MECHANISM OF HEAT FLOW IN FIBROUS MATERIALS

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ABSTRACT

A systematic investigation of the thermal conductivities of specimens composed of fibrous materials has been made. The experiments were designed to show the effects of such factors as density of packing, arrangement of fibers, kind and size of fibers, moisture content, air convection, and radiation, on the resultant conductivity of the specimens. Data on various mixtures of fibers were obtained, and it was found that in most cases the conductivity of the mixture lies between those of the constituents, taking the conductivity of each constituent which corresponds to a density equal to the density of the mixture.

It was found that for a given fibrous material and a given density, the conductivity may vary by several hundred per cent, depending entirely on the arrangement of the fibers. The maximum conductivity is obtained when the fibers are parallel to and the minimum conductivity when the fibers are perpendicular to the direction of heat flow. There is included a discussion of the part which contact resistance between the fibers may play in the over-all heat transfer.

At very low densities it was found that radiation plays an important part in the heat transfer; air convection plays a very minor part.

CONTENTS

		Page
I.	Introduction	973
II.	Thermal conductivity of packed fibrous materials in "bone-dry" condition	974
III.	Effect of moisture	977
IV.	Thermal conductivity of mixtures	978
V.	Effect of arrangement of fibers	979
VI.	Convection and radiation	983
VII.	Conclusions	984

I. INTRODUCTION

Fibrous materials, or those which can readily be reduced to fibers, represent one of the most important raw products for the manufacture of insulating materials for use at ordinary temperatures. Future developments in insulation may depend to a large extent on a knowledge of the insulating properties of such fibrous materials, as well as on the mechanism of heat flow through them.

A systematic investigation of the thermal conductivities of specimens of fibrous materials has been made. The experiments were designed to show the effects of such factors as density of packing, arrangement of fibers, kind of fibers, moisture content, air convection, and radiation on the resultant conductivity of the specimens.

Since the primary object of this work was to throw more light on the mechanism of heat flow, rather than to investigate the utility of various materials as insulators from all points of view, no mention is made of such questions as resistance to deterioration, fire hazard, workability, cost, etc., all of which influence the selection of a material for a particular purpose.

II. THERMAL CONDUCTIVITY OF PACKED FIBROUS MATERIALS IN "BONE-DRY" CONDITION

All measurements of thermal conductivity were made in a so-called "flat hot-plate" apparatus, with a guard ring, the outside dimensions being 8 by 8 inches. This apparatus has been described in several publications.[1]

Loose materials were packed within a wooden frame 8 inches square and 1 inch deep, so that when placed between the plates of the conductivity apparatus, the specimens were in the form of flat slabs 1 inch thick and nearly 8 inches square. For convenience in handling, the loose material was confined in the frame by thin paper over both surfaces. In the tests listed in this section and also those of section III, the specimens were prepared by packing the fibers in the frames from the 8 by 8 inch face without attempting to arrange the fibers in any particular direction, which resulted in their being arranged for the most part with their lengths perpendicular to the direction of heat flow.

The mean temperatures of the specimens during test were approximately 32° C., and for convenience this temperature was selected as a reference temperature to which all results were reduced, using the formula $K_t = K_{32}[1+\alpha\ (t-32)]$, where K_t is the observed conductivity corresponding to the mean temperature t° C. and K_{32} is the value corresponding to 32° C. The coefficient α has been taken equal to 0.0032; this is an average of values given for numerous materials.[2] It should be noted that for two extreme cases, where $\alpha = 0.0018$ and $\alpha = 0.0054$, respectively, and for $t-32=5$, the values for K_{32} do not differ by more than 1 per cent from those given in this paper. The values of K_{32} for any specimen may be considered accurate within 2 per cent, although some of the specimens were not reproducible to this accuracy.

In Table 1 are given the results obtained on various dried materials, each specimen being heated overnight at about 100° C. before test. Some of the data of Table 1 are plotted in Figure 1.

It will be noted that bagasse, wood pulp, and cornstalk pulp, which consist of rather coarse fibers, have about the same insulating value. Specimens made from finer fibers, such as jute, cotton, etc., have lower conductivities. The conductivity of asbestos wool appears to be anomalous, for this material has a very much higher conductivity than most others examined, even though the fibers were very fine. Comparing asbestos wool with rock wool, which is also mineral in character, the conductivity of the former lies within the upper range while that of the latter is at the lower range of the conductivities observed. Certain experiments to be described below may throw light on the cause of this anomalous behavior of asbestos wool.

From Figure 1 it will be seen that for each material there is a certain density, referred to in this paper as the "optimum" density, which corresponds to a minimum conductivity. For greater densities the conductivity increases with the density at an approximately uniform rate. As the density of the insulating material approaches zero, the conductivity will approach that of an air space of similar

[1] M. S. Van Dusen, J. A. S. H. V. E., 26, pp. 625–656; October, 1920; Van Dusen and Finck, Proc. Am. Inst. Refrig., pp. 137–150, May, 1928.
[2] See second reference footnote 1.

dimensions, orientation, and bounding surfaces. For a vertical air space 1 inch in width, bounded by paper (as were these specimens of insulation), with a temperature difference of 30° C. and a mean temperature of 32° C., the heat transfer will be as high as 1.7 milliwatts cm^{-1} $deg.^{-1}$ C. It is therefore obvious that the apparent conductivities at densities less than the optimum will have to increase at a very high rate as the density approaches zero.

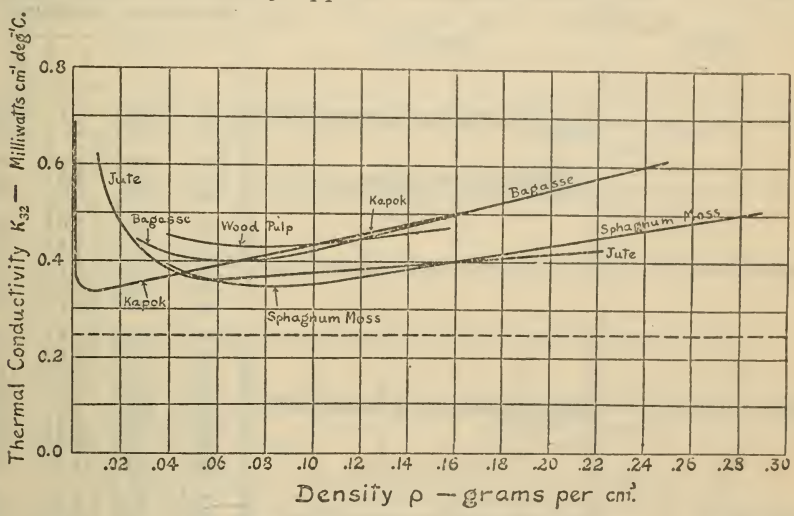

FIGURE 1.—*Thermal conductivity for different densities, in bone-dry conditions. The dotted line represents the conductivity for still air with no radiation*

TABLE 1.—*Thermal conductivity of materials in bone-dry condition*

ρ=density in g/cm³
d=density in lbs./ft.³
K_{32}=conductivity in milliwatts/cm °C. for a mean temperature of 32° C.
k_{90}=conductivity in $\frac{\text{B. t. u.}}{\text{hr. ft.}^2\ °\text{F./in.}}$ for a mean temperature of 90° F.
$1\frac{\text{B. t. u.}}{\text{hr. ft.}^2\ °\text{F./in.}}$=1.441 milliwatts/cm °C.

Material	Description	Metric units		British units	
		ρ	K_{32}	d	k_{90}
Kapok	Silky vegetable fiber	0.0014	0.658	0.09	0.457
		.0029	.514	.18	.357
		.016	.346	1.0	.240
		.032	.368	2.0	.255
		.064	.395	4.0	.274
		.096	.434	6.0	.301
Cotton		.032	.360	2.0	.250
		.053	.345	3.3	.239
Rock wool	Fine fibers made from limestone rock	.096	.372	6.0	.258
		.160	.386	10.0	.268
		.224	.399	14.0	.277
		.288	.386	18.0	.268
Silk noils	Waste from silk combings	.014	.369	.9	.256
Jute	Waste fibers	.014	.532	.9	.369
		.019	.519	1.2	.360
		.019	.479	1.2	.332
		.037	.388	2.3	.269
		.056	.359	3.5	.249
		.144	.395	9.0	.274
		.197	.414	12.3	.287

TABLE 1.—*Thermal conductivity of materials in bone-dry condition*—Continued

ρ=density in g/cm ^{3}
d=density in lbs./ft.^{3}
K_{32}=conductivity in milliwatts/cm °C. for a mean temperature of 32° C.
k_{90}=conductivity in $\frac{\text{B. t. u.}}{\text{hr. ft.}^2\ °\text{F./in.}}$ for a mean temperature of 90° F.

$$1\frac{\text{B. t. u.}}{\text{hr. ft.}^2\ °\text{F./in.}}=1.441 \text{ milliwatts/cm °C.}$$

Material	Description	Metric units		British units	
		ρ	K_{32}	d	k_{90}
Flax	Short fibers, with small quantity of oil in fibers.	0.019	0.516	1.2	0.358
		.038	.388	2.4	.269
Do	Waste flax, with bits of straw	.032	.456	2.0	.316
		.064	.401	4.0	.278
		.094	.392	5.9	.272
Sphagnum moss		.048	.362	3.0	.251
		.054	.369	3.4	.256
		.072	.358	4.5	.248
		.086	.342	5.4	.237
		.159	.401	9.9	.278
		.268	.489	16.7	.339
Bagasse	Sugar cane fiber, used in making insulating board.	.030	.435	1.9	.302
		.038	.417	2.4	.289
		.064	.399	4.0	.277
		.077	.411	4.8	.285
		.107	.427	6.7	.296
		.119	.454	7.4	.315
		.143	.486	8.9	.337
		.194	.540	12.1	.375
		.228	.581	14.2	.403
Corn stalk pulp	Material used in making insulating board	.061	.417	3.8	.289
		.095	.435	5.9	.302
		.118	.447	7.4	.310
		.147	.493	9.2	.342
Corn stalk pith	Not ground, but retained in same structure as in dried stalks.	.043	.430	2.7	.298
		.058	.427	3.6	.296
Wood pulp	Material used in making insulating board	.048	.438	3.0	.304
		.078	.431	4.9	.299
		.106	.445	6.6	.309
		.144	.458	9.0	.318
Sisal		.109	.385	6.8	.267
Manila hemp		.043	.493	2.7	.342
		.046	.490	2.9	.340
Redwood bark fiber		.048	.447	3.0	.310
		.080	.409	5.0	.284
Coconut husk fiber		.048	.535	3.0	.371
		.078	.447	4.9	.310
Excelsior	Shredded wood	.040	.568	2.5	.394
		.101	.514	6.3	.357
Buckwheat hulls		.195	.518	12.2	.359
Asbestos wool		.035	.548	2.2	.380
		.030	.552	5.0	.383
		.082	.519	5.1	.360
		.123	.666	7.7	.462
		.168	.724	10.5	.502
		.234	.771	14.6	.535
Wheat straw	Uncrushed	.074	.432	4.6	.300
		.220	.699	13.7	.485
Curled hair		.058	.539	3.6	.374
		.067	.499	4.2	.346
Steel wool	Marked grade 0, very fine	.048	.705	3.0	.489
		.079	.741	4.9	.514
		.109	.744	6.8	.516

From the above it will be seen that where the only consideration is maximum insulation for a given thickness, the packing should be at the optimum density.

III. EFFECT OF MOISTURE

There appear to be no available data on the effect of hygroscopic moisture on the conductivity of materials which consist of loose fibers. Measurements on very wet materials are subject to great uncertainties on account of transfer of heat by evaporation of water at one side and condensation at the other side, but little uncertainty is present in measurements on samples which have been conditioned at a moder-

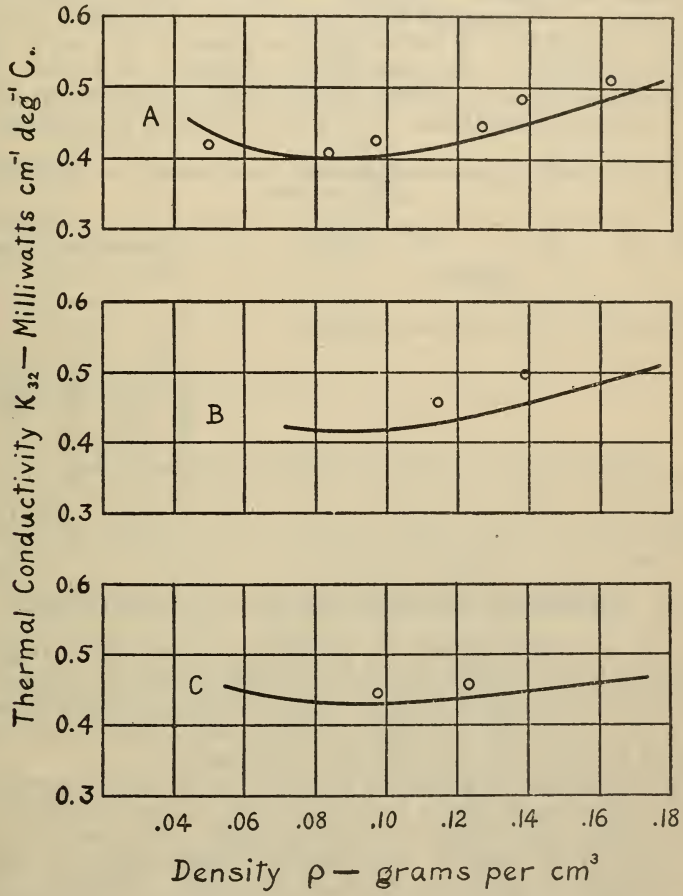

FIGURE 2.—*Comparison of data for dry and conditioned fibrous material*

Dry material ——; conditioned material ○.
A, Bagasse; *B*, cornstalk pulp; *C*, wood pulp.

ately high humidity. In the present work, samples were exposed for several days in an atmosphere which was in equilibrium with a saturated solution of Ca $(NO_3)_2$, giving a relative humidity of approximately 53 per cent at room temperature. Each sample was removed from this atmosphere and placed immediately in the hot-plate apparatus.

Three materials were studied under these conditions, and the results are given in Table 2 and Figure 2. In the figure the circles corre-

spond to the values for the specimens exposed to this humid atmosphere, while the solid lines represent values under bone-dry condition. It will be noted that the increase in conductivity, due to this exposure, is less than 10 per cent in all three cases.

It may be concluded from these results that for installations where moisture does not tend to condense within the insulating material, the latter will have nearly the same insulating properties for varying atmospheric humidities. However, in cases such as the insulation of refrigerators or cold-storage buildings, if there are points within the insulating material at or below the dew point of the air in contact therewith, moisture will continually condense as liquid. Unless effective precautions are taken to prevent the penetration of water vapor, in time the insulation value will be reduced excessively.

TABLE 2.—*Thermal conductivity of materials conditioned at a relative humidity of 53 per cent*

Material	Metric units		British units	
	ρ	K_{32}	d	K_{90}
Bagasse	0.030	0.418	1.9	0.290
	.064	.407	4.0	.282
	.077	.424	4.8	.294
	.107	.447	6.7	.310
	.118	.482	7.4	.334
	.143	.510	8.9	.354
Cornstalk pulp	.095	.459	5.9	.318
	.119	.499	7.4	.346
Wood pulp	.078	.443	4.9	.307
	.104	.457	6.5	.317

IV. THERMAL CONDUCTIVITY OF MIXTURES

Data on mixtures of fibers are of interest, since such mixtures offer a flexibility in the manufacture of insulating material greater than can be obtained by use of a single fibrous product in meeting specifications; as, for example, a certain thermal conductivity to be accompanied by a given density, strength, cost, etc.

Tests were made on a number of mixtures, of various proportions, in many cases combining a material which in itself is of high conductivity with one of very low conductivity. The results of these tests are given in Table 3. The partial densities given in this table are the weights in g/cm^3 for the two components of each sample.

It will be observed that in most all cases the conductivity of the mixture lies between the conductivities of the constituents separately when these are packed to a density equal to that of the mixture. For densities exceeding the optimum there appears to be considerable flexibility in changing the proportions of the components, keeping the same total density, without altering the resultant conductivity appreciably. For example: consider mixtures of sphagnum moss and bagasse, with a total density equal to 0.19 g/cm^3. The conductivity of sphagnum moss alone at $\rho = 0.19$ is equal to 0.427, and that of bagasse 0.538. For a mixture with partial density of sphagnum moss = 0.08, and that of bagasse = 0.11, the resultant conductivity is equal to 0.484. In a second mixture where ρ_A is increased to 0.13,

and ρ_B reduced to 0.06; the resultant conductivity is equal to 0.479, practically the same as that of the first mixture.

TABLE 3.—*Thermal conductivity of mixtures of fibers*

ρ_A = partial density of component A in g/cm³.
ρ_B = partial density of component B in g/cm³.
ρ = total density of mixture.
K_{32} = thermal conductivity of mixture in milliwatts cm⁻¹ deg⁻¹ C.

Component A	Component B	ρ_A	ρ_B	ρ	K_{32}
Asbestos	Kapok	0.026	0.012	0.038	0.386
Kapok	Flax	.004	.017	.021	.422
Flax	Wood shavings	.021	.104	.125	.477
Do	do	.024	.070	.094	.453
Steel wool (marked grade 0)	Cotton	.048	.005	.053	.736
Do	do	.034	.016	.050	.561
Wood shavings	Sphagnum moss	.080	.021	.101	.458
Do	do	.050	.050	.100	.408
Sphagnum moss [1]	Excelsior [1]	.155	.077	.232	.473
Jute	Sphagnum moss	.058	.089	.147	.424
Do	Bagasse	.085	.114	.199	.492
Sphagnum moss	do	.082	.110	.192	.484
Do. [1]	do. [1]	.082	.110	.192	.513
Do. [2]	do	.133	.062	.195	.479
Asbestos	Sphagnum moss	.070	.141	.211	.529
Do	do	.115	.058	.173	.538

[1] Small quantity of water glass used as binder.
[2] No binder.

V. EFFECT OF ARRANGEMENT OF FIBERS

From Figure 1 it will be noted for bagasse, as an example, that the thermal conductivities for densities from 0.19 to 0.24 g/cm³ will range from 0.53 to 0.59. A fabricated board made from bagasse according to the present commercial methods of manufacture will have a conductivity lower by more than 10 per cent than that of a specimen of bagasse fiber packed to the same density by the method described above. Since the fibers in such boards lie for the most part in planes parallel to the surfaces of the boards, while in the specimens they are oriented at random, it was thought that the arrangement of the fibers might have some effect on the conductivity of the material. To test this hypothesis a manufactured board was reduced to its original pulp, and remade into a board of the same density, taking no pains to arrange the fibers in any particular fashion. The pulp was merely soaked in water and the mixture thrown into a mold, pressed, and dried. The observed conductivity of the board prepared in this way was 10 per cent higher than that of the original.

TABLE 4.—*Results on tests of specimens prepared with different arrangements of fibers*

Item	Description	ρ	K_{32}
		g cm⁻³	*Milliwatts cm⁻¹ deg⁻¹ C.*
(*a*)	Flax, fibers perpindicular to heat flow	0.079	0.343
(*b*)	do	.155	.378
(*c*)	Flax, fibers parallel to heat flow	.079	.768
(*d*)	do	.154	1.20
(*e*)	Flax, lengths of approximately 5 mm, random arrangement	.079	.401
(*f*)	Glass wool, fibers perpendicular to heat flow	.16	.375
(*g*)	Glass wool, fibers parallel to heat flow	.16	.80
(*h*)	Board A (with glue)		1.14
(*i*)	Board B (with glue)		.86
(*j*)	Board A (without glue)		1.04
(*k*)	Hair felt, fibers perpendicular to heat flow	.18	.375
(*l*)	Hair felt specimen, portion of fibers parallel to heat flow	.18	.574
(*m*)	Excelsior, fibers perpendicular to heat flow	.106	.466
(*n*)	Wheat straw, fibers perpendicular to heat flow	.074	.457
(*o*)	Excelsior, random arrangement	.101	.514
(*p*)	Wheat straw, random arrangement	.074	.432
(*q*)	Flax, with fibers in each layer perpendicular to those in adjacent layer	.151	.369
(*r*)	Wheat straw, partial density=0.075 Flax, partial density=0.013	.088	.442
(*s*)	Excelsior, partial density=0.104 Flax, partial density=0.029	.133	.468

Additional experiments were made to test the effect of arrangement of fibers in altering the resultant conductivity. The first experiments were performed on flax, because a sample was available which was well combed, and this suited the purpose in hand. Two test specimens were prepared with all fibers at right angles to the direction of heat flow. The values of the densities and thermal conductivities of these specimens are given under items (*a*) and (*b*), Table 4. Two additional specimens of the same flax were prepared with the fibers parallel to the direction of heat flow. The results for these are given under items (*c*) and (*d*), Table 4. A specimen of the same flax was prepared by cutting the fibers to lengths of approximately 5 mm., and packing them without any attempt at order. The results, incicated under item (*e*), are seen to be somewhat higher than (*a*), but considerably lower than (*c*).

Tests on glass wool with fibers perpendicular and parallel to the direction of heat flow gave the results indicated under items (*f*) and (*g*), respectively.

Tests were made on manufactured boards as follows: Samples of two kinds of commercial insulating boards, each single ply (approximately one-half inch thick), with conductivities equal to 0.49 for each board were cut into 1-inch strips and laid together so that the original surfaces were in direct contact, forming specimens 1 inch thick. The fibers in the original boards lie largely in planes parallel to the finished surfaces. Within each plane the fibers are arranged in all directions. In the prepared specimens these planes are parallel to the direction of heat flow, so that in effect a considerable proportion of the fibers themselves will be arranged parallel to the general direction of heat flow. Two such specimens were prepared with the 1-inch strips cemented together with glue. A third specimen was made without glue and held together mechanically to obtain a value for the conductivity unaffected by glue or binder. The results are given under items (*h*), (*i*), and (*j*), Table 4.

A sheet of hair felt 1 inch thick was cut in the same manner as these insulating boards, and a test sample prepared similar to those from the boards, using no binder. The conductivities of the original sheet and the prepared specimen are indicated under items (*k*) and (*l*), Table 4.

The above results on flax fibers, glass wool, manufactured insulating boards, and hair felt indicate that the fibers themselves have a very high conductivity, and the conductivity of a fabricated product may be very greatly affected by the arrangement of the fibers. The effect of increase in mean temperature on the conductivity is much greater for those samples where the fibers are parallel to the heat flow. This is shown by the results obtained on flax (specimen given under item (*d*), Table 4), where the conductivity has been found to increase with temperature approximately twice as fast as that for specimens (*a*) and (*b*).

Additional experiments were tried on very coarse materilas, excelsior and uncrushed wheat straw, with the purpose of observing how low a conductivity may be obtained by arranging all the strands or stalks normal to the direction of the flow. In each case the strands or stalks were laid parallel to each other and perpendicular to the direction of heat flow. The results are given under items (*m*) and (*n*), Table 4. The same materials were again packed without any attempt at order, and the results are given under items (*o*) and (*p*). Although in case of excelsior the parallel arrangement reduces the conductivity, and in wheat straw there is an apprent slight increase, the differences are not sufficiently great to be of any significance. It may be said that materials, in general, and coarse materials, in particular, will tend to take a position such that the direction of the fibers will be approximately perpendicular to the direction of the packing pressure. Therefore, in (*o*) and (*p*) the fibers may have been to avery large extent perpendicular to the direction of heat flow. This natural tendency in fiber arrangement accounts for the moderate variations in the conductivity of fibers packed at random, compared with the large range possible with special fiber arrangements.

Considering the possible range of conductivities, which mayreach at least as high as 1.1, it might seem surprising that by arranging the fibers perpendicular to the heat flow conductivities as low as 0.35 to 0.37 can be obtained; for, it must be remembered that the conductivity of still air (no radiation) is equal to 0.245, and the difference between that and 0.35 to 0.37 is only about one-seventh the range from air to the value 1.1.

The explanation lies in the fact that the arrangement of fibers perpendicular to heat flow is in effect a series arrangement of fibers and air, the thermal contact between fibers being on the average very poor in any ordinary density of packing, unless they are well cemented together with some binding material. Since the actual volume of the fiber present is but a small fraction of the total volume of the mass, the high conductivity of the fiber itself does not affect the heat transfer by conduction through the mass to any large extent. The presence of the fiber is, of course, indispensable, since it reduces heat transfer by radiation and air convection to a small amount. Arrangement of fibers parallel to the direction of heat flow is in effect a parallel arrangement (as in electric circuits) of fibers and air. In this case the high conductivity of the fibers themselves exerts

the maximum influence on the resultant conductivity of the mass. The high conductivity of asbestos wool as ordinarily packed may be due in part to the fact that the individual fibers adhere to each other and the nature of this contact may be such as to make the contact resistance low.

It is conceivable that the effect of the presence of liquid water within a material is also to reduce contact resistance between fibers and thus increase the conductivity. If through capillary attraction water fills the individual fibers, there may also be a film of water on the surface of each fiber. In this case the fibers will be connected at their points of contact by liquid films of relatively high conductivity. Coating the individual fibers with a substance which is not wetted by water will, of course, avoid this capillary effect. Nevertheless, if moisture condenses within insulating material, due to the fact that the temperatures within the material are at or below the dew point, the liquid water will still reduce contact resistance.

A few experiments were tried to see if the contact resistance between fibers could be increased. A specimen of flax fiber was prepared as follows: A thin layer of fibers was arranged with all the fibers running in one direction. A second thin layer was placed upon the first, with its fibers running perpendicular to those in the first layer. A third layer had its fibers parallel to those in the first layer. Numerous layers were built up in this fashion, each succeeding layer having its fibers perpendicular to the fibers in the preceding layer. It will be noted that within each layer, consisting of a number of strands in thickness, the points of contact may not have been any different from those in the former samples; that is, adjacent parallel strands or fibers may have been touching each other over a large portion of their entire length. However, between the adjacent layers, the contacts were only at the points of crossing. The direction of heat flow was perpendicular to all the fibers. The results on this specimen are given under item (*q*), Table 4. Comparing this with (*b*) in the table, it will be observed that there is a slight reduction in conductivity. It is conceivable that if each layer consisted of single strands of flax, the reduction might have been greater.

Additional experiments were tried with mixtures, one a mixture of wheat straw and flax, and a second of excelsior and flax. In each case the specimen was prepared as follows: A thin layer of coarse fibers was arranged so that its fibers were parallel. The second layer consisted of flax, with its fibers perpendicular to those in the first layer. A third layer of coarse fibers parallel to those in the first layer was placed on the second. Thin layers of coarse fibers, separated by much thinner layers of flax, were built up in this fashion, the idea being that the layers of flax would serve to break up the points of contact of the coarse fibers. The results of tests on these specimens are given under items (*r*) and (*s*), Table 4. Comparing (*r*) with (*n*) above, the reduction is 3 per cent; comparing (*s*) with (*m*) the reduction is nil.

The results of the experiments on fiber arrangement indicate very definitely that the arrangement of the fibers has much to do with the resulting insulating value of a material. The present methods of manufacture of fibrous sheet materials do accomplish to a large extent the orientation of the fibers so that they are most effective for insulation.

VI. CONVECTION AND RADIATION

As has been mentioned above, the conductivity-density curve for a given material will always have a minimum point. For densities less than the optimum it is usually assumed that convection and radiation increase at such a rate that they more than compensate for the low conduction of the diminished number of fibers. It is interesting to inquire what part, if any, radiation and convection play in heat transfer at low densities.

The first set of experiments was made on kapok, packed to the very low density of 0.003 g/cm^3. In the first experiment the specimen tested was in a vertical position. In a second experiment, the specimen, together with the hot and cold plates was placed in a horizontal position with the hot plate above and the cold plate below the specimen. Over the upper side of the hot plate was placed a calibrated specimen of cork, and the heat flow through this cork specimen was taken into account in calculating the thermal conductivity of the kapok. The results in the two cases are given under items (*a*) and (*b*), Table 5. The difference between these two values is less than 3 per cent. In case of (*b*) it may be assumed that there was no convection. Since the difference is so small, it may be concluded that in the vertical position the fibers retarded air circulation sufficiently to make convection play but a minor part.

To observe the effect of radiation within the same sample of kapok, dry aluminum powder was dusted throughout its mass. The fibers were thus partially coated with aluminum, which would tend to lower their radiation emissivity and reduce the heat transfer through the mass, provided radiation plays an appreciable part in the heat transfer process. A test on this sample in a vertical position gave the result indicated under item (*c*), Table 5. Comparing this with (*a*) in the table, the reduction is 17 per cent. A test on a second specimen of kapok of denisty 0.016 with dry aluminum powder scattered throughout its mass gave the result indicated under item (*d*), Table 5. Comparing this with the results of Figure 1, it will be noted that this is very close to plain kapok at the same density. This indicates that at such densities radiation plays a negligible rôle.

Similar tests were made on asbestos and bagasse, aluminum powder being scattered throughout the mass of each. The results are given under items (*e*), (*f*), (*g*), and (*h*), Table 5. The reduction in the case of (*e*) is about 17 per cent, while for the higher denisty of asbestos it is hardly appreciable. For bagasse there is an increase in conductivity, but that may be due to the effect of metallic conduction. In fact for that density of bagasse radiation is not expected to be of great significance.

These experiments indicate that convection, which was formerly believed to be the prime cause of the increase in the heat transfer at very low densities, is very slight. Radiation plays a much larger part than is ordinarily credited to it.

TABLE 5.—*Results on tests of specimens prepared to study convection and radiation*

Item	Description	ρ	K_{32}
		g cm^{-3}	*Milliwatts cm*$^{-1}$ *deg*$^{-1}$ *C.*
(*a*)	Kapok, test specimen vertical	0.003	0.540
(*b*)	Kapok, test specimen horizontal	.003	.524
(*c*)	Kapok, dusted with aluminum powder, test specimen vertical	.003	.455
(*d*)	do	.016	.353
(*e*)	Asbestos, dusted with aluminum powder	.035	.451
(*f*)	do	.079	.516
(*g*)	Bagasse, with small quanitity of aluminum powder	.101	.467
(*h*)	Bagasse, with larger quantity of aluminum powder	.096	.491

VII. CONCLUSIONS

The results of this paper throw light on the manner in which heat is transferred through fibrous materials. It may safely be said that technique is as important as the choice of raw materials in the manufacture of insulation. As has been noted above, the fibers themselves are potentially capable of conducting much heat, but fortunately the presence of the air provides very poor thermal contacts. Yet, for materials at densities used in practice from 30 to 50 per cent of the total heat transferred is by conduction in the fibers, and the remainder by conduction through the inclosed air. At these densities convection and radiation are negligible.

It is of interest to consider how the insulating value of products made from a given fiber may be improved. Since the air present within the material conducts from 50 to 70 per cent of the heat, the air might be replaced by a gas which has a lower thermal conductivity. In cases where the material is effectively sealed, this may be feasible, but such cases are very limited in number. In the large majority of cases where rigid insulation is used as in building construction, railroad refrigeration cars, etc., it would hardly be practicable.

A more promising method of attack would be to study the effect of size of fibers on the conduction. It is conceivable that in breaking up coarse fibers into fine ones, the contact resistances might be increased, for this would yield a more homogeneous mixture of air and solid material. However, there will be some limit to the fineness of fiber beyond which it will not be feasible to proceed, and the effect of shredding on the mechanical properties of the product must also be considered.

In the manufacture of insulating boards it is common practice to coat the fibers with some water-repelling material before forming them into a board. It is conceivable that different materials may produce different contact resistances; for example, the application of a coating which hardens so that it ceases to be tacky before the board is formed, may offer a higher contact resistance than a coating which is still soft and tends to fuse the contact points.

WASHINGTON, July 22, 1930.