THE THERMAL CONDUCTIVITY OF INDIAN TIMBERS

Part I. Variation of Conductivity with Density in the Air-Dry Condition at Ordinary Temperature

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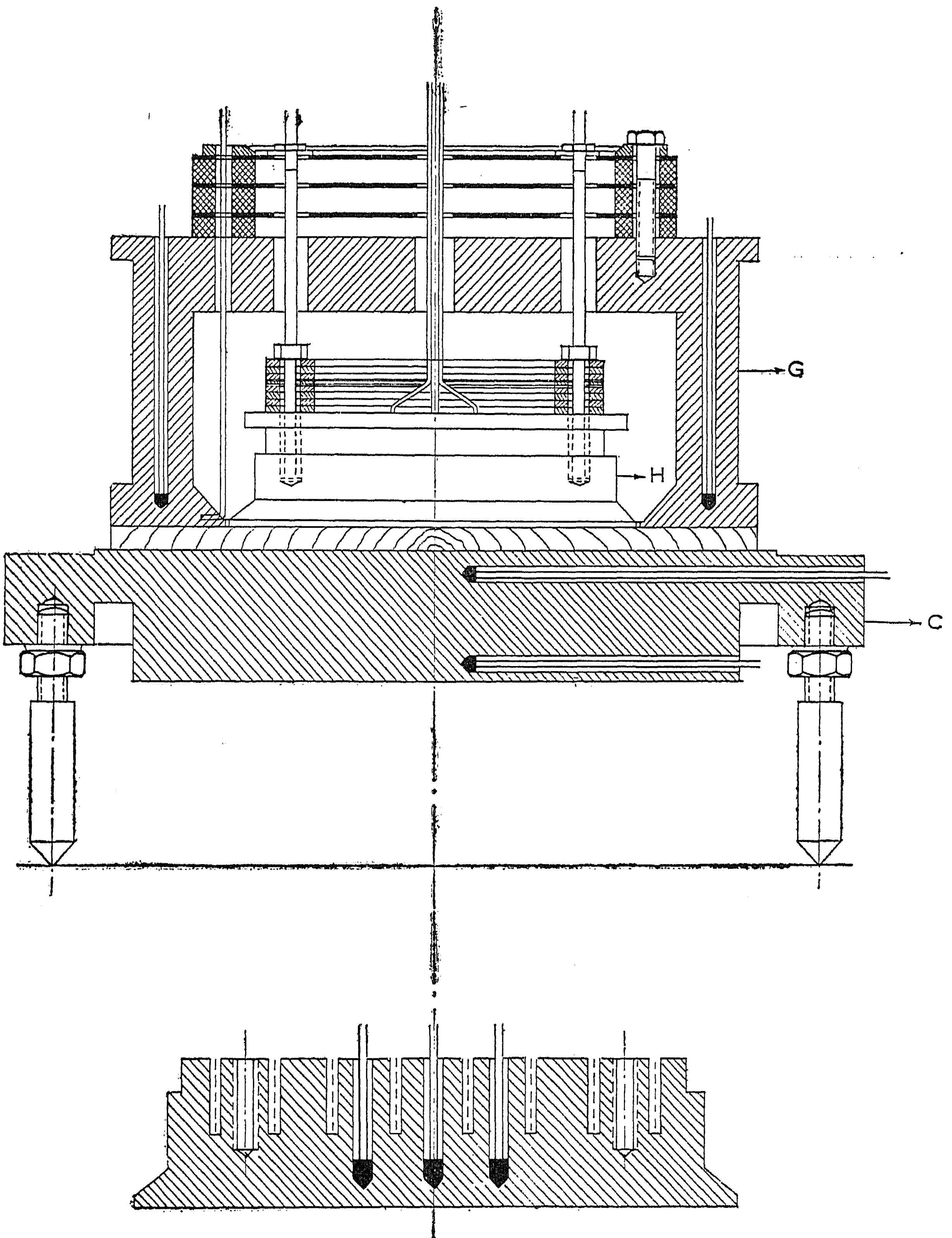
Introduction

The thermal conductivity of wood is an important property. As remarked by Cammerer (1938) while for good thermal insulating properties a substance should be porous, good strength properties on the other hand demand a compact structure. Structural and insulating materials should therefore satisfy both the requirements. Wood in this respect is in a specially advantageous position, for, in its case, the relation between thermal insulation and strength is extraordinarily favourable. Its low thermal conductivity makes it an ideal material for house construction, water pipes, tanks, casings, railway and other carriages, drying chambers, cold rooms, etc. Further, thermal conductivity in conjunction with volumetric specific heat determines the rate of temperature change in wood when it is heated or cooled. A knowledge of this is of interest and importance for studies in preservation, sterilisation, fire resistance, the drying of wood and in the making of plywood. Despite the importance of the thermal properties of wood accurate data on these properties are lacking to a large extent. Such few reliable data as may be available refer to European or American timbers. Apart from a small number of measurements carried out by Narayanamurti (1935) no data at all is available with regard to Indian timbers. The data published by Rowley (1933) for American woods deal with a density range of 409 Kg./m.^{3} to 745 Kg./m.^{3} Other data with regard to non-Indian timbers reported in the literature are not complete, in that the moisture content, temperature, density, etc., are not always given (*cf. The International Critical Tables*, Vol. II). Moreover, often the work has been carried out without taking all the necessary precautions one has to observe when dealing with timber.

In view of the above, it is the intention to investigate the thermal properties of Indian timbers in detail, and the present paper deals with the thermal conductivity of 56 timbers in the air-dry condition, varying in density from 265 Kg./m.^{3} to 1310 Kg./m.^{3} Future communications will deal with the effect of moisture content, temperature, etc.

The Apparatus.—The apparatus used in the investigation is schematically shown in Fig. 1. It is a guard-ring apparatus and is suitable for the measurement of the thermal conductivity of not only wood and similar materials but



also liquids. It differs from the usual guard-ring apparatus used in such studies in that it is a single plate apparatus. It is made of copper and consists of a cold-plate C on which the specimen to be tested is placed, and a hot-plate H of about 10 cm. diameter. The guard-ring G is shaped like a dome and is maintained at the same temperature as the hot-plate, the space between the upper surface of the hot-plate (which is also insulated) and the inner surface of the top of the guard dome being filled with air.

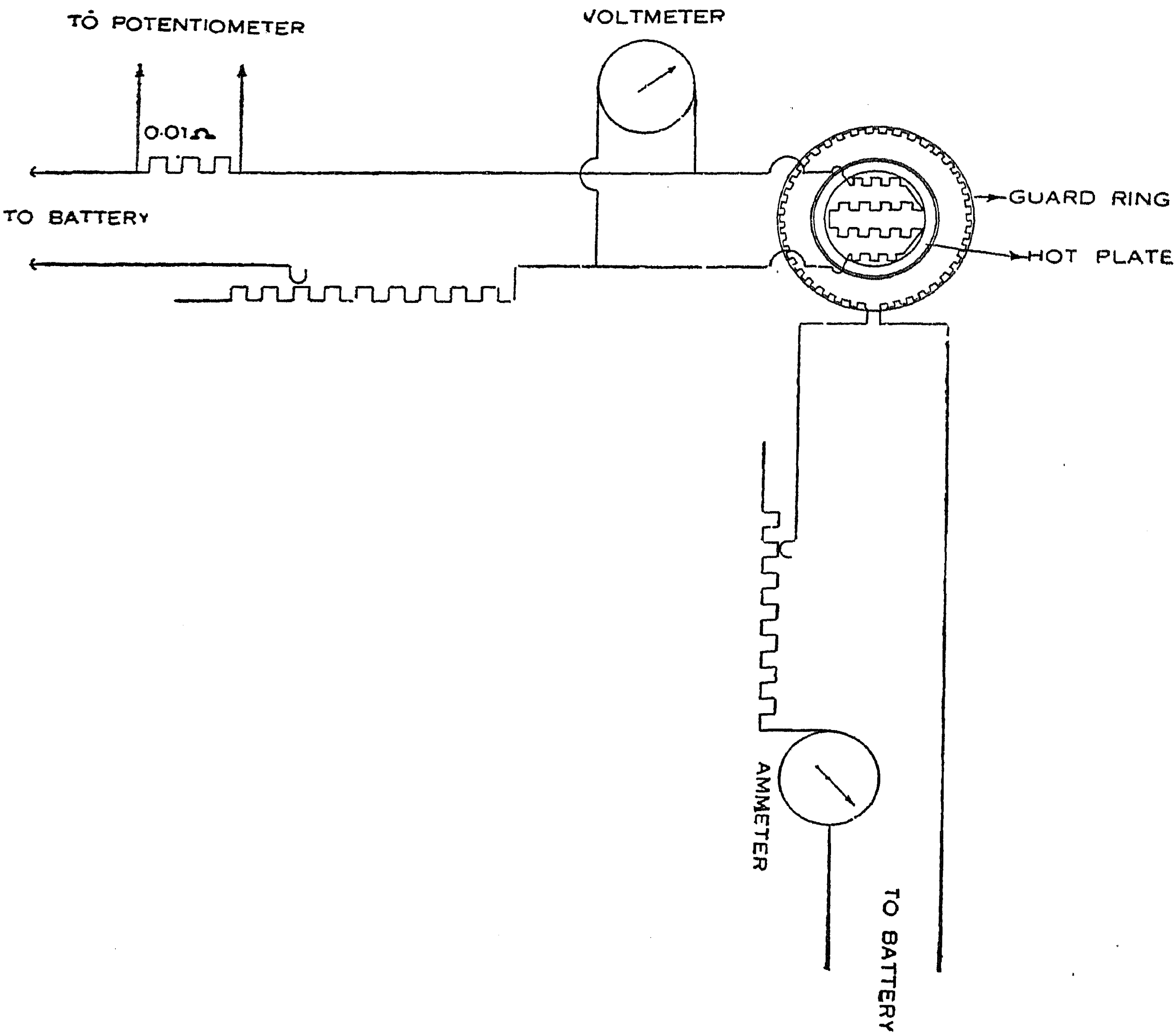


FIG. 2

Hot-plate, guard dome and specimen can be brought when required under a bell jar which sits on the outer rim of the cold-plate. By means of suitable salt solutions placed inside the bell jar any humidity corresponding to the moisture content of the specimen being tested can be maintained, thus avoiding any danger of the drying of the specimen during the test, which will result in incorrect values. This is of great importance in the study of hygroscopic materials and has been neglected by previous workers which sometimes led to erroneous results (especially at high moisture contents). Despite the fact that the apparatus is made of copper every care was taken in the design of the heating coil for the hot-plate so that the heating will be uniform throughout the plate. By the circulation of water of constant temperature the cold-plate was maintained at any desired temperature. A battery of accumulator cells of sufficient capacity was used, as the source of energy.

Material Used and the Preparation of the Test Specimens.—Fifty-six species of air-seasoned timbers that were available at the Forest Research Institute were included in this study. It is proposed to investigate other important timbers, as also the influence of the locality of origin, in the near future. The specimens were made from the heart-wood of the various species by the Wood Working Section and were kindly identified by the Wood Technologist of this Institute. The surfaces were made as smooth as possible. In order to avoid any error that might be caused by any slight irregularity that was still present the method of mounting the specimen devised by Narayanamurti (1936) was adopted.

Measurement of Temperature.—For the measurement of temperature, calibrated soft soldered manganin-constantan thermocouples (0·3 mm. diameter) were employed. The hot-plate was provided with three thermocouples, one embedded in the centre of the plate and the other two at points on either side of the centre on a diameter. In the case of the guard dome temperatures were measured at three points (being the apices of an equilateral triangle), at two points by means of thermocouples and at the third place by means of a standard mercury thermometer, thus ensuring a check on the calibration during any experiment. In the case of the cold-plate the temperature was likewise measured at three points by means of suitably located thermocouples. For the measurement of the thermal e.m.f.s a Tinsley Diesselhorst thermo-electric potentiometer with a Tinsley galvanometer of about 10 ohms coil resistance and a deflection of 130 millimetres at 1 metre per micro-ampere as null instrument was used.

Measurement of Energy.—The electrical energy supplied for the production of heat was measured in two ways: In some experiments the current in the hot-plate coil and the potential difference across its terminals were measured with the help of a Siemens precision volt- and ammeter with the necessary shunts and series resistances. In the second method the current was measured by determining the potential difference across a 0·01 ohm standard resistance connected in series with the hot-plate coil. This potential difference was measured by means of the Diesselhorst potentiometer. The potential difference across the heating coil was measured in this case also with the help of the precision voltmeter.

Measurement of Thickness, etc.—The thickness of the specimens was measured at a number of places by means of vernier callipers or micrometer screw gauge and the average taken. In addition, by measuring the area of the specimen and weighing it, its volume and density were calculated. For the determination of the moisture content the oven drying method was adopted.

Accuracy of the Measurements.—Temperature measurements could be read to an accuracy of 0·01° C. with ease. The measurement of the heat input was accurate to 0·2%, as a calibrated precision instrument was used and 0·1 division of a division in a range of 150 scale divisions could be read. While individual measurements of the thickness were accurate to 0·1%, the variation between the mean and the individuals was higher. On the whole it is estimated that the conductivity values are accurate to 1% in most cases and 2% in the unfavourable cases.

Experimental Procedure.—The general procedure of carrying out a test was to put the specimen in the apparatus, when the heat supply was switched on and adjusted from time to time till the desired temperature was attained for the hot-plate. Care should be taken not to heat the plate above the desired temperature. It was therefore brought up to that temperature slowly. With moist materials there is a movement of moisture whenever a temperature gradient exists and if the temperature of the hot-plate is above the desired experimental temperature, errors may be caused due to this moisture movement. To cut down this movement of moisture to a minimum, a temperature difference of about 6° C. on an average was used. Theoretical calculations of Krischer (1934) show that as long as the ratio of the thermal conductivities of the extreme boundary layers of the material does not exceed 2, the value obtained does not deviate from the true value significantly. When the ratio is 2, the deviation from the correct value is 3·5%, it being considerable when the ratio exceeds 2. The temperature of the guard dome was also brought to the same temperature as that of the hot-plate by careful adjustment of the current in its heating coils. The apparatus was then left undisturbed with a constant energy input from the battery. Readings of temperature, current and voltage were taken once every fifteen minutes or half an hour and after the steady state was reached observations were continued for a further period of at least about two hours.

Evaluation of the Experimental Data.—For the calculation of the thermal conductivity the following equation was used:

$$k = \frac{d \cdot Q}{A\,(t_1 - t_2)},$$

where k is the thermal conductivity in K.cal./m. h. °C.,

d is the thickness of the specimen in m,

A is the effective area of the specimen in m^2,

Q is the heat energy produced in the hot-plate in K.cal./h.,

t_1 is the mean temperature of the hot-plate in °C., and

t_2 is the mean temperature of the cold-plate in °C.

The method of evaluation of the experimental data can best be illustrated by means of a typical example.

Example of the evaluation of the experimental data for Michelia *Sp.*: *Experiment carried out on* 24–2–1940. *Direction of heat flow*: Radial.

Heating current	Mean value of the e.m.f. of the thermocouples	
	Hot-plate	Cold-plate
0·140 amp., 4·83 volt.	0·987 mv.	0·713 mv.
Mean temperatures	0·987 mv. = 23·30° C.	0·713 mv. = 17·15° C.

Thickness of the specimen	d = 0·01009 m.
Effective area of the specimen	A = 0·008079 m.^{2}
Mean temperature of the hot-plate	t_1 = 23·30° C.
Mean temperature of the cold-plate	t_2 = 17·15° C.
Temperature difference between the hot-plate and the cold-plate ..	$t_1 - t_2$ = 6·15° C.
Watts dissipated	E.I. = 4·83 × 0·14 watt = 0·6762 watt
Voltmeter correction	$\frac{(4\cdot83)^2}{5000}$ = 0·00467 watt
Corrected heat input	= 0·6715 watt

Thermal conductivity according to equation

$$(1)\ k = \frac{d \cdot Q}{A\,(t_1 - t_2)} = \frac{0\cdot01009}{0\cdot008079} \cdot \frac{0\cdot6715 \times 0\cdot86}{6\cdot15} = 0\cdot1172 \frac{\text{K.cal.}}{\text{mh °C.}}$$

Results and Discussions

The results of all measurements are given in Table I. The conductivity is represented as a function of the density in Fig. 3, and as a function of

TABLE I

No.	Species of timber	Direction of heat flow	Moisture content %	Mean temperature °C.	Density* Kg/m.³	Percentage air space	Thermal conductivity K cal/mh °C.
1	*Bombax* sp.	Radial	12·2	20·78	265·0	81·4	0·07342
2	*Cryptomeria japonica* ..	do.	9·7	20·47	287·0	79·97	0·07513
3	do. ..	do.	..	20·39	304·0	..	0·08012
4	*Bombax* sp.	do.	..	31·0	400·0	..	0·08751
5	*Erythrina* sp.	do.	11·7	20·52	427·0	70·05	0·0871
6	*Gmelina arborea*	do.	8·8	20·53	431·0	69·99	0·1014
7	*Anthocephalus cadamba* ..	Radial-Tangential	9·8	20·72	439·0	69·36	0·1043
8	*Abies pindrow*	do.	13·0	20·66	442·8	68·85	0·0959
9	*Pinus longifolia*	do.	12·9	20·21	444·0	68·77	0·0959
10	*Machilus* sp.	do.	11·0	20·11	459·0	67·87	0·1012
11	*Pinus excelsa*	do.	..	20·40	480·0	..	0·0933
12	*Terminalia* sp.	do.	8·0	20·57	522·0	63·72	0·0988
13	*Cedrus deodara*	do.	7·0	21·00	542·0	62·42	0·1124
14	*Swintonia* sp.	do.	10·0	20·49	559·0	60·96	0·1190
15	*Michelia* sp.	Radial	12·1	20·23	564·0	60·40	0·1172
16	*Cupressus torulosa*	do.	13·2	20·50	570·0	59·86	0·1143
17	*Picea morinda*	Tangential	14·0	20·94	571·0	59·68	0·1034
18	*Terminalia* sp.	Radial-Tangential	10·4	20·35	586·0	59·05	0·1063

19	*Adina cordifolia*	Tangential	9·6	20·17	593·0	...	0·1281
20	*Morus* sp.	Radial-Tangential	11·1	20·80	625·0	56·24	0·1434
21	*Artocarpus* sp.	Tangential	11·7	20·45	643·0	54·92	0·1395
22	*Holoptelea integrifolia* ..	Radial	7·7	30·04	651·9	54·72	0·1448
23	*Cedrela toona*	Tangential	10·5	20·22	672·0	53·02	0·1474
24	*Tectona grandis*	do.	10·8	20·22	672·0	52·98	0·1222
25	*Pentace* sp.	Radial	10·3	20·95	675·0	52·83	0·1360
26	*Parashorea stellata* ..	Radial-Tangential	11·7	20·56	679·0	52·39	0·1284
27	*Calophyllum* sp.	do.	13·9	20·74	684·0	51·75	0·1370
28	*Albizzia* sp.	do.	12·0	20·23	685·0	51·93	0·1264
29	*Schima wallichii*	do.	13·1	20·35	737·0	48·13	0·1308
30	*Albizzia* sp.	do.	11·6	20·09	754·0	47·14	0·1458
31	*Amoora* sp.	Radial	10·9	27·95	755·0	47·17	0·1485
32	*Pterocarpus marsupium* ..	do.	..	20·31	755·0	..	0·1722
33	*Lagerstrœmia* sp.	Tangential	13·2	20·81	767·0	46·00	0·1400
34	*Dalbergia latifolia*	Radial	10·6	20·50	779·0	45·52	0·1828
35	*Albizzia* sp.	Tangential	12·5	23·70	798·0	43·93	0·1641
36	*Palaquium* sp.	Radial-Tangential	13·1	20·18	806·0	43·28	0·1514
37	*Stereospermum* sp.	Radial	11·8	20·15	808·0	43·32	0·1473
38	*Bischofia javanica*	Tangential	14·2	20·22	808·0	42·97	0·1472
39	*Carallia lucida*	Radial	9·0	20·55	809·0	43·65	0·1484
40	*Pentace* sp.	do.	10·6	20·48	816·4	42·89	0·1390

* The density values relate to whole specimens and are accurate to 2 to 3%.

TABLE 1 (*Contd.*)

No.	Species of timber	Direction of heat flow	Moisture content %	Mean temperature °C.	Density Kg/m.^{3}	Percentage air space	Thermal conductivity K cal/mh °C.
41	*Terminalia* sp.	Radial	12·8	20·44	865·0	39·17	0·1523
42	*Homalium* sp.	Radial-Tangential	12·8	22·54	867·0	39·03	0·1884
43	*Pterocarpus macrocarpus* ..	Radial	9·2	20·70	894·0	37·70	0·1813
44	*Quercus* sp.	Tangential	12·4	19·66	897·0	36·99	0·1631
45	*Terminalia* sp.	Radial	10·9	19·92	898·0	37·15	0·1618
46	*Dalbergia sissoo*	Tangential	10·2	20·01	916·0	36·01	0·1901
47	*Anogeissus* sp.	Radial-Tangential	11·5	22·73	953·0	33·21	0·2029
43	*Terminalia tomentosa* ..	Radial	12·0	20·45	972·0	31·78	0·1987
49	*Carapa* sp.	do.	11·0	20·58	975·0	31·75	0·1969
50	*Dipterocarpus* sp.	Radial-Tangential	13·1	20·04	1014·0	28·65	0·1846
51	*Dalbergia* sp.	Radial	9·4	20·35	1027·0	28·39	0·2026
52	*Todallia bilocularis* ..	do.	12·1	23·91	1038·0	27·12	0·2132
53	*Hopea* sp.	Tangential	13·0	20·53	1064·0	25·13	0·2014
54	*Dalbergia* sp.	Radial	8·5	25·55	1070·0	25·54	0·2100
55	*Millettia* sp.	do.	8·9	19·87	1080·0	24·79	0·2119
56	*Xylia* sp.	do.	11·6	20·24	1112·0	22·05	0·2139
57	*Hardwickia binata*	Radial-Tangential	12·9	20·42	1156·0	18·45	0·2271
58	*Diospyros ebenum*	Radial	12·9	20·35	1310·0	7·89	0·2286

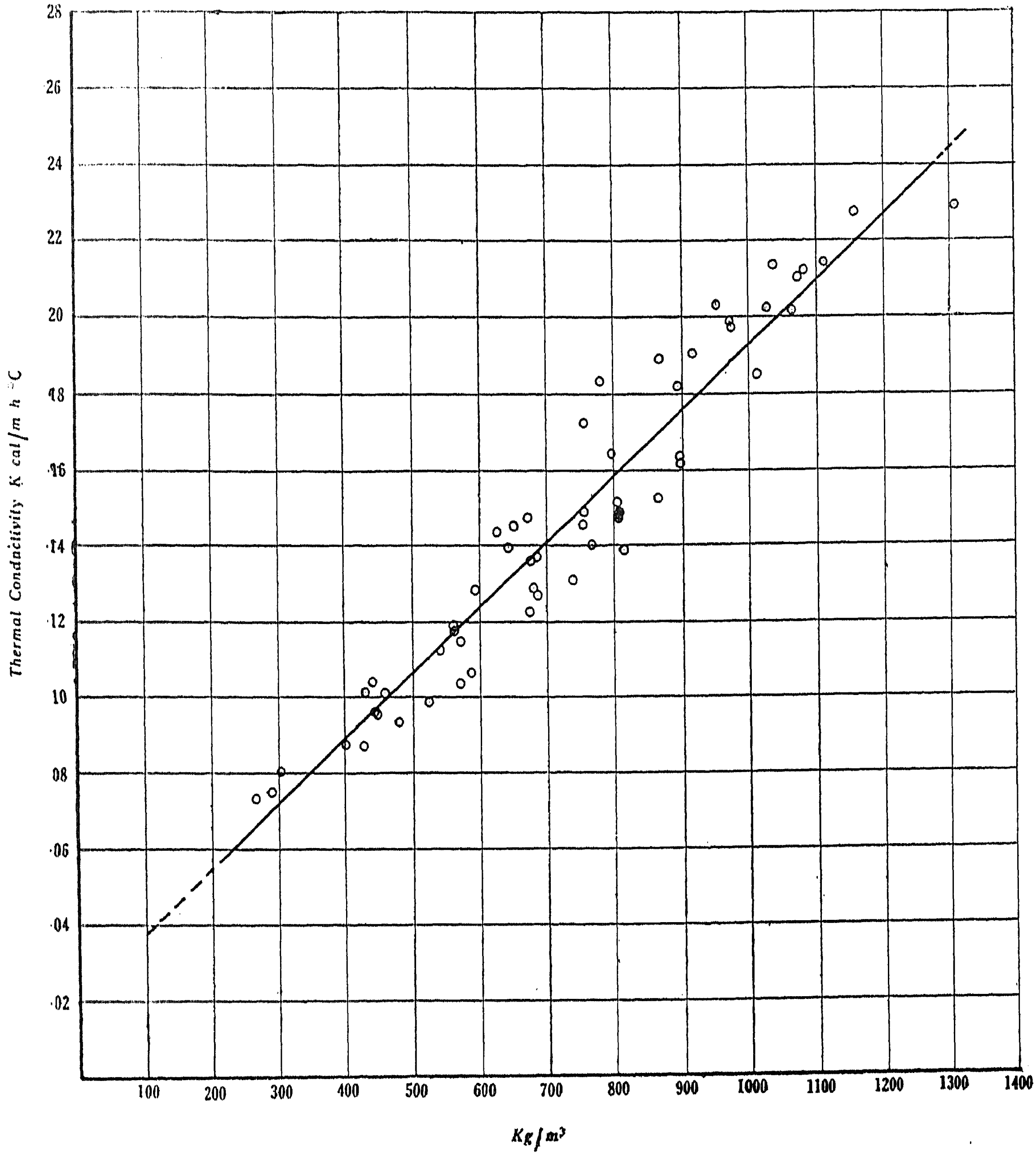
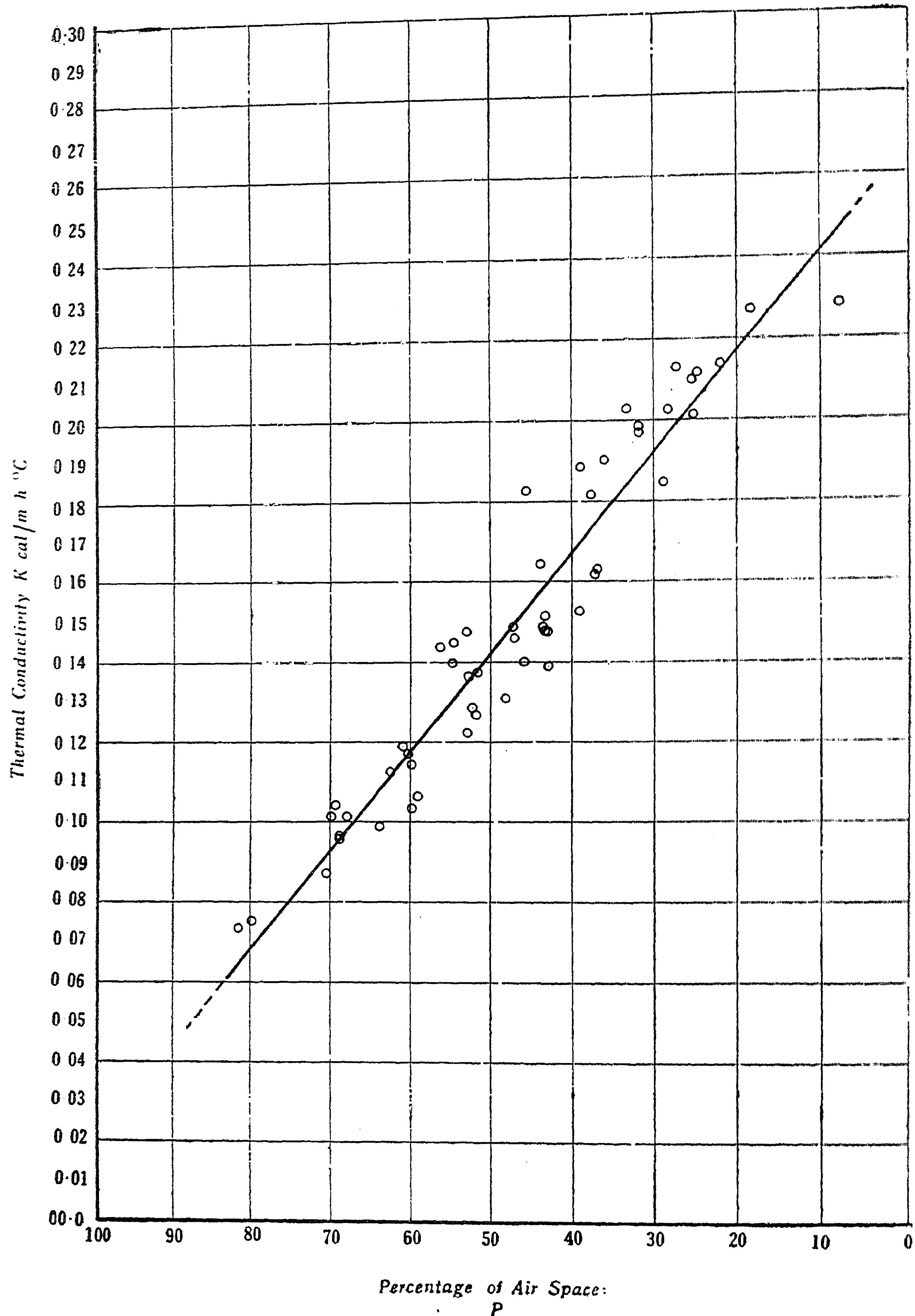


FIG. 3

the porosity in Fig. 4. The percentage of the air space in the wood was calculated according to MacLean's (1938) formula:

$$P = \left[1 - S\left(\frac{1}{1 \cdot 46} + \frac{M_f}{(100)\, d_f} + \frac{M_a}{(100)\, d}\right)\right] 100, \qquad (2)$$

where P is the percentage of air space, S is the specific gravity of the wood based on the oven-dry weight and volume at current moisture content, d_f is the density of water in the cell walls, d the density of the water in the cell cavities, M_f the percentage of moisture in the cell walls and M_a is the percentage of moisture above the fibre saturation point. The density of wood substance is taken as 1·46 g./cm.[3]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Thermal Conductivity K cal/m h °C
100
90
80
70
60
50
40
30
20
10
0
Percentage of Air Space:
P

The measurements reported cover a density range of 265 Kg./m.^{3} to 1310 Kg./m.^{3}, and perhaps represents the first set of values covering this entire range from a single laboratory. The percentage air space in the timbers studied varied from 7·89 to 81·4. The conductivity appears to be a linear function of the density. The graph is similar to those of Cammerer (1938), Rowley (1933) and Metz (1936). Kollmann (1934) on the other hand believes that the ralationship between thermal conductivity and density is best represented by the following empirical relationship:

$$k = 0{\cdot}15\left(\frac{R}{1000}\right) 1{\cdot}5 + 0{\cdot}04. \qquad (3)$$

According to Kollmann, the constant factor 0·4 is the value for the limiting case of zero density, *i.e.*, when the pore volume is 100%. This he believes to be the value for air under the conditions of convection and radiation that can be expected for wood pores. If the curve in Fig. 3 is extrapolated it cuts the conductivity axis at about 0·2 which is considerably less than the value given by Kollmann but rather close to the conductivity of still air. Following Schmidt (1927) the apparent conductivity k_w may be considered to be the sum of the conductivity of the substance k, the conductivity due to convection k_k and the conductivity due to radiation k_s. Thus

$$k_w = k + k_k + k_s. \qquad (4)$$

According to Kraussold (1934) the ratio of the heat transmitted by convection to that transmitted by pure conduction k_k/k for plane and cylindrical air layers can be represented as a function of the product of the Grashof and Prandtl numbers (Gr. Pr.). It can be shown (*cf.* Schmidt, 1936) that for an air layer of 1 cm. in thickness the increase in conductivity due to convection is only about 10%, and for an air layer of 1 mm. thickness it is practically zero. Schmidt (1927) expresses the conduction due to radiation by

$$k_s = \frac{d\,C_s}{1/E_1 + 1/E_2 - 1} \quad \frac{\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4}{T_1 - T_2}, \qquad (5)$$

where $C_s = 4{\cdot}96$ K.cal./m.^{2}h. degree^4 is the black body radiation constant, T_1 and T_2 the absolute temperatures and E_1 and E_2 the emissivities of the surfaces which are in radiative exchange. With $E = 0{\cdot}9$ for wood it is seen that for air layers 0·5 mm. in thickness k_s is 0·00205 K.cal./m.h. °C. and k_k is zero. Under these conditions k_w will be

$$k_w = k + k_k + k_s = 0{\cdot}0215 + 0{\cdot}0 + 0{\cdot}00205 \text{ K.cal./m.h. °C.}$$

$$= 0{\cdot}02355 \text{ K.cal./m.h. °C. at 20 °C.}$$

It must be pointed out, however, that the problem has here been simplified by assuming the pores to be bounded by parallel surfaces perpendicular to the direction of heat flow. It is proposed to go into the subject in detail when more data have been accumulated. The diameters of wood cells are on the average less than 0·5 mm. The limiting value of 0·04 given by Kollmann appears to be improbable and the figure obtained in the present investigation appears to be nearer the theoretical value to be expected. In addition, a great majority of the experimental points lie above Kollmann's curve indicating that the relationship proposed by him does not correctly represent the experimental data.

Coming to the results of the present experiments it is interesting to note that the values for *Abies pindrow* and *Pinus longifolia*, *Albizzia* sp. (No. 30) and *Amoora* sp. (No. 31), *Stereospermum* sp., *Bischofia javanica* and *Carallia lucida*, *Quercus* sp. and *Terminalia* sp. (No. 45), *Terminalia tomentosa* and *Carapa* sp. show good agreement even though the tests were carried out on different days. On the other hand, differences in the values for timbers of the same density are noticeable, *e.g.*, *Cupressus torulosa* and *Picea morinda*, *Cedrela toona* and *Tectona grandis*, *Calophyllum* sp. and *Albizzia* sp. (No. 28), *Albizzia* sp. (No. 30) and *Pterocarpus marsupium*, and *Terminalia* sp. and *Homalium* sp. Among the specimens tested the *Terminalias*, *Tectona grandis*, *Schima wallichii*, *Carallia lucida* and *Pentace* sp. (No. 40) had a comparatively low value, while *Dalbergia latifolia* and *Pterocarpus marsupium* showed a high value, thus indicating that while a general density-conductivity relationship exists some species and specimens may show a fairly wide variation from the values demanded by this relationship. It is possible that various species can be divided into groups where the variation of conductivity with density, etc., will follow the same relationship. But a large volume of data will have to be accumulated before attempting any such analysis.

Comparison with the Results of Other Investigators.—Values for European and American timbers reported by Griffiths and Kaye (1924) and Rowley (1933) are given for comparison in Table II. The agreement with the results of the present investigation in general may be considered to be good, Rowley's values being in closer agreement than the results of Griffiths and Kaye. For the densities of timbers studied by Rowley the conductivity values read from the curve, Fig. 3, give values in satisfactory agreement with the experimentally determined values and the latter values are more or less evenly distributed on both sides of the curve. On the other hand, the values derived from Kollmann's curve are all lower than the experimentally determined values. As mentioned while discussing the results, sometimes for

TABLE II

Thermal Conductivity across the Grain of Different European and American Woods

Authority: 1–19, Griffiths and Kaye; 20–41, Rowley

No.	Species of timber	Direction of heat flow	Moisture content %	Mean temperature °C.	Density Kg. m.^{3}	Thermal conductivity Kcal/m.h.°C
1	Balsa	Tangential	13·0	20	100·0	·0396
2	Spruce	Radial	16·0	,,	410·0	·1045
3	do.	Tangential	16·0	,,	410·0	·0900
4	do.	Radial	16·2	,,	410·0	·0871
5	do.	Tangential	16·2	,,	410·0	·0853
6	Cedar	do.	13·0	,,	480·0	·0972
7	Fir	Radial & Tangential	15·0	,,	600·0	·1008
8	Oak	Tangential	14·0	,,	600·0	·1008
9	Walnut	Radial	12·0	,,	650·0	·1260
10	do.	Tangential	12·0	,,	650·0	·1188
11	Mahogany	Radial	15·0	,,	700·0	·1440
12	do.	Tangential	15·0	,,	700·0	·1332
13	do.	Radial	14·9	,,	700·0	·1498
14	do.	Tangential	12·7	,,	700·0	·1393
15	Teak	do.	10·0	,,	720·0	·1188
16	Ash	Radial	16·0	,,	740·0	·1670
17	do.	Tangential	16·6	,,	740·0	·1498
18	do.	Radial	15·0	,,	740·0	·1512
19	do.	Tangential	15·0	,,	740·0	·1404
20	Cedar, western ..	Across the grain	12·0	24	410·5	·0893
21	Fir, white	do.	,,	,,	400·5	·0806
22	Pine, sugar	do.	,,	,,	408·5	·0856
23	Redwood	do.	,,	,,	416·5	·0942
24	Spruce, sitka ..	do.	,,	,,	425·5	·0843
25	Pine, northern white ..	do.	,,	,,	440·6	·1029

TABLE II (*Contd.*)

No.	Species of timber	Direction of heat flow	Moisture content %	Mean temperature °C.	Density Kg. m.^{3}	Thermal conductivity Kcal/m.h.°C
26	Hemlock, eastern ..	Across the grain	12·0	24	456·5	·0992
27	do. western ..	do.	,,	,,	456·5	·0942
28	Cypress, southern ..	do.	,,	,,	464·6	·1029
29	Pine, Norway ..	do.	,,	,,	480·6	·1042
30	do. ponderosa ..	do.	,,	,,	488·6	·1054
31	Elm (soft)	do.	,,	,,	520·6	·1128
32	Douglas fir	do.	,,	,,	528·6	·0955
33	Pine, short-leaf ..	do.	,,	,,	544·7	·1215
34	do. long-leaf ..	do.	,,	,,	608·7	·1191
35	Larch, western ..	do.	,,	,,	624·7	·1227
36	Maple (soft) ..	do.	,,	,,	624·7	·1300
37	Ash, white	do.	,,	,,	640·8	·1302
38	Birch, yellow ..	do.	,,	,,	688·8	·1240
39	Maple (hard) ..	do.	,,	,,	712·9	·1438
40	Oak, red	do.	,,	,,	720·9	·1488
41	do. white	do.	,,	,,	744·9	·1513

Rowley's values taken from the *Wood Hand-book*, U.S. Dept. of Agriculture, September 1935, p. 44.

the same density appreciable differences in the conductivity values are also noticeable in the results of Rowley as well as of Griffiths and Kaye.

Summary

Accurate data on the thermal conductivity of 56 species of Indian timbers, varying in density from 265 Kg./m.^{3} to 1310 Kg./m.^{3} in the air-dry condition at about 20° C., are reported.

The data represent the first set of results covering this entire range of density reported from a single laboratory.

The influence of convection and radiation on the conductivity of wood is discussed and the results compared with those of other investigators.

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