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Free Water Content of Wet Snow*

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Abstract

In Japan, a "combination calorimeter" is now widely used for measuring the free water content of wet snow covers. This calorimeter was designed by the author seven years ago. Together with its description, an outline will be given on the series of attempts which were made to find a method of measuring the free water content before the combination calorimeter was put to use.

As you know, the snow cover on mountains supplies rivers with a considerable amount of water, and many investigations have been made on the amount of water from the snow cover melted by sunlight, air temperature, wind and so on. But, as far as I know, questions concerning the free water in the snow cover, such as, how the melting water migrates in the snow cover, how long the water stays in the various parts of it, have not been answered satisfactorily. Twenty five years ago, when our institute was opened, I planned to study this subject and tried to produce a method of measuring the free water content in wet snow. It seems essential to have such a method if a study of this kind is to be made in any way. With your permission, I would like to give you an outline on how we came up with our "combination calorimeter".

I

Now, soil usually contains water. When dried by heating, the soil loses its water and the decrease in its weight gives the amount of water which the soil had initially. In the case of snow, however, obviously this method can not be applied. But heat can still be used for determining the free water content of snow, if the amount of heat added to it can be measured exactly.

Suppose we have a sample of wet snow weighing 100 g. We heat it and get water of a temperature 16°C after we have melted the snow. Now suppose we have some means to measure the heat q supplied and find it to be 8 000 cal. Of the 8 000 cal, 1 600 cal must have been expended for raising the temperature of the melted water from 0 to 16°C. Then the heat Q used for melting the ice in the wet snow is given by the remaining 6 400 cal. As 80 cal is needed for melting 1 g of ice, 1 600 divided by 80, that is, 80 g gives the quantity of the ice which was in the wet snow. The sample of wet snow weighed 100 g. Therefore the difference $100\,\mathrm{g}-80\,\mathrm{g}=20\,\mathrm{g}$ would give the amount of free water which was contained in the sample.

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* The special lecture read at this conference.
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Based on the above reasoning, I began my experiments for determining the free water content of snow, twenty five years ago (Yosida, 1940, 1949). For this purpose I made a calorimeter shown in Fig. 1. It was of such a simple type as used by students for the practice of calorimetry. I put a definite quantity M of hot water in the copper vessel of the calorimeter, and, after measuring its temperature T_1, a sample of wet snow was dropped into it. The snow and the hot water were stirred violently, which gave, in the copper vessel, water having a temperature T_2 which was lower than T_1. The heat quantity q added to the wet snow is obviously given by the product of the amount of the hot water into the temperature depression, that is to say, by $M(T_1-T_2)$ cal. In this manner I measured the free water content of the snow covers around our institute and published the results.

But I was forced to give up this calorimeter after one winter, as it was too inconvenient to use in the field. As you know, in calorimetry, we have considerable trouble in making corrections for the heat which strays out from the calorimeter because of incomplete heat insulation. In the calorimeter I used, the hot water and the snow had to be mixed by a stirrer manipulated from the outside of the calorimeter. For that purpose, a hole was made in its lid and much heat escaped through that hole. The only way to reduce the stray heat was to make the measurement quickly, which required intensive concentration on my part. I was not up to this type of stress, so I had to give up using the calorimeter.

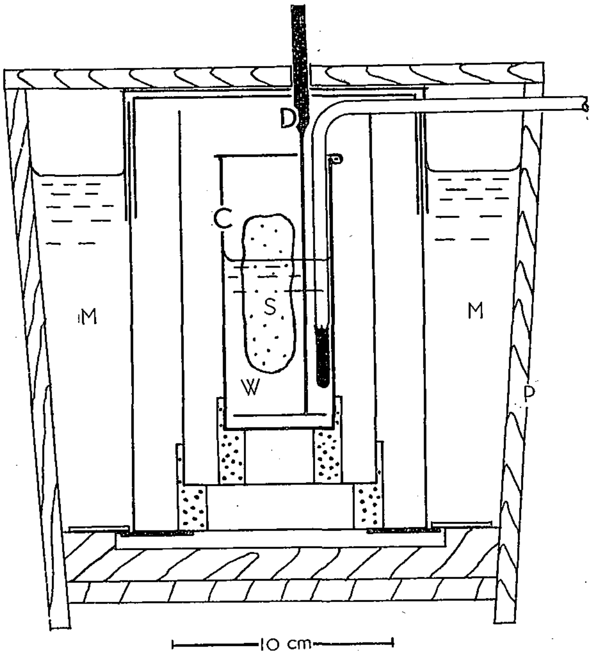


Fig. 1. Calorimeter which the author used at first. C, copper vessel in which hot water W and sample of wet snow S are put; D, stirrer; P, wooden pail; M, water bath

II

After that, Dr. Kuroiwa in our institute made a series of studies on the dielectric constants of snow (Kuroiwa, 1951; Yosida *et al.*, 1958). In these studies he took up the problem to determine what change would be brought to the dielectric constant of snow by the free water in it. He made experiments using an alternating electric current of 3 500 kc/s. Since the dielectric constant of ice differs much from that of water at this frequency, in other words, since the dielectric constant of ice is only 3.4 whereas that of water amounts to 80, the presence of free water in snow must give rise to a large increase in its dielectric constant. Furthermore the impurities, which are contained in snow in variable amounts and which give a large disturbance to the measurement at low frequencies, cause no harm at such a high frequency.

The dielectric constant of any material can be obtained by measuring the increase in the capacity of an electric condenser which arises when it is filled with the material. Dr. Kuroiwa first filled his condenser with wet snow. After having determined the dielectric constant e_W of the wet snow, he cooled the condenser down to −11°C to make the free water in it freeze completely and determined the dielectric constant again. Now wet snow can be dried in two ways, by heating and cooling. By heating, it disappears in the end. But cooling adds ice to the snow by changing the free water into ice. If the value of dielectric constant in this frozen state is given by e_D, the letter D suffixed to e indicates this desiccation by cooling. Then the excess in dielectric constant of the snow in the original wet state may be given by the difference

$$\Delta e = e_W - e_D \,.$$

But it is not expected that this Δe can be put into any definite relationship with the free water content, because the dielectric constant depends largely on the density of snow. If there is a definite relationship at all, it will be found only for snows of the same density. Dr. Kuroiwa filled the condenser with wet snows of the same free water content in such a way that they were packed in the condenser at different densities. In this manner he found formulas relating the dielectric constant with the density, and by the use of these formulas he converted the dielectric constants obtained into those which the snows would have if they were compacted to a density of 0.5 g/cm³.

Let us denote the converted values of e_W and e_D by e'_W and e'_D. Dr. Kuroiwa found that the difference between them, namely,

$$\Delta e' = e'_W - e'_D \,,$$

was connected to the free water content W' by a linear relationship as shown in Fig. 2. By the use of this relationship, we can obtain the free water content if the value of $\Delta e'$ is determined from measurement of the dielectric constants e_W and e_D.

In the field it would not be practical to cool the wet snow to make it dry. So it was desirable to have some other means to know the value of e_D. Dr. Kuroiwa suggested the use of the relationship he found between the dielectric constant and the density of dry snow. This relationship indicates that the dielectric constant of dry snow of the density ρ g/cm³ lies between

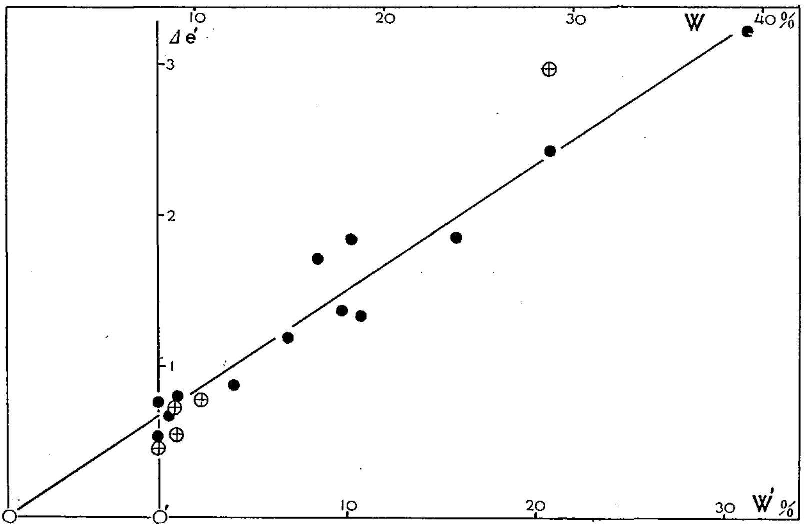


Fig. 2. $\Delta e'$ (change in the dielectric constant accompanying the freezing of wet snow) versus W and W' (free water content). W' (bottom scale), uncorrected free water content as observed by use of a centrifuge; W (top scale), true free water content. $\Delta e'$ was determined under a condition where the wet snow had a density of 0.5 g/cm^3 in the condenser. Otherwise the measured Δe was corrected to that density. Circle with cross, soft snow; solid circle, granular snow

$$e_{\mathrm{I}}=\frac{13.5+27.3\,\rho}{13.5-2.73\,\rho} \quad \text{and} \quad e_{\mathrm{II}}=\frac{6+6.82\,\rho}{6-2.73\,\rho}\,.$$

If we use the mean value of e_{I} and e_{II} for e_{D}, the error in e_{D} will be limited to 10%.

In order to practice the measurement of free water content in the field, it is necessary to have an instrument for dielectric measurement conveniently designed for handling and carrying. But unfortunately Dr. Kuroiwa did not produce such an instrument. Three years later, Dr. Gerdel (1954) of SIPRE designed an instrument to be used in the field. But his instrument was applicable only for qualitative purposes; this can be said because he used his instrument only for the observation of relative changes in the free water content occurring at certain spots in the snow cover. Recently I heard that Dr. Ambach in Austria constructed a convenient instrument to measure the dielectric constant of snow, for the purpose of determining the degree of wetness of snow. I hope his instrument may be put to practical use as soon as possible. However, I think, the dielectric method, by its nature, is not an absolute method, but can give only a rough estimation of the free water content.

III

Dr. Kuroiwa, in his experiments mentioned above, used a hand driven centrifugal separator shown in Fig. 3 for measuring the free water content of wet snow. It is obvious that the amount of the water drawn from the snow by a centrifugal force gives the free water content, provided that no residual water is left in the snow or is generated by its melting. The separator he used was that which had been designed

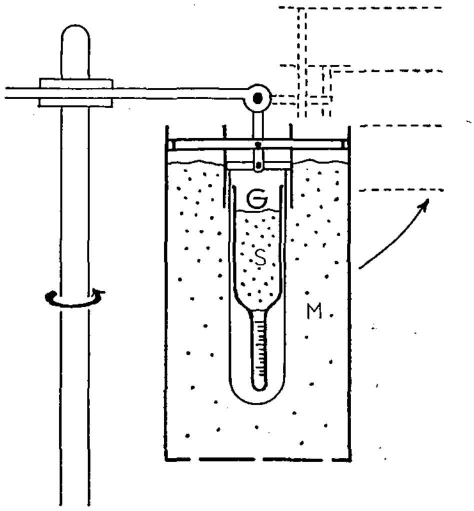


Fig. 3. Rotating part of centrifugal separator. G, glass cylinder for the sample S of wet snow; M, protecting mantle made of wet snow. While rotated, the part is in the position indicated by the dotted lines

and produced in our institute (Yosida, 1951). The sample of wet snow is put in a glass cylinder which has a thin tube at its bottom for collecting the separated water. The glass cylinder was covered with a snow mantle while it was being rotated so that the sample might be held at 0°C against the higher temperature of the surrounding air. A centrifugal force more than one hundred times larger than the gravity was produced in this separator, but still some water was left behind in the sample. In Dr. Kuroiwa's diagram (Fig. 2) $\Delta e'$ versus W', the straight line cuts the ordinate axis of $\Delta e'$ at a point lying above the origin O′ of the coordinates, which is nothing but an indication of the presence of residual water. The diagram should be read by shifting the origin of coordinates leftward to the point O where the straight line joins the axis of abscissas.

Dr. Kuroda was the first to use the centrifugal separator for the free water measurement in our country, and in those days many attempts were made to improve this method. For instance, Dr. Kuroda and Mr. Furukawa (1952) added diethylaniline to the sample of snow in the glass cylinder of the centrifuge; diethylaniline is a liquid which has a density intermediate to those of ice and water. They maintained that they could thus reduce the remaining water, enhancing the separation of free water from the snow, but, Drs. Ôura and Kinosita (1954), after reexamination, came to the conclusion that the liquid did not accelerate the separation but rather retarded it. I myself designed a large centrifugal separator as shown in Fig. 4 (Yosida, 1955). The wet snow was placed in a cylindrical cage A (12 cm in diameter and 12 cm high) of which the cylindrical surface was made of tightly stretched wire gauze. The cage was then put in a water collector B made of iron plate as shown in the figure. An electric motor rotated the water collector in a space maintained at 0°C by being enclosed on all sides with double walls containing snow. The free water in the snow sample was drawn out by the centrifugal force through the cylindrical gauze of the cage and ran down along the

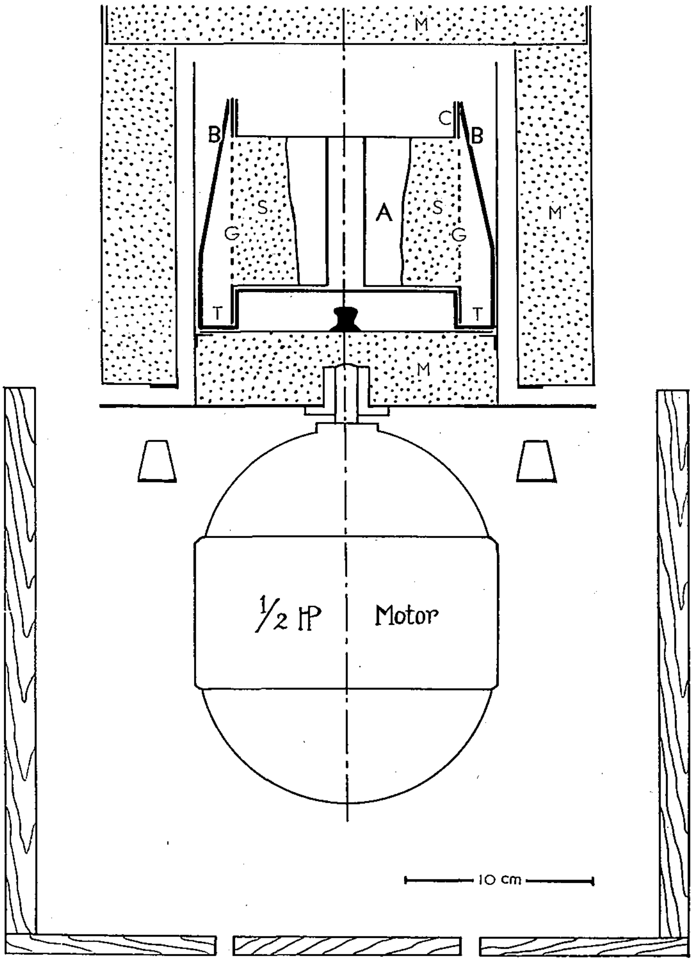


Fig. 4. Large centrifugal separator. A, cylindrical container for snow sample S with the side surface made of stretched wire gauze G; B, water collector with ring-formed groove T; M, double walls containing wet snow

sloping wall of the collector and was collected in a ring-formed groove T at its bottom. This separator could handle wet snow amounting to 200 g or more, while the hand driven separators used by others could only process 10 g at the largest. In this large separator the centrifugal force reached one handred and fifty times the gravity, but there still remained unseparated free water in an amount varying from case to case even after a long running of twenty five minutes.

Although the centrifugal method looked promising at first, we gave it up finally because of the water which the centrifugation did not release. Besides, practical use of this method in the field was not as easy as might be supposed.

IV

After such experiences as mentioned above, we were coming back again to the calorimetric methods. Dr. Wakiya and I made a calorimeter which gave the amount of heat finding its way in through its walls from the outside (Yosida and Wakiya, 1951). It consisted of two brass cylinders, one of which is placed in the other with a uniform clearance of 2 mm in between (Fig. 5). The cylinders were closed by two thick bakelite plates at their top and bottom. A small bore was made in the outer cylinder and a vertical capillary tube was so attached to it that the space between the two cylinders was connected with the capillary bore. This connected space was filled with an aqueous solution of 50% alcohol with its surface in the capillary tube. The calorimeter was placed in a water bath at a constant temperature u_0, say 20°C, and a sample of wet snow was dropped into it. Due to the depression in temperature u_i of the inner cylinder, the mean temperature of the layer of solution became lower than u_0 by the amount $\Delta u = \frac{1}{2}(u_0 - u_i)$. The thermal contraction of the solution caused by this temperature depression appeared as displacement h of the free surface of the solution in the capillary tube. As the temperature gradient in the layer of solution was proportional to $(u_0 - u_i)$, $\mathrm{d}q/\mathrm{d}t$, the heat quantity flowing into the calorimeter in a unit time, was proportioned to Δu. On the other hand, h also increased in proportion to Δu. So $\mathrm{d}q/\mathrm{d}t$ was given by

$$\mathrm{d}q/\mathrm{d}t = kh\,,$$

where k is a constant characteristic to the calorimeter. The free surface of the solution in the capillary tube returned to its initial position, when the sample of snow had melted completely and the melted water warmed up to the outside temperature u_0. Until this time the observation of h should be continued. Then the amount of heat Q needed for melting the ice in the wet snow can be known from u_0 and the total heat q supplied to the sample which is given by

$$q = k\int h\,\mathrm{d}t\,,$$

just in the same manner as in the case of the calorimeter mentioned at the beginning of this speech. The integration on the right side of the above formula can be carried out by the use of the curve h versus time t.

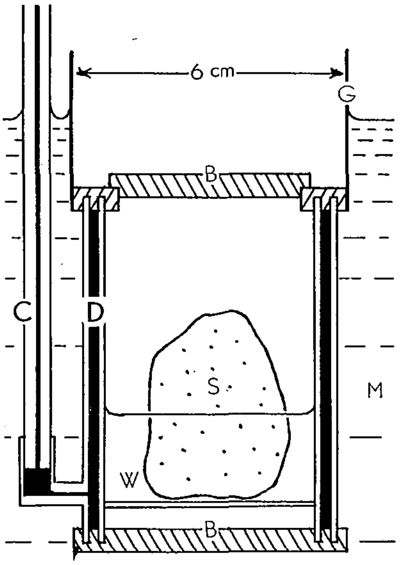


Fig. 5. Double wall calorimeter. D, double cylinder of brass; C, capillary tube; S, sample of wet snow; W, melted water from the sample; B, bakelite plates; M, water bath; G, guard ring to keep the water of the bath away from the top of the calorimeter

As we can move the sample in the calorimeter by shaking the latter, we need not provide it with a stirrer. But it took a long time for one measurement, ten minutes or more, not counting the time of preparation. For this reason this calorimeter was not suitable for field work.

Let ρ be the density of wet snow. If we denote by W the free water content expressed in percentage, $\rho_d=\rho[1-(W/100)]$ gives the amount of ice contained in 1 cm^3 of the wet snow. It is obvious that the free water content W can be determined if ρ and ρ_d are known. I called ρ_d "dry density" and made a calorimeter which might be called a "dry density meter" (Yosida, 1960). The calorimeter is schematically shown in Fig. 6. It consists of a copper vessel A with a flat bottom b, covered with thick layers of heat insulator, porous polystyrene, on all sides except the bottom. I put hot water in the calorimeter and then placed it on the surface of wet snow. It descended slowly into the snow by melting it and the temperature of the hot water in the calorimeter decreased. The melted water was quickly pulled in by the snow below the calorimeter and had no time to be warmed by it. So the heat expended for melting the ice in the wet snow should be equal to the heat delivered from the calorimeter, which can be known from the decrease in temperature of the hot water in it. The heat quantity divided by the latent heat of ice and by the volume of the melted snow gave the dry density ρ_d. I also used the electric calorimeter invented by Dr. de Quervain (1948) in Switzerland and by Miss Enju in Japan (Enju, 1951; Takahashi and Enju, 1951). This is a thermos flask with an electric heater in it. The temperature of the wet snow put in the flask is continually observed while the snow is being melted by an electric current. As long as the ice remains in the flask the temperature is maintained at 0°C and begins to rise at the moment when the snow is entirely melted. The heat quantity Q

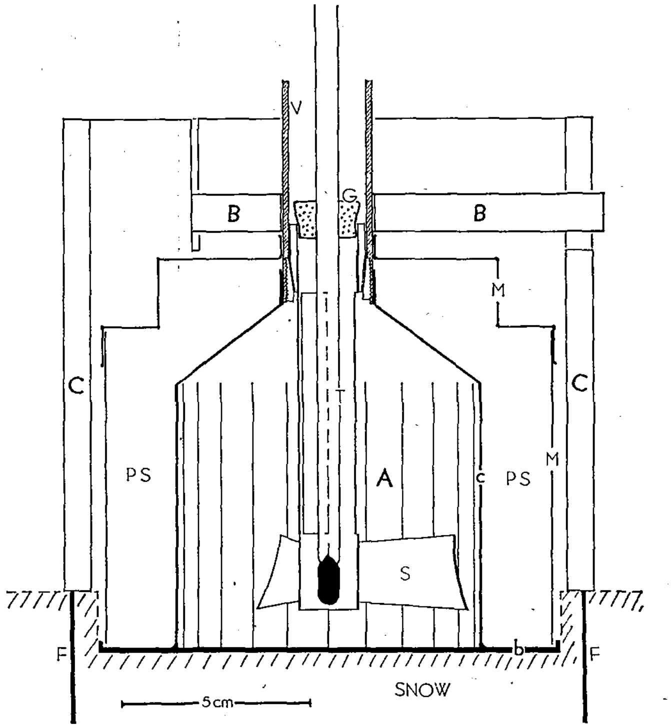


Fig. 6. Dry density meter. A, copper vessel with flat bottom b, insulated by layers of porous polystyrene PS. Hot water is put in this vessel. S, rotating stirrer; T, thermometer

used for melting the ice in the wet snow is given by the electric energy which was spent until that moment.

But we did not adopt either of these two calorimeters for practical use in the field, because we found that they would give rise to considerable errors in the measurement unless they were improved in many points.

V

Finally we came to the calorimeter which we named "combination calorimeter" and are now using (Yosida, 1959, 1960). Although I have written about it in the Journal of Glaciology and in *Teion Kagaku* (Low Temperature Science), the journal issued from our institute, I would like to take this opportunity to actually show you the apparatus.

The combination calorimeter is composed of two containers made of thin copper plate, the snow container and the hot water container. A thermometer, the top and bottom of which are bent at right angles to the scale, is fitted to the hot water container. As the bulb of the thermometer passes into a small channel formed in the bottom of the container, the temperature of the hot water in it appears accurately on the thermometer. The two containers each have a wide round mouth of brass and can be combined at their mouths as shown in Fig. 7. The rims of the mouths are tapered to make the joint air-tight. The containers are insulated, except at the mouth, by jackets of porous polystyrene, which in turn are each encased in a thin steel shell. The jackets consist of two parts, so that both containers can be withdrawn from them. The jacket on the hot water container has a long narrow window through which the thermometer can be read.

The bottle C with a capacity of approximately 250 cm^3 made of iron plate and

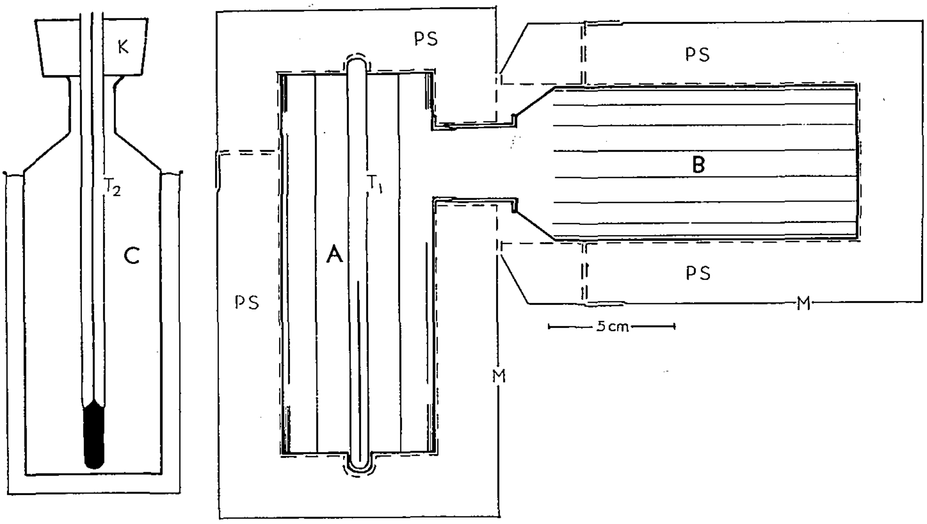
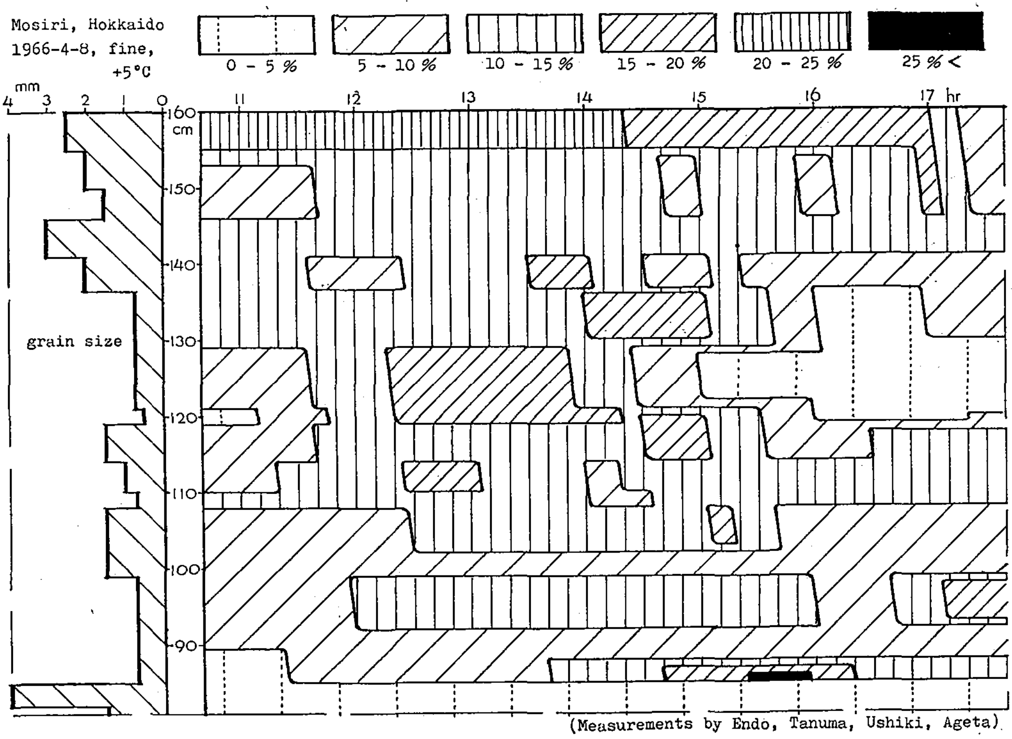


Fig. 7. Combination calorimeter. A, hot water container with thermometer T_1; B, snow container; PS, porous polystyrene, insulating material; C, bottle for measuring the hot water to be put in container A; T_2, thermometer with cork *K*

shown on the left side of Fig. 7 is for measuring the hot water to be put in the hot water container. The bottle is filled up to its mouth with hot water warmed by a kettle and oil burner used by mountaineers. A thermometer with a cock near its middle point is passed into the bottle so that the cork closes its mouth. By the use of a diagram prepared beforehand which relates the amount of hot water in the bottle with its temperature, we can know at once how much water is in the bottle. The temperature of the hot water should be a few degrees above 50°C.

The hot water is moved from the bottle to the hot water container of the calorimeter. The container is corked and placed in the jacket. In this state the hot water loses only 0.1°C in one minute. Then we collect the sample of wet snow in the snow container by pushing its beak into the snow cover. With its content of snow, the container is weighed on a small balance, corked and placed in the jacket.

We shake the hot container well to ensure even heat distribution and read the thermometer. Then we uncork both containers and join them at their mouths. We hold the combination in our hands and turn it upside down so that the hot water flows from the hot water container into the snow container. The water is moved three or four times from one container to the other by tilting the combination. In this manner the hot water and the snow are well mixed in one minute or so without any particular stirrer. When the mixing is finished, we read the thermometer again.



(Measurements by Endo, Tanuma, Ushiki, Ageta)

Fig. 8. Distribution of free water in an actual snow cover. Ordinates: Height above the ground. Abscissas: Time. Curves connect points of the same free water content expressed in percentage

The combination calorimeter does not differ in the principle of measurement from the old calorimeter which I used at first. But this new calorimeter has no stirrer and is so well insulated that no correction is needed for the heat straying out from the calorimeter. Furthermore, as no quick performance is required, we can work at a leisurely pace which even I can tolerate during the whole course of the measurement.

VI

Figure 8 is a map showing how the free water content changed with time in a snow cover lying on a sloping ground of an inclination of 17°. The height above the ground is taken vertically while the time is taken horizontally from left to right. The curves in the map are so drawn as to connect the points of the same free water contents expressed in percentage. To draw this map, one hundred and twenty measurements were made by four active young members of our institute using four separate combination calorimeters. As the duration of measurement was seven hours, it turned out that each individual made one measurement every fifteen minutes on an average. Of course, this time includes the time of preparation, sampling and rest.

It is five years since we began to use the combination calorimeter in the field. During that period, we have presented duplicates of the combination calorimeter to many snow scientists in our country and they are obtaining good results. At present we have several duplicates in reserve. If anyone among you wishes to have one, we shall be more than willing to make a gift of the instrument.

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