THERMAL CONDUCTIVITY OF SOME WEARING MATERIALS.

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Synopsis.

Thermal Conductivity of Woolen, Cotton, Linen and Silk Materials.—Measurements of the conductivity of samples of knitted and woven materials have been made by the disk method of Lees, corrected for variation of emissivity with temperature. From one to eight or more layers of one of the materials were held between two copper disks with a pressure of 6 gm./cm.^{2}, one disk being heated electrically by a coil between it and a third disk, and all three radiating to a constant temperature enclosure. The temperature of the samples was 30 to 40°. The values obtained are greater for dense than for loosely woven or knitted samples, ranging from 76 for unspun silk, 94 to 120 for wool, 101 to 122 for silk, 131 for flannelette, 158 to 167 for linen, to 168 to 184 for cotton, all times 10^{-6}. The results come out greater for several layers than for a few, and greater for moist than for dry samples. When the materials are arranged according to conductivity for equal weight instead of equal thickness, the order depends largely on the looseness of texture, beginning with unspun silk, loosely woven wool and knitted artificial silk, and ending with closely woven silk cotton and linen.

THE common textbooks on heat and the standard physical tables show both a lack of data, and great discrepancies in the results given for the thermal conductivity of materials such as wool, cotton, silk. Poynting and Thomson quote Péclet's value for wool .00012 and for cotton .00011. Edser gives the value .00003 for flannel, and Draper .00011 for wool and neither give values for cotton. The Smithsonian Tables (sixth edition) give .00012 for flannel, while three other well-known tables give the value .000035 with Forbes as authority. Lees obtained in 1892 for flannel the value .00023, and Lees and Chorlton in 1896 the value .00012, with no explanation of the difference. Similarly the values given for cotton vary from .00003 to .0005. It was hence suggested by Professor Laird that it would be worth while to undertake a new set of measurements of thermal conductivities of some materials used in clothing.

The method chosen was the disc method described in detail by Lees in the Philosophical Transactions of the Royal Society, A, 191, 1898. In the present experiment three copper discs, 4 cm. in diameter and approximately 3 mm. thick, were used. Copper and constantan wires were soldered at opposite ends of a diameter of each disc. Between the first and second discs was a flat heating coil, and between the second and third discs the material to be tested made into disc form. The whole was shellacked, tied with a silk thread, and suspended in a constant temperature enclosure made from a Lavoisier ice calorimeter, with oil between the walls. A thermocouple was soldered to the inner surface of the calorimeter. The other junctions of the thermocouples were in mercury cups outside the calorimeter, the temperature of which was read on a calibrated .1° thermometer. The various thermocouples were calibrated in position; a heating wire wound around in the oil filled space between the walls of the calorimeter, and separated from the inner wall by some pieces of wood, served to raise the temperature as required.

The formula for conductivity used by Lees for this disc method, with some change in notation, is:

$$k = H\frac{(\pi r^2+2\pi r t_3)v_3+\frac{1}{2}(v_2+v_3)\pi r t_s}{(\pi r^2+2\pi r t_3)v_3+\pi r t_s(v_2+v_3)+2\pi r t_2 v_2+(\pi r^2+2\pi r t_1)v_1}\times\frac{t_s}{(v_2-v_3)\pi r^2},$$

where H = total heat supplied,

r = radius of discs,

t_1, t_2, t_3, t_s = thickness of the three copper discs and of the substance respectively,

v_1, v_2, v_3 = temperature excess of the three copper discs over the surroundings.

In computing the thickness of the discs half the thickness of the heating coil is added to the first disc and half to the second. A correction for the heat conducted along the wires of the thermocouples is also made by adding $\sqrt{qkph}/2\pi rh$, where q is the cross section, p the perimeter, k the conductivity, and h the emissivity of the wires.

In the above formula it is assumed that for the intervals used the heat emitted per square centimeter by each disc is proportional to the corresponding temperature excess, or that the emissivity is a constant. In the course of the experiments it was found that this assumption is unjustified for the temperature range used. Accordingly separate observations were made on the rate of cooling of the discs and a curve plotted with emissivity and temperature as coordinates, this method was checked later by a measurement of the steady temperature attained by the two copper discs alone for different values of the heating current. This curve gave a correction factor to be used in each case with the above formula. The emissivity at 10° and 15° temperature excess was found to be 0.000256, and 0.000276 respectively; the difference is greater than that found by McFarlane.[1] The effect of the correction is to reduce the value of the conductivity over that given by the Lees formula from

[1] Smithsonian Tables, 6th edition, p. 252.

four to seven per cent., or up to ten per cent. in extreme cases, since the numerator should be reduced by a factor h_3/h_1 nearly, where h_1 and h_3 are the emissivities at the temperatures of the corresponding discs, and only one term of the denominator is reduced. In the conditions used by Lees the difference in temperature between the two sides of the substance being tested was smaller than here, but even in some of his experiments the correction would probably amount to over two per cent., and it is possible that some of the apparant decrease in conductivity with rise in temperature observed by him was due to failure to apply such a correction.

The power was supplied from a storage cell, and was measured by a volt-ammeter method. The voltmeter and ammeter were tested by potentiometer methods. A correction was applied for the heat lost in the connecting wires. No readings were used when the temperature of a disc changed more than .1° in 15 minutes, or when the difference in temperature on the two sides of the material being tested changed more than .05° in 15 minutes. The whole difference here was from 3° to 9°, but was usually between 3° and 4°, and the temperature of the material being tested was between 30° and 40°. Lees and Chorlton[1] worked out the problem of the variation of temperature in a brass disc similarly placed, and from their solution it would appear that the temperature throughout the copper discs used in these experiments could be considered uniform. As an experimental check the one thermocouple was soldered to the top of the upper disc for a time instead of in a small hole at the side and this alteration made no perceptible change in the results.

Twelve different wearing materials, and unspun silk were tested. Five were from common knitted underwear, namely, artificial silk, linen mesh, medium weight cotton, and two kinds of woolen wear, wool no. 1 a loosely knit light weight sample, wool no. 2 a more tightly knit one. The woven materials were cotton cloth, flannelette, a closely woven wool suiting, white dress linen, and three kinds of silk dress material. Silk no. 1 was a soft dress silk, pure except for the dye, silk no. 2 tussah silk, (wild silk), silk no. 3 white parachute silk (cultivated Japanese silk). Silks nos. 2 and 3 and the unspun silk (French cocoons combed) were kindly furnished by Cheney Bros. as pure silk. The knitted materials and the cotton cloth had all been washed many times, being cut from worn articles of clothing. The others were in new condition.

Several thicknesses were generally used in making the discs. The edges were sewed together with ravellings to make a smoother surface, and were coated with shellac, melted or in solution. In a number of

[1] Phil. Mag., 41, p. 497, 1896.

instances no shellac was used with no difference in the result. In order to check the values found and to see that no error was introduced due to a constant difference of temperature between the substance and the copper, experiments were made with discs of different thickness for most of the various materials. The values agreed for small thicknesses, but as the thickness increased the values increased as illustrated by a set of values obtained for the wool suiting, 125, 114, 119, 137, and 154×10^{-6} with discs of one, two, three, four and six layers respectively. It is evident that the formula is not intended for use when the difference in temperature on the two sides of the substance being tested is large, since it assumes that the temperature decreases uniformly in it and that the heat conducted through may be taken as the mean of that entering and leaving the disc. A formula was worked out by assuming a simple exponential distribution of temperature in the given disc, which gave relatively smaller values for the greater thicknesses, but not sufficiently smaller to bring them into agreement with the first values, and it probably did not take into consideration all the factors involved. It is true also that the correction for the variation of emissivity with temperature is large in these cases, and makes the results more doubtful.

The discs were kept in a drying chamber with calcium chloride, and calcium chloride was placed in the calorimeter. With one of the knitted woolen samples, that by chance was not dried before using, the value .000152 was obtained instead of .000120 as found later. It was hence suggested that the effect of moisture should be investigated. For this purpose the discs were left in a moist atmosphere, and a little water was put in the bottom of the calorimeter. When the discs were heated they naturally dried somewhat, so that in the steady state there was a limit to the moisture possible. Wool with 4 per cent. moisture gave a value .000099 as against .000093 when dry, and with 8 per cent. moisture a value .000104; and for a sample of cotton the value increased from .000185 to .000191 on an average for 1.5 per cent. moisture. These increases are less than those given by Lees and Chorlton (*l.c.*), and less than that suggested by the discrepancy noted with the earlier sample. Somewhat lower values on an average were obtained for cotton, wool and silk in months when the laboratory was heated, than in the summer, but the amount of moisture must have been small at any time as fresh calcium chloride was constantly used.

In carrying out the experiments the largest source of error apart from the effects of moisture is in the measurement of the thickness of the discs. It is thought that this error would not be more than 2 per cent. The materials were generally under a pressure of 6 gm./cm.^{2}, determined by the weight of the discs. Small constant errors in the calibration factor for the thermocouples, in the constants of the discs, and in the correction for the power used might amount to between 1 per cent. and 2 per cent. These errors would not affect the relative values. The "probable error" computed from the measurements on any one material is less than 1 per cent., except for the woven cotton where with a small number of measurements it is 2 per cent.

Table I. gives values of the conductivity obtained for knitted cotton at different times and with different samples and different thicknesses. They show fair agreement. Table II. shows in column 1 the materials used. Column 2 gives the thickness of a single layer of the material, column 3 its weight in grams per 100 sq. cm., column 4 the average value of the conductivity found not including the values for thick discs, column 5 this conductivity multiplied by the density. This latter is the flow of heat per sq. cm. per sec. for a unit difference of temperature between surfaces such that a gram of material would lie between, this may be called the conductivity per equal weight. Column 6 gives values obtained by Lees and Chorlton[1] by a slightly different method for some similar materials. The woolen materials show plainly the effect of loose texture in increasing warmth where wind is not a factor, both in the values of absolute conductivity and more strikingly in the conductivity for equal weight. The silk materials show this even more so, there being an approximately linear relation between conductivity and density, so that it should be possible to estimate the conductivity of any given sample fairly closely if the density were known. Extrapolating

TABLE I.

Cotton (Knit).

Date.	Number of Pieces.	Thickness.	Conductivity.
June 2, 1919	4	.32 cm.	.000191
June 6, 1919	8	.632 cm.	.000211
June 9, 1919	8	.632 cm.	.000212
June 9, 1919	6	.46 cm.	.000190
June 10, 1919	6	.46 cm.	.000194
July 25, 1919	4	.32 cm.	.000186
Feb. 18, 1921	4	.316 cm.	.000180
Feb. 19, 1921	4	.32 cm.	.000184
May 2, 1921	4	.32 cm.	.000180
May 5, 1921	4	.35 cm.	.000177
July 12, 1921	4	.344 cm.	.000182
July 15, 1921	4	.32 cm.	.000182
July 20, 1921	4	.32 cm.	.000184

[1] Phil. Mag., 5, 41, p. 495, 1896.

TABLE II.

Material.	Thickness per Piece.	Weight per 100 sq. cm.	Conductivity.	Conductivity × Density.	Conductivity, Lees and Chorlton.
Wool no. 1	.068 cm.	1.20 gm.	.000094	1.66×10^{-5}	
Wool no. 2	.126 "	2.65 "	.000120	2.53	.00012 (New flannel)
Wool suiting	.094 "	3.6 "	.000118	4.51	.00013 (Old flannel)
Unspun silk		.12[1] "	.000076	0.91	.0000613[2]
Silk no. 1	.0194 "	.578 "	.000101	3.00	.000095
Silk no. 2	.0138 "	.605 "	.000111	4.87	
Silk no. 3	.0138 "	.64 "	.000122	5.66	
Silk (artificial)	.045 "	.75 "	.000117	1.95	
Flannelette	.097 "	1.55 "	.000131	2.09	.00015
Cotton (woven)	.030 "	1.0 "	.000168	5.60	.00018 (Calico)
Cotton (knit)	.079 "	1.94 "	.000184	4.52	
Linen (mesh)	.098 "	2.6 "	.000158	4.19	
Linen (woven)	.033 "	1.95 "	.000167	9.87	.00021

[1] Density in gm./cm.^{3} under a pressure of 6 gm./cm.^{2}

[2] Rubner, Landolt and Bornstein Tables, 1905, p. 509.

however to pure silk (density 1.56) gives only about .0003 instead of .0008 as found by Rubner.[1] The advantage of wool over cotton for warmth shows up in column 5, for in considering the favorable position of flannelette, it should be recalled that the sample was new. The linen appears to have a distinctly lower conductivity than previous measurements show; one set of readings was made on an unbleached sample, of slightly less density, and a still lower value was found. From the results it may be inferred that at equal density the substances would come in the order silk, wool, artificial silk, linen, cotton, as to conductivity, and that of materials as actually found unspun silk is the warmest and woven linen the coolest, the linen changing place with cotton because of its actual greater density in manufacture.

In conclusion, the author expresses her appreciation of the aid received from Professor Laird in carrying out the experiment, and especially of the help in working out the correction of the errors involved.

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[1] Landolt and Bornstein Tables, 1905, p. 509.