which the heater is placed between the two surfaces of the half-cut core.

The theoretical basis of the model is the long cylindrical probe method of Carslaw & Jaeger (1959). The probe is fitted with an axial heating wire which produces a single thermal pulse for a finite time whith constant heating power, and generates cylindrical coaxial isotherms.

The transient temperatures T, for sufficiently long times t since start of heat generation, can be written (Jaeger, 1965, p. 19) in the form

$$T = (Q/4\pi\lambda)\,[\ln(4at/r^2) + A + B\,(r^2/at) + C\,(r^4/a^2t^2) + ...]$$

where A, B and C are constants that depend on the probe, Q is the heat supply per unit length of the heating line source of heat and per unit time, λ is the thermal conductivity, a is the diffusivity and r is the radius of the heating wire.

If the (r^2/at) values are small, T can be expressed with good approximation by the simplified form

$$T = (Q/4\pi\lambda)\,[\ln(4at/r^2) + A]$$

In fig. 1 T is plotted against t in semilogarithmic scale, and the straight segment of the diagram shows the range of validity of the theoretical model.

The thermal conductivity λ can be determined by tracking the temperature variations. If the temperatures T_1 and T_2 are measured at times t_1 and t_2 within the validity range, the conductivity λ is obtained from the difference $T_2 - T_1$

$$\lambda = \frac{Q}{4\pi} \cdot \frac{\ln t_2/t_1}{T_2 - T_1}$$

In this case λ is directly determined without being affected by the diffusivity.

THE PROBE

The heater is a flat-wire platinum resistor. For practical reasons the line-source of heat lay on the plane surface separating two half-spaces: the half-spaces are the sample medium (material undergoing the test) and the insulating medium of the probe.

The thermal conductivities of the two half-spaces are «in parallel», that is the conductivity of the insulating medium of the probe is added to that of the sample material and must therefore be considered in the calculation of the final result; small errors may occur if the diffusivities of the media in the two half-spaces are different.

Assuming t_2/t_1 = constant (for instance $t_2 = 2\,t_1$) we obtain a more simplified form of λ

$$\lambda = \frac{KP}{T_2 - T_1} - H$$

where K includes $\ln t_2/t_1$ and other constant terms, P is a parameter proportional to the electric power supplied to the heating flat-wire, and H is a constant term that depends on the insulating material of the probe. Both K and H are determined by calibration procedures, by means of standard samples with a certified λ value, for the precise adjustment of the laboratory apparatus.

The theoretical model has a heating line-source of infinite length in an infinite homogeneous space; the real probe must have adequate geometric dimensions for preventing the thermal impulse of the measurement cycle from going too far from the heating flat-wire, thus minimizing possible deviations from the cylindrical symmetry and boundary effects. It is also important that the selected times t_1 and t_2 of the measurement cycle are not too short and always within the range shown in fig. 1 in order to keep the behaviour of the physical system within the limits of validity of the theoretical model.

The heat impulse transferred by the flat wire of the probe to the samples for a time of 40 seconds gives a temperature increment of about 7-14°C just at the contact between sample surface and probe. The operations for each measurement require a few minutes only.

The probe has been fitted with a platinum resistor (flat-wire) with a double function, heating and measuring the temperature. A central segment of the same platinum resistor is, in fact, used as thermal sensor .

The technical solution that permits these two independent functions consists of a dual electric power supply operating independently and simultaneously.

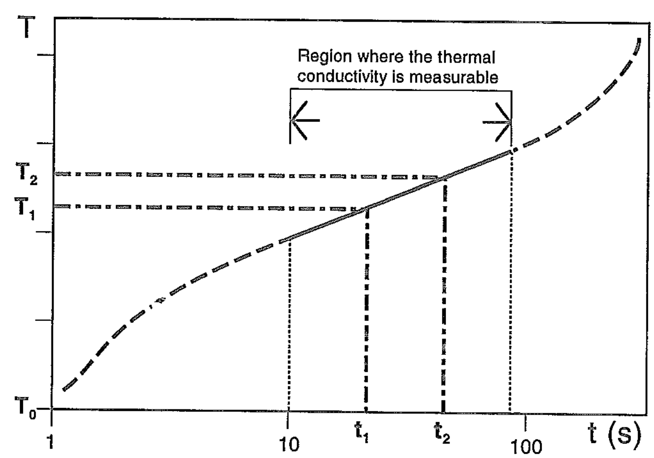

FIG. 1 - Time-temperature relationship, with starting temperature assumed at –20°C.

A first, relatively low, AC current is supplied permanently to the platinum flat-wire, so that it can operate as a thermal sensor recording the temperature of the wire.

A second, DC current of suitable intensity is overlapped on the AC current on the same platinum string, to operate as a heating unit, generating a cylindrical symmetry thermal wave whose axis coincides with the heating flat wire.

For every measurement cycle DC heating power is supplied for 40 seconds only and is automatically regulated to remain constant.

The AC temperature signal is easily separated from the DC heating power by a filtering procedure. The heating effect of the low-power AC thermal sensor is negligible compared to the DC heating power.

The new instrument has undergone calibration and repeatability tests. Some calibration tests and measuring procedures have also been carried out in a cold room at working temperature down to –25°C, that is, at the temperatures that could be expected in ice samples and rock samples in permafrost condition.

The calibration tests were run with different silica standard samples with certified values of thermal conductivity .

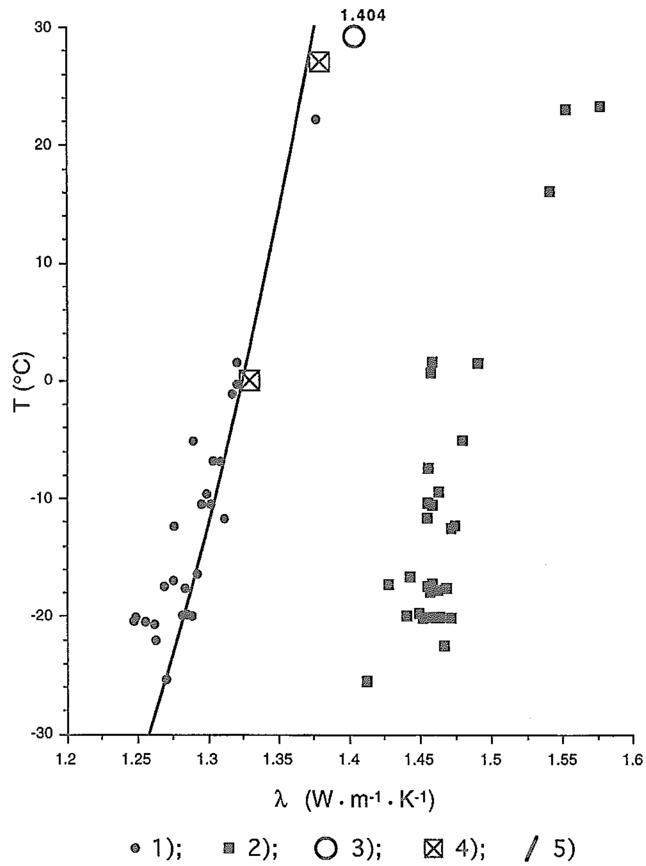

FIG. 2 - Measurement of λ at different temperatures with:1) silica glass standard sample; 2) Zerodur glass sample. For the silica standard sample the reference λ values are also indicated as: 3) certified by Showa Denko K.K., Tokio, Japan; 4) reported from Nsrds-Nbs, vol. 8; 5) curve of λ as from Ratcliffe (1959).

ERRORS

In good experimental conditions, measurements are easily reproducible within ± 3% of the λ value. Fig. 2 shows some experimental results of measurements with this apparatus, at different temperatures, with a silica glass standard sample and a Zerodur glass sample. The precision of this relative method depends on whether the instrument has been calibrated by reliable standard samples certified by absolute methods. In the case of homogeneous sampling rates, a statistical analysis can control the quality of the data; small changes in the parameter λ can be detected along with the errors.

The measurements carried out so far in a cold room give λ values varying from 2.1 to 2.5. W $m^{-1}K^{-1}$ at –20°C for several samples of ice prepared with tap water. These values are within the range reported by S. P. Clark in the Handbook of Physical Constants - Gsa Memoir 97, (1966).

The main sources of error affecting the measurements are:

— roughness, uneven surface of the ice sample and irregular contact between the ice surface and probe surface (contact resistance), which can prevent reliable measurements;

— extraneous thermal drift affecting the sample before and during the test period (sample not in a thermal steady-state condition).

The main requirements for good experimental conditions are:

— temperature of the samples should have stabilised and be in equilibrium with that of the measurement room (shelter);

— temperature no higher than about -20°C;

– flat plane surface of the cut half-ice core, allowing good contact with the thermal probe;

– a table wide enough to contain the measurement apparatus and the samples of the cores to be measured that day.

MEASUREMENT OF ICE CORES

The ice core can be scanned with 6 measurement points per meter on the flat surface of the half-core longitudinal cut. The suggested working room temperature is about –20°C and the samples before the measurement test must be in a thermal steady-state condition, that is, in equilibrium with the temperature of the room.

We assume that heat flow is perpendicular to the surface and to the ice layers; we also assume that the core hole is almost vertical.

The ice core is layered and anisotropic. We must determine the vertical component of λ by taking measurements in two orthogonal directions (fig. 3).

In the first position the thermal pulse generated by the line source of the probe lies on the axis of the cylindrical

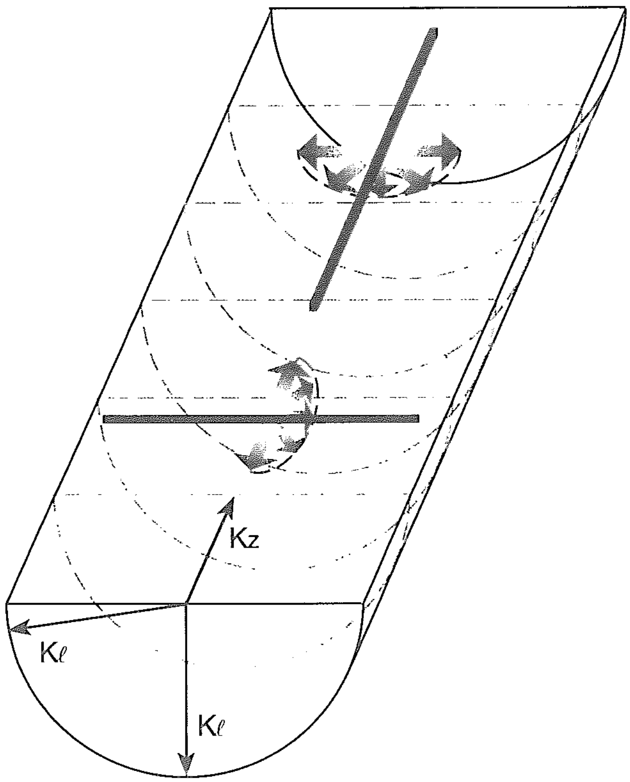

FIG. 3 - Scheme of thermal conductivity measurement of an anisotropic drill core.

ice core; in this case the induced thermal wave propagates in a radial direction, always following the horizontal layering planes; the thermal conductivity of the horizontal layer is then determined (λ_l).

In the second position the line source of the probe lies orthogonal to the axis of the ice core; in this case the radial thermal wave propagates both horizontally and vertically, and we measure a combined value of thermal conductivity (λc). The vertical component λz of the thermal conductivity is then given by (Grubbe & *alii*, 1983):

$$\lambda z = \frac{\lambda_c^2}{\lambda_l} .$$

OBJECTIVES

Apart from heat flow determination, the measured values of the parameter λ can provide some important stratigraphic information.

The value of λ of the natural ice is a variable quantity, depending on temperature, density, porosity and gas content, tephra and powder content, chemical content (salts, clathrate hydrates), crystal and structural anisotropy, etc.

Discontinuous measurements of λ (Tcm) could therefore provide a diagram (points) and characterise the stratigraphic sequence of the ice core versus time (or depth), along with the continuous temperature log of the drill hole.

The diagram can be matched with those of other parameters (Ecm, Dep, etc.); the reliability of any anomaly can be strengthened.

A programme of measurements of about 20 m of ice core per day could consist of:

1) *Preparation phase*
The samples (cut half-cores) are laid out on the bench, numbered, identified and prepared for measurement; the diametrical-cut surface is controlled, cleaned and, if necessary, smoothed and polished.
Time required: 1 to 2 hours (depending on operating conditions). This should be the last part of the day's work.

2) *Night time phase*
The samples are resting and reaching a thermal steady-state condition within the shelter.

3) *Measuring phase*
In the morning of the day after sample preparation, the samples are measured at a rate of about 1 measurement point every 2 to 3 min. (1 minute for the thermal cycle + 1 minute to cool the probe on the thermal sink plates).
About 20 m of ice core per day with 6 measurements per m and a total of 120 measured points would require 5 hours.

4) *Final phase*
The measured samples are moved to the next process site. The experimental data are retrieved and controlled.
Time required: 1 hour (depending on operating conditions).

A total of about 7 hours/man job per day is required for 20 m of ice cores, with 120 measurements (60 longitudinal and 60 transversal).

There may be a possibility of reducing the operating time by utilising two instruments with two well calibrated probes. This would save about 1/3 of the measuring time and reduce the total time per day to about 6 hours only.

The above-described programme could be modified and reduced to a «minimum» by considering different possibilities and solutions. For instance, in the case of large sequences of homogeneous ice with no expected detectable changes in the parameter λ, the measurements could be reduced to a rate of just a couple per meter or even less.

In this case the experimental data would, however, become less reliable, with the risk of losing information and of increasing the uncertainty of the measurements with single points by the transient hot wire method; possible errors could not be easily detected. In this case it would be better to repeat the measurements several times (say 4 longitudinal + 4 transversal = 8) in a few points, for instance every 5 m; that is, 32 measurements every 20 m. This procedure would give λ values with good accuracy for heat flow determination only. The stratigraphic sequence could not be tracked in detail. The 8 measurement tests per point should be distributed over two days because the samples need several hours to recover their steady thermal condition after every test. The total time required to run this «minimum» programme can be tentatively quantified in about 4 hours per day: two hours in the morning + two hours in the evening, leaving 6 hours in between.

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